Appendix B

Advanced Creations in Electrical Engineering

Die polnischen Juden machen nach gewissen gesprochen Gebeten und gehaltenen Fasttägen, die Gestalt eines Menschen aus Thon oder Leimen, und wenn sie das wunderkräftige Schemhamphoras darüber sprechen, so muß er lebendig werden. Reden kann er zwar nicht, versteht aber ziemlich was man spricht und befiehlt. Sie heißen ihn Golem, und brauchen ihn zu einem Aufwärter, allerley Hausarbeit zu verrichten, allein er darf nimmer aus dem Hause gehen. An seiner Stirn steht geschrieben *aemaeth* (Wahrheit, Gott) er nimmt aber täglich zu, und wird leicht größer und stärker denn alle Hausgenossen, so klein er anfangs gewesen ist. Daher sie aus Furcht vor ihm den ersten Buchstaben auslöschen, so daß nichts bleibt als *maeth* (er ist todt) worauf er zusammenfällt und wiederum in Ton aufgelöst wird.

The Polish Jews, after speaking certain prayers and observing fast days, made the figure of a man out of clay or loam, and when they speak the miracle-working Schemhamphoras over it, the figure comes alive. It is true that he cannot speak, but he understands reasonably well what anyone says to him and commands him to do. They call him Golem and use him as a servant to do all sorts of housework, but he may never leave the house alone. On his forehead is written *Aemaeth* (Truth, God). However, he increases in size daily and easily becomes larger and stronger than all his housemates, regardless of how small he was at first. Therefore, fearing him, they rub out the first letter, so that nothing remains but *Maeth* (he is dead), whereupon he collapses and is dissolved again into clay.

Jakob Grimm. 1808. *Zeitung für Einsiedler* [*Journal for Hermits*] No. 7, 23 April.
English translation by Edan Dekel and David Gantt Gurley.

German-speaking research groups designed and developed revolutionary microelectronics technologies years before those technologies were officially "invented" at Bell Laboratories and other non-German firms.

This appendix presents documentary evidence for:

B.1. The invention of transistors by German-speaking creators.

B.2. The invention of printed circuits/multi-pin connectors by German-speaking creators.

B.3. The invention of integrated circuits by German-speaking creators.

B.4. The invention of light emitting diodes (LEDs) by German-speaking creators.

B.5. The transfer of those technologies to other countries and companies.

Much more archival research is needed to clarify the historical details for the development and transfer of microelectronics technologies.

B.1 Transistors

[According to official histories, the first transistor was invented in the United States at AT&T Bell Telephone Laboratories in late 1947 and early 1948 by John Bardeen (American, 1908–1991), Walter Brattain (American, 1902–1987), and William Shockley (American, 1910–1989).

However, there is evidence that transistors were actually developed (or under development) earlier by at least 12 independent groups in the predominantly German-speaking research world that were led by the following scientists (Fig. B.1):

1. Julius Edgar Lilienfeld (Austrian, 1882–1963)
2. Oskar Heil (German, 1908–1994)
3. Gilles Holst (Dutch, 1886–1968) and Willem Christiaan van Geel (Dutch, 1895–1967)
4. Rudolf Hilsch (German, 1903–1972) and Robert Pohl (German, 1884–1976)
5. Erich Habann (German, 1892–1968)
6. Walter Schottky (Swiss/German, 1886–1976)
7. Heinrich Welker (German, 1912–1981) and Herbert Mataré (German, 1912–2011)
8. Erwin Weise (German?, 19??–19??)
9. Frank Rose (German?, 19??–19??), Eberhard Spenke (German, 1905–1992), and Erich Waldkötter (German?, 19??–19??)
10. Karl Seiler (German, 1910–1991) and Paul Ludwig Günther (German, 1892–1969)
11. Helmar Frank (Moravian, 1919–2015) and Jan Tauc (Bohemian, 1922–2010)
12. Bernhard Gudden (German, 1892–1945) and Kurt Lehovec (Bohemian/Austrian/Czech, 1918–2012)

In addition to these 12 groups, were there any other German-speaking groups developing transistors, for example at laboratories run by AEG, Askania, Blaupunkt, Fernseh, Loewe Radio, C. Lorenz, Philips, the Reichspost, Siemens, the SS, Telefunken, various universities, or other laboratories in Germany, Austria, Czech territory, Polish territory, or elsewhere? Much more archival research is needed in this area.]

Figure B.1: At least 12 groups in the predominantly German-speaking scientific world apparently developed or were developing transistors 1922–1947 (prior to AT&T Bell Laboratories).

[**1. Julius Edgar Lilienfeld (Austrian, 1882–1963)** filed several patent applications on a field effect transistor during the period 1925–1928, including:

> Julius Edgar Lilienfeld. Filed in 1925 in Canada and in 1926 in the United States. U.S. Patent 1,745,175. Method and Apparatus for Controlling Electric Currents. (pp. 2657–2660)
>
> Julius Edgar Lilienfeld. Filed in 1928. U.S. Patent 1,900,018. Device for Controlling Electric Current. (pp. 2661–2670)
>
> Julius Edgar Lilienfeld. Filed in 1928. U.S. Patent 1,877,140. Amplifier for Electric Currents. (pp. 2671–2677)

The great level of detail in those applications regarding the production and performance of such transistors strongly suggests that he built and tested them [Arns 1998; Crawford 1991], although exactly what results he achieved are not clear from currently available documents.

Much later, Bell Laboratories secretly built fully functioning devices based directly on Lilienfeld's patents, lending further support to the view that the patents were based on Lilienfeld's own successful experimentation [Arns 1998; Shockley and Pearson 1948].

In the 1920s, Lilienfeld moved to the United States, where he married an American woman. It appears that he was unsuccessful in finding sufficient financial and political support for his transistor approach in the United States. In the 1930s, Lilienfeld and his wife moved to the island of Saint Thomas in the Caribbean, where they lived the rest of their lives.]

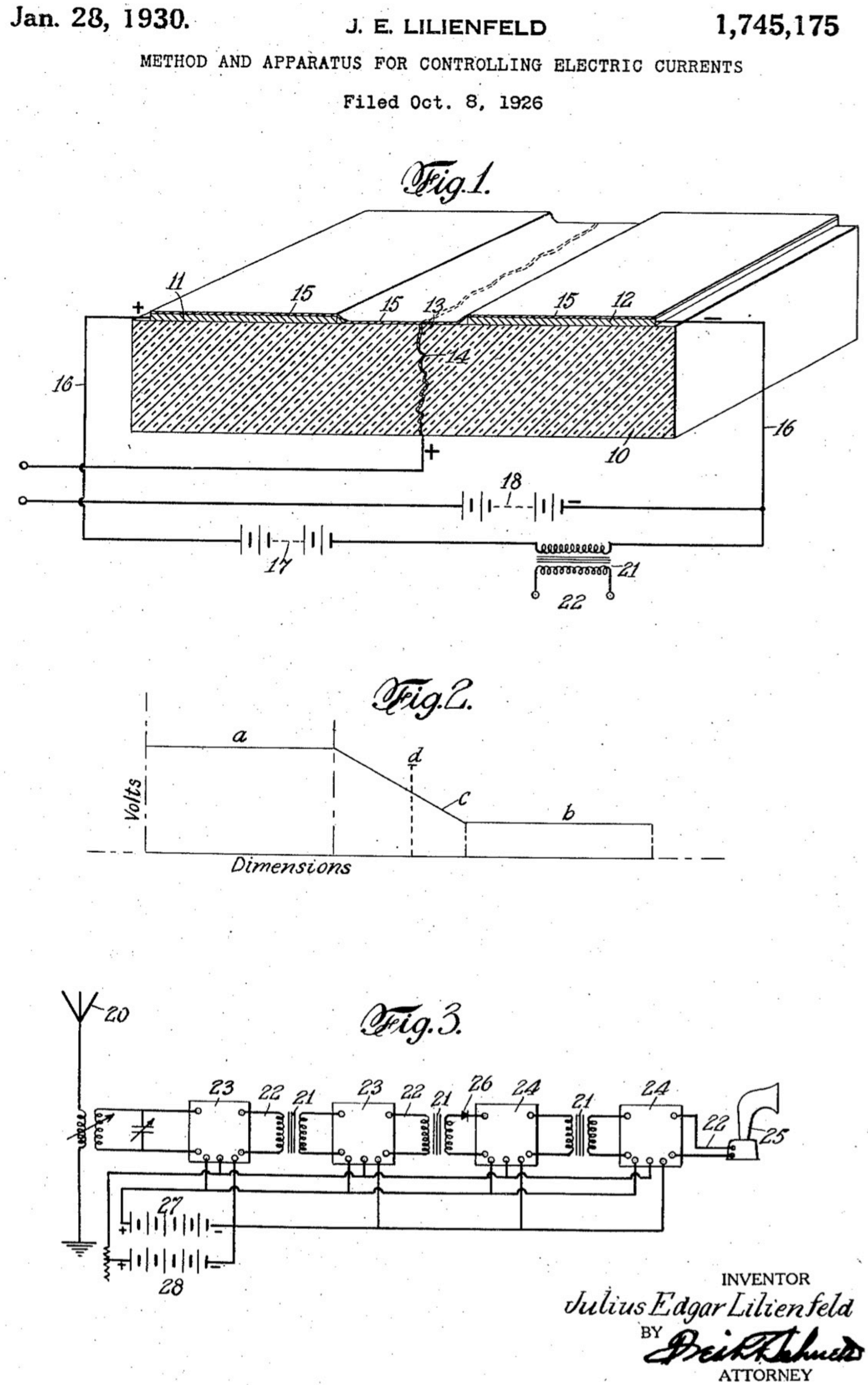

Figure B.2: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,745,175 (originally filed in 1925 in Canada).

Patented Jan. 28, 1930 **1,745,175**

UNITED STATES PATENT OFFICE

JULIUS EDGAR LILIENFELD, OF BROOKLYN, NEW YORK

METHOD AND APPARATUS FOR CONTROLLING ELECTRIC CURRENTS

Application filed October 8, 1926, Serial No. 140,363, and in Canada October 22, 1925.

The invention relates to a method of and apparatus for controlling the flow of an electric current between two terminals of an electrically conducting solid by establishing a third potential between said terminals; and is particularly adaptable to the amplification of oscillating currents such as prevail, for example, in radio communication. Heretofore, thermionic tubes or valves have been generally employed for this purpose; and the present invention has for its object to dispense entirely with devices relying upon the transmission of electrons thru an evacuated space and especially to devices of this character wherein the electrons are given off from an incandescent filament. The invention has for a further object a simple, substantial and inexpensive relay or amplifier not involving the use of excessive voltages, and in which no filament or equivalent element is present. More particularly, the invention consists in affecting, as by suitable incoming oscillations, a current in an electrically conducting solid of such characteristics that said current will be affected by and respond to electrostatic changes. Means are associated with the aforesaid conducting solid whereby these electrostatic changes are set up conformably with the incoming oscillations which are thus reproduced greatly magnified in the circuit, suitable means being provided, also, to apply a potential to the said conducting solid portion of the amplifier circuit as well as to maintain the electrostatic producing means at a predetermined potential which is to be substantially in excess of a potential at an intermediate point of said circuit portion.

The nature of the invention, however, will best be understood when described in connection with the accompanying drawings, in which—

Fig. 1 is a perspective view, on a greatly enlarged scale and partly in section, of the novel apparatus as embodied by way of example in an amplifier.

Fig. 2 is a diagrammatic view illustrating the voltage characteristics of an amplifier as shown in Fig. 1.

Fig. 3 is a diagrammatic view of a radio receiving circuit in which the novel amplifier is employed for two stages of radio frequency and two of audio frequency amplification.

Referring to the drawings, 10 designates a base member of suitable insulating material, for example, glass; and upon the upper surface of which is secured transversely thereof and along each side a pair of conducting members 11 and 12 as a coating of platinum, gold, silver or copper which may be provided over the glass surface by well-known methods such as chemical reduction, etc. It is desirable that the juxtaposed edges of the two terminal members 11 and 12 be located as closely as possible to each other; and substantially midway of the same there is provided an electrode member 13, which is of minimum dimensions to reduce capacity effect. This member consists of a suitable metal foil, preferably aluminum foil, and may conveniently be secured in position by providing a transverse fracture 14 in the glass and then reassembling the two pieces to retain between the same the said piece of aluminum foil of a thickness approximating one ten-thousandth part of an inch. The upper edge of this foil is arranged to lie flush with the upper surface of the glass 10.

Over both of the coatings 11 and 12, the intermediate upper surface portion of the glass 10, and the edge of the foil 13 is provided a film or coating 15 of a compound having the property of acting in conjunction with said metal foil electrode as an element of uni-directional conductivity. That is to say, this coating is to be electrically conductive and possess also the property, when associated with other suitable conductors, of establishing at the surface of contact a considerable drop of potential. The thickness of the film, moreover, is minute and of such a degree that the electrical conductivity therethru would be influenced by applying thereto an electrostatic force. A suitable material for this film and especially suitable in conjunction with aluminum foil, is a compound of copper and sulphur. A convenient way of providing the film over the coatings

Figure B.3: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,745,175 (originally filed in 1925 in Canada).

2 1,745,175

11 and 12 and the electrode 13 is to spatter metallic copper by heating copper wire within a vacuum, or by depositing copper from a colloidal suspension, over the entire upper surface and then sulphurizing the deposited copper in sulphur vapor, or by exposure to a suitable gas as hydrogen sulphide or a liquid containing sulphur, as sulphur dissolved in carbon bisulphide.

To produce the required flow of electrons through the film 15 a substantial potential is applied across the two terminal coatings 11 and 12 as by conductors 16 leading from a battery or like source 17 of direct current. As shown in the diagrammatic view, Fig. 2, the dimensional volt characteristics of the device indicate a substantially steady voltage of value *a* over the coating 11 and a corresponding steady voltage *b* of diminished value over the coating 12, while over the portion of the surface between said coatings the voltage in the film 15 will be according to the gradient *c*. As aforesaid, the electrode 13 is located substantially midway of the inner ends of the terminal coatings 11 and 12 and there is arranged to be supplied thereto a potential indicated by the value *d*, Fig. 2, and somewhat in excess of the voltage prevailing along the gradient *c* at this point. This potential may be applied by means of a battery or like source of potential 18, the negative pole of which is connected to the negative pole of the battery 17. In the circuit of the electrode 13 and source of potential 18 is also included some exterior source of oscillating or fluctuating current, which source is indicated, by way of example, in Fig. 3, as the antenna 20 of a radio communication circuit.

The effect of thus providing an excess positive potential in the electrode 13 is to prevent any potential in the oscillating circuit hereinbefore described from rendering said electrode of zero potential or of a negative potential, which would then permit a current to pass from the electrode edge to the film 15; as in the reverse direction where a positive voltage is maintained, the two members—namely electrode and connecting film—act as an electric valve to prevent the flow. Maintaining a positive potential at this point, however, insures that the flow of the electrons from the piece 11 to the piece 12 will be impeded in a predetermined degree, a variation therein being effected conformably to the changing amount of this potential under the influence of the oscillating or fluctuating current introduced. This effect will be repeated on a greatly magnified scale in the circuit of the conducting coatings 11 and 12 and may be reproduced in various circuits or for various purposes as thru a transformer 21, from the secondary of which leads 22 extend to any suitable device, which, as shown in Fig. 3, may be further amplifiers of this character as the radio frequency amplifiers 23 and audio frequency amplifiers 24, the last of which is shown connected to a loud speaker or similar device 25. A current rectifying member 26, however, is necessary where it is desired to convert the radio frequency into audio frequency oscillations. It will be observed that but two sources of potential 27 and 28—which may be combined into a single, properly tapped source—are required and of potentials approximately 30 and 15 volts respectively for the particular elements employed.

The basis of the invention resides apparently in the fact that the conducting layer at the particular point selected introduces a resistance varying with the electric field at this point; and in this connection it may be assumed that the atoms (or molecules) of a conductor are of the nature of bipoles. In order for an electron, therefore, to travel in the electric field, the bipoles are obliged to become organized in this field substantially with their axes parallel or lying in the field of flow. Any disturbance in this organization, as by heat movement, magnetic field, electrostatic cross-field, etc., will serve to increase the resistance of the conductor; and in the instant case, the conductivity of the layer is influenced by the electric field. Owing to the fact that this layer is extremely thin the field is permitted to penetrate the entire volume thereof and thus will change the conductivity throughout the entire cross-section of this conducting portion.

I claim:—

1. The method of controlling the flow of an electric current in an electrically conducting medium of minute thickness, which comprises subjecting the same to an electrostatic influence to impede the flow of said current by maintaining at an intermediate point in proximity thereto a potential in excess of the particular potential prevailing at that point.

2. The method of controlling the flow of an electric current in an electrically conducting solid of minute thickness, which comprises establishing an electrostatic influence in proximity to said flow in excess of the potential prevailing thereat, and varying the said electrostatic influence to correspondingly vary the said flow.

3. The method of controlling the flow of an electric current in an electrically conducting medium of minute thickness, which comprises subjecting the same to an electrostatic influence to impede the flow of said current by maintaining at an intermediate point in proximity thereto a potential in excess of the particular potential prevailing at that point, and varying the degree of excess potential by an impressed oscillating current.

4. An amplifier for oscillating current, comprising a film of conducting material and an output circuit including a source of potential connected across said film, an electrode associated with the said film for maintaining

Figure B.4: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,745,175 (originally filed in 1925 in Canada).

at the surface of contact a third potential, means to establish in said electrode a voltage substantially in excess of the voltage in the film at the coacting electrode portion, and means to vary the voltage of said electrode.

5. An amplifier for oscillating current, comprising a film of conducting material and and an output circuit including a source of potential connected across said film, an electrode operating in conjunction with said film intermediate the point of application of the potential thereto to provide an element of uni-directional conductivity thereat, means to maintain said electrode at a voltage substantially in excess of the voltage prevailing at the coacting portion of said conducting film, and an input circuit connected with the said electrode and the negative end of the said film.

6. An amplifier for oscillating current, comprising two insulating members, an intermediate strip of aluminum foil, conducting terminals carried by said insulation members upon either side of the said foil retained thereby, a film of copper sulphur compound extending over said conducting terminals and the edge of the said aluminum strip, output connections to said conducting terminals for applying a potential across the same, and a connection to the said aluminum strip to maintain the same at a higher potential than that prevailing in the film at its portion opposite the aluminum strip.

7. An amplifier for oscillating current, comprising two insulating members, an intermediate strip of aluminum foil, conducting terminals carried by said insulation members upon either side of the said foil retained thereby and in close proximity thereto, a film of copper sulphur compound extending over said conducting terminals and the edge of the said aluminum strip, output connections to said conducting terminals for applying a potential across the same, and a connection to the said aluminum strip to maintain the same at a higher potential than that prevailing in the film at its portion opposite the aluminum strip.

8. An amplifier for oscillating current, comprising a glass block fractured transversely, a strip of aluminum foil retained in the fracture of said block with an edge substantially flush with the corresponding surface of the block, copper terminal coatings carried by the glass block upon opposite sides of said foil and out of contact therewith, a film of copper sulphur compound extending over the surface of said copper terminals and the aluminum edge, output connections to the said copper terminals to apply a potential across the same, and a connection to the aluminum foil to maintain the same at a higher potential than that prevailing in the film at its portion opposite the aluminum strip.

9. An amplifier for oscillating current, comprising a glass block fractured transversely, a strip of aluminum foil retained in the fracture of said block with an edge substantially flush with the corresponding surface of the block, copper terminal coatings carried by the glass block upon opposite sides of said foil and out of contact therewith, a film of copper sulphur compound extending over the surface of said copper terminals and the aluminum edge, output connections to the said copper terminals to apply a potential across the same, a connection to the aluminum foil to maintain the same at a higher potential than that prevailing in the film at its portion opposite the aluminum strip, and a source of fluctuating current in circuit with the aluminum foil.

In testimony whereof I affix my signature.

JULIUS EDGAR LILIENFELD.

Figure B.5: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,745,175 (originally filed in 1925 in Canada).

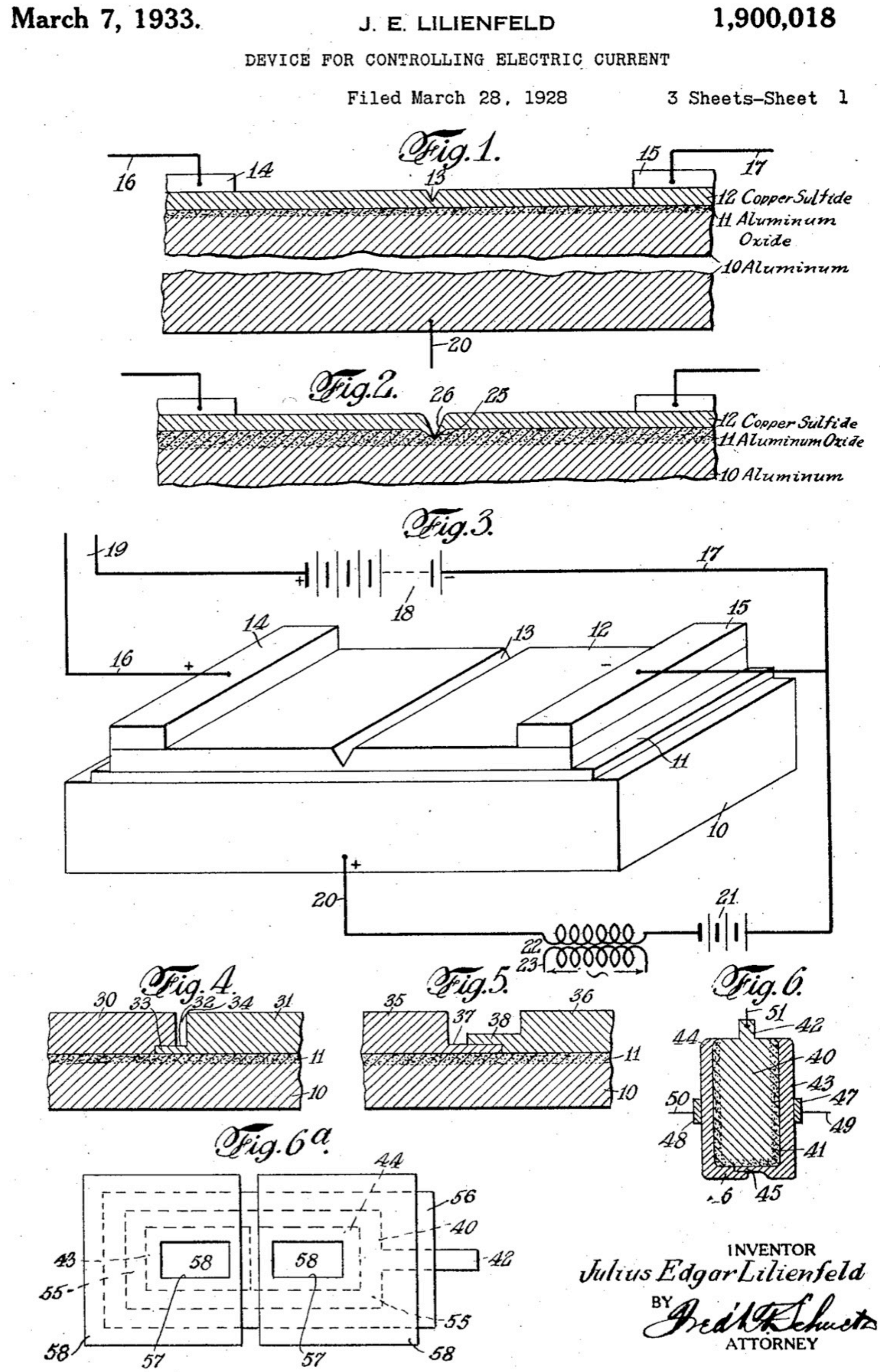

Figure B.6: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,900,018 (filed in 1928).

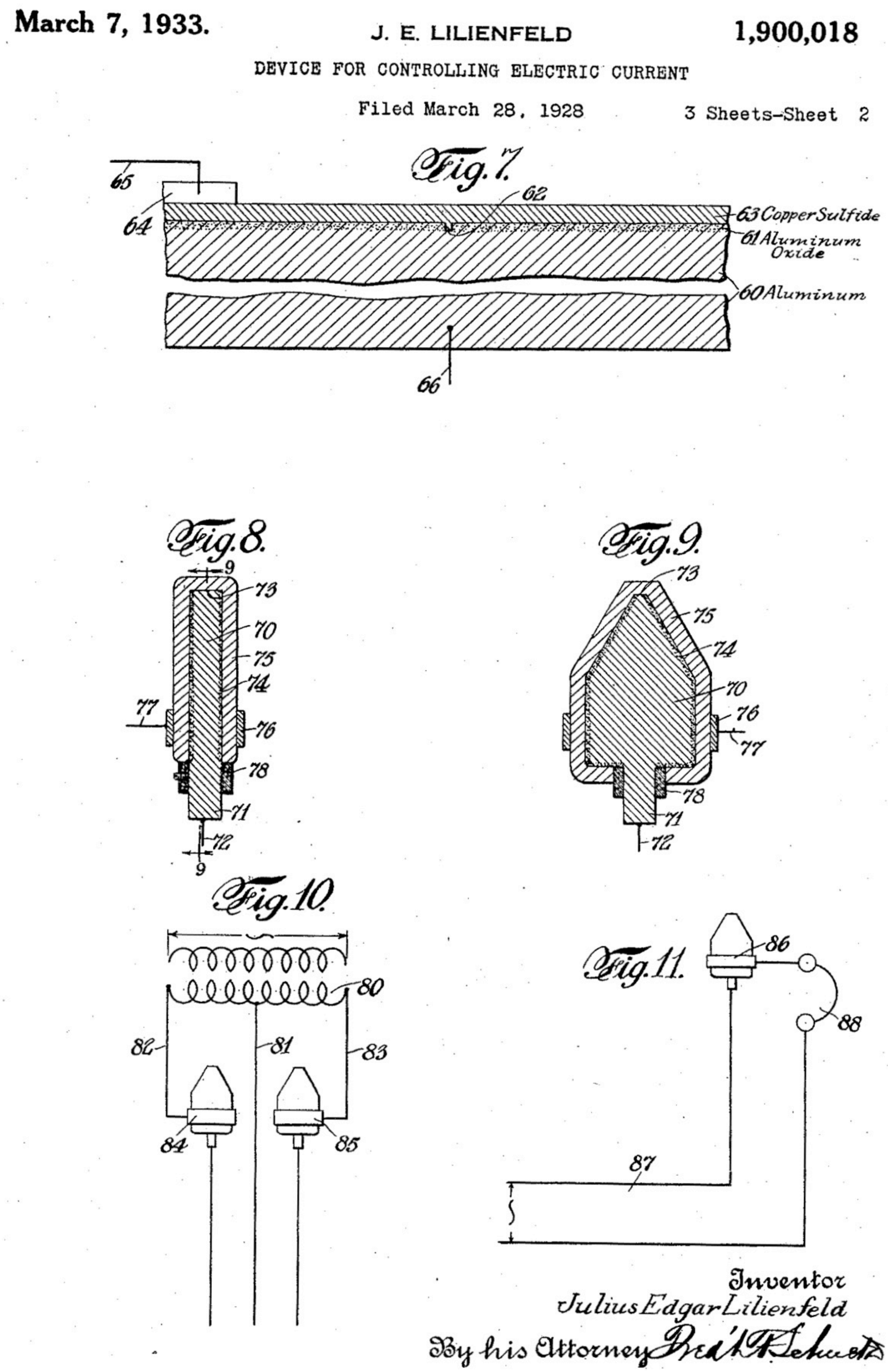

Figure B.7: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,900,018 (filed in 1928).

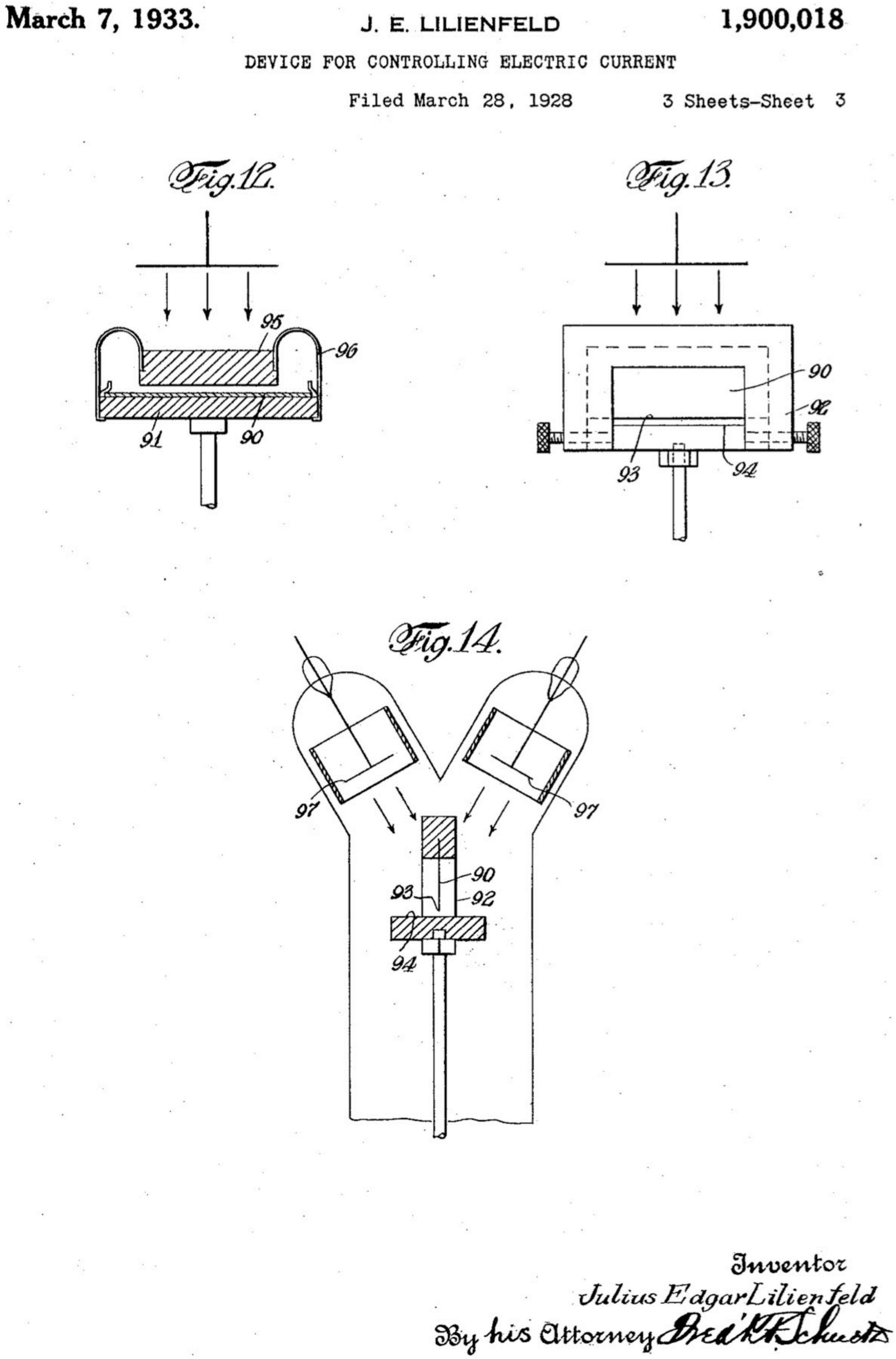

Figure B.8: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,900,018 (filed in 1928).

Patented Mar. 7, 1933 **1,900,018**

UNITED STATES PATENT OFFICE

JULIUS EDGAR LILIENFELD, OF BROOKLYN, NEW YORK

DEVICE FOR CONTROLLING ELECTRIC CURRENT

Application filed March 28, 1928. Serial No. 265,372.

The invention relates to a device for use in connection with electric circuits, more particularly in the variation of the current characteristics thereof, for example, as a novel amplifier or rectifier (detector) element to be included in a suitable circuit.

It has for its object the provision of a simple, compact and substantial device of this character which withal shall be comparatively inexpensive to construct. The novel device may embody, for example, an amplifier in the use of which no filament heating or electron-producing means of this character are required, which device, moreover, may be operated under much lower voltage conditions than heretofore. Likewise, it is also adaptable to the rectification (detection) of oscillating currents.

If a coating of compounds of a metal, for example, the oxide of aluminum, magnesium, tantalum, tungsten, etc., be provided partly or entirely over a surface of the respective metal selected, or an alloy of several of these metals, an insulating layer having high dielectric properties may be attained; and I have discovered that an extremely intensive electric field may be established in a minute thickness of this layer, provided a further layer or coating of substantially more conductive material be integrally associated therewith by applying this material in disintegrated or finely subdivided state, e. g. by spraying or by spattering it cathodically in a vacuum from such metals as copper, lead, aluminum, etc., over said dielectric layer. Or, said layer may be applied by colloidal precipitation, it being understood that substantially molecular contact over the whole area is had between it and the dielectric layer.

Under these circumstances, such insulating layers, I also have discovered, do not possess the rectifying properties similar to those which are shown by different combinations, for example, when aluminum oxide is deposited on an aluminum electrode of an electrolytic cell with ammonium borate as electrolyte; on the contrary, the layers show insulating properties for voltages applied in either direction.

The underlying or base material is preferably of relatively thin metal, approximately 0.03 mm. or less to prevent, in case of bending distortion of the same and injury to the superposed layers.

In some cases it may be advisable to apply in succession in the manner indicated more than one coating partly or wholly over the first and insulating layer in order to increase the effectiveness of the insulation, a final coating of particularly good conducting quality, as of silver, platinum, tin, nickel, aluminum, etc., however, being generally provided so as to secure a good contact for the outside lead. These coatings, in particular as well as in certain instances also the initial coating, may be precipitated from colloidal metal suspensions; or they may be "metal sprayed."

The dielectric layer or layers when thus coated maintains its highly insulating property, affording a substantial insulation between the said underlying metal and the said coating or coatings; so that it is possible to apply voltages of the order of magnitude of 100 volts across a dielectric thus produced and of a thickness of the order of magnitude of only 10^{-4} mm. without puncturing it. In fact, the device will in many instances possess self-healing properties. In the aluminum-aluminum oxide embodiment with an oxidizable layer of copper, aluminum, magnesium, etc., short circuits will disappear as soon as the device is momentarily subjected to load.

This is a possible explanation of the fact, which I have discovered, that the allowable voltage appears to be a function not only of the nature and thickness of this dielectric layer but also of the physical and chemical properties of the superposed coatings. A coating produced by spattering from a copper cathode over the dielectric layer, for example, imparts to the layer the property of withstanding a higher voltage than silver similarly applied. These more effective coatings, however, may, in some cases, not be very highly conductive; and it is, therefore, sometimes desirable to provide more than one coating over the layer, the outer of them to possess a particularly good conducting quality and the same may be applied in any suitable manner, for example, electrolytically.

Figure B.9: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,900,018 (filed in 1928).

The dielectric layer may readily be attained of this minute thickness by electrolytic or by purely chemical methods, e. g. heat oxidation, sulfurization, etc., forming the same of and directly on the metal base; and a dielectric layer consisting of the oxide of aluminum thus formed directly of an underlying solid conducting base of aluminum has been found very satisfactory for the purpose. Over this layer is to be provided the superposed coating of substantially greater conductivity than the dielectric, and suitable provision is to be made for affording electrical connection on the one hand with the base element and on the other hand with the conducting coating located about the intermediate dielectric.

In many cases, very satisfactory results are had with the superposed coating consisting partly or wholly of a compound of certain metals; and this may be attained in different ways. For instance, if a metal, e. g. copper, electrode is used in spattering, layers of different natures may be obtained according to the gas filling of the spattering container as well as to the electrical conditions prevailing therein. Thus, either a pure metallic layer, (Cu), layer of a compound (Cu_2O) or, preferably, a mixture of both may be produced directly by the spattering process.

On the other hand, compounds particularly suitable for this purpose may be obtained by subjecting a spattered coating to subsequent chemical treatment. For example, the coating initially deposited may be treated in sulfur vapor or with carbon disulfide in which elemental sulfur is dissolved; or, it may be subjected to oxidation by heat treatment or to oxidizing reagents, e. g. H_2O_2 etc.; or it may be treated, as in the case of a coating of lead, in vacuo with atomic oxygen in order to convert it into PbO_2.

This discovery of the insulating property of a minute layer provided as aforesaid, enables one to subject a conducting layer of extreme thinness (approaching molecular thickness) throughout its full volume to a very strong electrostatic field, for example, in the provision of an amplifier device. In its design for this particular use, the coating provided over the dielectric need not be of uniform thickness throughout, but is to be modified to the extent that at least an extremely narrow portion thereof and located, for example, transversely across the surface of the device to afford a line of complete demarcation between the two separated coating portions, is reduced to a degree approaching molecular thickness. Or, the gap may be omitted and the entire coating possess molecular thickness only. A predetermined potential, also, is to be applied to the underlying solid conductor so that by this expedient a high electrostatic field is set up, or rather rendered available. The conductivity of such coating portion or layer of minute thickness will depend then upon the electrostatic field applied across the insulating intermediate layer. Incoming oscillations will modify this field and affect thereby changes in the conductivity of the conducting layer of molecular thickness, which variation may be used for amplification purposes in manner well understood.

If the device be intended for use as a rectifier (detector) of alternating or oscillating currents, the insulating layer itself is punctured or broken at a point or line through to the underlying conducting plate or strip. This produces a conductive connection of a very definite but minute area between the underlying solid conductor and said conducting coating. Moreover, the specific arrangement admits, when voltage is applied to the two conducting elements, of a current to pass freely in the one direction through the said wall contacting-area but to be substantially impeded in the other direction and thus conforming to the requirements of a rectifier (detector) for oscillating currents. By this expedient, a contact of a very definite and invariable characteristic is produced, which is a decided improvement over the usual solid contact detectors of uncertain performance.

It will readily be appreciated, furthermore, that when the intermediate layer of dielectric, provided between the base and a relatively more conductive coating, is of substantially uniform thickness throughout and not exceeding 10^{-4} mm. a highly efficient condenser is afforded which, I have discovered, has extremely high specific capacity; and, withal, the same is very permanent, rugged and compact. This feature of the invention, however, forms the subject of separate application for Letters Patent, filed by me of even date herewith.

The invention contemplates, also, a novel method for providing the devices hereinbefore set forth.

The nature of the invention, however, will best be understood when described in connection with the accompanying drawings, in which:

Fig. 1 is a fragmentary vertical section through the novel amplifier device, greatly magnified and on a disproportionate scale for purpose of illustration.

Fig. 2 is a similar view illustrating a modification.

Fig. 3 is a perspective view illustrating the novel amplifier device and shows diagrammatically the electrical connections involved.

Figs. 4 and 5 are fragmentary vertical sections through the amplified device and illustrate further modifications therein.

Fig. 6 illustrates in vertical section a practical embodiment of the invention, but on greatly magnified and disproportionate scale.

Figure B.10: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,900,018 (filed in 1928).

Fig. 6a is a plan view of a further embodiment.

Fig. 7 is a fragmentary vertical section, similar to Fig. 1, and illustrates a further modification whereby the device is rendered suitable for use as a rectifier (detector) of alternating or oscillating currents.

Fig. 8 is a longitudinal section on a greatly magnified and disproportionate scale of a rectifier element; and Fig. 9 is a transverse vertical section therethrough taken on the line 9—9, Fig. 8.

Figs. 10 and 11 are diagrammatic views illustrating the application of the device respectively as a rectifier and detector.

Fig. 12 is a front elevation of the apparatus illustrating the method of applying cathodically a coating or stratum of conductive material to the novel electrical device.

Fig. 13 is a front elevation of a different form of apparatus employed in applying cathodically the said coating or stratum; and Fig. 14 is an end view, partly in section, illustrating a further modification in the method of application of said coating.

Referring to the drawings, 10 designates a metal such as aluminum, magnesium, tantalum, tungsten, etc. which forms the base or supporting element of the novel device; and in accordance with the invention, there is provided over a portion of one surface thereof, or over substantially the entire surface if desired, a non-conducting or insulating layer 11 which is formed as a compound of the particular metal forming the base member. For example, if aluminum be selected as the base member, the insulating layer 11 will be the oxide of aluminum (Al_2O_3), which may be provided thereon in any suitable and well-known manner as by electrolytic or purely chemical methods. If, in the former instance, a high voltage operation is required, it is advisable to employ voltages as high as possible; and when aluminum is utilized as the base material, the voltage in the electrolytic process will range up to 400 volts in an aqueous and up to 1500 volts in an alcoholic solution. This layer is then an integral part of the base material which is selected, also, to be of relatively thin stock—approximating 0.03 mm. or less, so that in case of bending of a completed amplifier unit there will be no serious distortion of said base member and resulting injury to said layer of oxide, as well as to further coatings hereinafter more fully set forth. The dielectric layer itself is to be of minute thickness only, or at least over a narrow portion thereof, being of the order of magnitude not exceeding approximately 10^{-4} mm., so that a very strong or intense electrostatic field may be set up by applying a suitable potential to the underlying base material 10.

Over the aforesaid layer of insulating material or oxide layer 11 is to be provided, and in a molecular contact with it over the total contact area, a superposed coating or stratum 12 of substantially greater conductivity than said coating and consisting of disintegrated or finely subdivided metal or metallic compounds, or mixtures of such metal and compounds.

These coatings may be attained by spattering cathodically from such metals as copper, lead, aluminum, etc.; or, by precipitation from colloidal metal suspensions or by pressure spraying. For example, the coating may consist of a layer of copper sulfide which may be applied thereto by cathodically spattering copper thereover and subsequent sulfurization thereof. Or, as hereinafter noted, coatings of various characteristics may be applied, it being essential only that at least an extremely narrow portion thereof and located, for example, transversely across the surface of the insulation 11 to afford a line of complete demarcation between the two thus separated coating portions, approaches molecular thickness.

In order to apply potential across this gap or depression affording a complete demarcation between the two coating portions, contact plates or blocks 14 and 15 are mounted thereover upon opposite sides thereof and to which leads 16 and 17 respectively may be connected. These leads, reference being had more particularly to Fig. 3 of the drawings, are included in a circuit embodying the direct current source of potential 18 and an output circuit 19 including apparatus (not shown) to which amplified current is to be supplied from the said source of potential 18. Similarly, a potential is applied through a conductor 20 to the base member 10 to polarize the same, preferably positively, from a suitable source of direct current potential 21, the negative side of which may be connected to the negative side of the source of potential 18, or grounded if desired. The conductor 20 includes also the secondary of a transformer 22 whose primary is connected to the input circuit 23 containing apparatus (not shown) producing or receiving current which is to be amplified by the apparatus hereinbefore described.

An intense electrostatic field is thus set up, or rather rendered available, at the depressed portion 13 of coating 12 throughout its full volume and controls the conductivity of the coating at said portion. Incoming oscillations delivered through the circuit 23 and transformer 22 into the amplifier unit will affect this field to cause thereby changes in said conductivity of the conducting layer, more particularly at its said depressed portion or portion of molecular thickness 13, which changes in conductivity effect variations in the current delivered to the output circuit 19, in manner well understood.

As hereinbefore noted, it is not essential that either the dielectric layer or the rela-

Figure B.11: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,900,018 (filed in 1928).

tively more conducting coating superposed thereover be, over the entire extent of such layer and coating, of the minute thicknesses set forth; and in Fig. 2, the layer 11 of insulating material is indicated as of relatively substantial thickness but is provided with a depressed portion or groove 25 and coinciding with which is the depressed or grooved portion 26 of the substantially more conductive coating 12.

Moreover, reference being had more particularly to Figs. 4, 5 and 6 of the drawings, the outer more conductive coating may be varied to comprise differently constituted portions and the same may also be arranged to afford effects not only throughout the volume of a layer but also at its contact area with another, different layer. For example, reference being had more particularly to Fig. 4 of the drawings, the one portion 30 of the conductive layer provided over the oxide layer 11 of the aluminum base 10 may consist af aluminum while the other portion 31 may consist of copper disulfide (Cu_2S), lead dioxide (PbO_2), etc., or vice versa, the effect taking place at the contact area of the two layers as well as through the volume of one of them.

Other combinations may consist of copper for the portion 30 and copper oxide for the portion 31, etc; or, both of the portions may consist of metal or both of compounds of a more or less conductive nature. It will be observed, also, that the portion 31 is provided with a bottom extension or lip 32 which is of molecular thickness and fits a corresponding recessed portion 33 in the underface of the portion 30, a gap 34 remaining, of course, between portions 30 and 31, while the former portion also partly overlies the latter at the said lip portion. In this manner, a contact area is provided utilizing the surface effect.

In Fig. 5, a further overlapping arrangement is indicated, each portion 35 and 36 of the conductive coating being provided with a laterally extending lip, as the lips 37 and 38 respectively, affording a variation both in volume effect of both layers and in surface effect at their mutual contact area.

Another embodiment of the invention is indicated in the construction shown in Fig. 6 of the drawings, which illustrates in vertical section an amplifier unit constructed according to the arrangement described in connection with Fig. 4 of the drawings. In this embodiment, 40 indicates a centrally disposed base element, as of aluminum, about which is provided a layer of aluminum oxide 41 substantially covering the entire surface thereof with the exception of a projecting tongue 42. A substantially more conductive coating about the same is indicated by the coating 43, for example of copper disulfide, and the coating portion 44, as of aluminum. The former coating is indicated as provided with or tapering down to the lip portion 45 which is to be of molecular thickness, while the latter coating has a portion 46 overlapping the said lip. Terminal members 47 and 48 as of tin foil or the like are provided over the coatings 43 and 44 to which are connected conductors 49 and 50, respectively, for affording connection to the amplifier; and a conductor 51 is secured to the tongue 42 to polarize the element 40 of said amplifier.

While it has been found in the case of operation with lower voltages, that the contacts to the conducting coatings may be established by applying thereover a soft foil, as tin foil or the like, without further precaution, as shown in Fig. 6, for the operation under high voltages it is advisible to design the device in a manner such that the conducting coating should not touch the edges either of the underlying oxide coated aluminum or of the contact-making foil. To satisfy these conditions, reference being had to Fig. 6*a*, the aluminum is oxide-coated over the entire area (except tongue 42) as in the previously described embodiments, but the conducting coatings 43 and 44 are to be applied thereover to provide for a surrounding oxide margin 55 so that the edges of the coatings will be displaced somewhat from the corresponding edges of the oxide-coated aluminum base element 40. Furthermore, insulating wrappers 56 of paper, mica, etc. and having windows 57 therein slightly smaller than the coating may be wrapped about the coatings, the edges of the paper overlapping the outline or perimeter of said coatings; and over the respective windows are applied a pair of tin foil elements 58 for making contact through said windows with the corresponding coatings, a foil being pressed firmly through a window to insure good contact.

When the device is intended for use as a rectifier or detector of alternating or oscillating currents, reference being had more particularly to Figs. 7 to 9 inclusive, a similar underlying or base element 60, of metal, such as aluminum, is provided, and an insulating layer 61 as of aluminum oxide formed over a portion or the whole of one of its surfaces. In this embodiment, however, the insulating layer is punctured or broken over a very definite but minute area, as at the portion indicated at 62 so that a conductive material may be applied therethrough to make contact with the covered surface of the underlying base element 60. This contact may readily be effected by providing a substantially more conductive layer 63 over the insulating layer 61, the same extending through the break in said insulation to make direct and molecular contact with the base element 60, as aforesaid. This more conductive layer 63 may consist of a metal such as copper, aluminum, etc., or a compound thereof, or a mixture of a metal and a compound, and is readily ap-

Figure B.12: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,900,018 (filed in 1928).

plied thereto by spattering the same cathodically thereover or in any other suitable and well known manner, as by pressure spraying or by precipitation from colloidal suspension, or by electrolytic deposition, etc. In this instance, also, it is not essential that the said layer 63 be of extreme thinness, although to reduce bulk of apparatus this may be desirable. A terminal element 64 is provided to make contact with the layer 63 and to which element is connected a conductor 65 for applying to the rectifier or detector the current to be rectified or detected, the other connection being through a conductor 66 attached to the base element 60.

Figs. 8 and 9 indicate respectively in transverse and longitudinal vertical section a practical construction of the invention as embodied in a rectifier or detector device. As shown, the base element is constituted by the centrally disposed element 70 having a projecting tongue 71 to which an outgoing conductor 72 may be attached. At its upper end, the element 70 is tapered to a substantially narrow edge 73, the surrounding insulating layer 74 entirely enclosing said element except at this edge 73 and at the tongue portion 71, while about the entire central element with the exception of its tongue 71 and over the insulation layer 74 as well as the edge portion 73 of the base element, is provided the more conductive coating 75. About the latter is provided a terminal band or connection member 76 to which is attached a conductor 77 for connecting the unit for service. An insulating bushing or coating 78 is provided over the tongue portion and insulation layer to prevent short-circuiting of the centrally disposed element 70 and the outer coating 75.

Figs. 10 and 11 indicate, respectively, the arrangement of these novel rectifier units, more particularly of the type indicated in the Figs. 8 and 9, respectively, in a full wave rectification system and in a system for detecting oscillating currents. As shown in Fig. 10, the incoming current to be rectified is connected to a transformer 80 having a divided secondary with neutral lead 81 and between which and the other leads 82 and 83 are connected the novel rectifier units 84 and 85, respectively, and in manner well understood. As shown in Fig. 11, a detecting unit 86 is connected in series in a circuit 87 in which oscillating currents prevail, said circuit including suitable means for indicating or receiving the detected oscillations, for example, a pair of head phones 88.

In order conveniently to prepare the elements employed in the foregoing apparatus, I have found it desirable to spatter the coating or coatings over the base member by directing, for example a stream or streams, from a metallic electrode over or to opposite sides of the base element, such as a strip of aluminum which may be suitably supported or suspended within the container in which the cathodic spattering is conducted. Reference being had more especially to Fig. 12 of the drawings, this element is indicated at 90 as horizontally supported on and clamped to a conducting table or platform 91 while in Figs. 13 and 14 it is shown as held along three of its edges by means of a frame 92, its free edge 93 in the latter embodiments being set very closely to a surface 94. This surface is, preferably, highly polished and mirror-like so that the said edge may be set parallel thereto with great precision. In the embodiment illustrated in Fig. 12 there is mounted over element 90 a shadow casting object 95, the same being held by brackets 96 and located in the path of a stream of cathodically spattered matter directed to said element; or when the same is suspended, streaming by the same in the direction indicated by the arrows. In the latter instance, generally, this will result in a rather non-uniform distribution of the material constituting the coating, the same fading away before it reaches the edge 93 which is more or less remote from the source or spattering cathode. It is preferred, therefore, to slightly incline the beams of spattered material toward the element 90, for example, as indicated in Fig. 14, where the spattering cathodes 97 are located upon opposite sides of the strip 90 and are both slightly inclined thereto. This affords a practical means of control of the application of the coating to the base element, and the attainment of an appreciable coating substantially up to the edge 93 which is to be then graduated thereover for application more especially in the manner set forth in Figs. 4 to 6.

I claim:

1. An electrical device comprising a conducting solid material having on one surface an insulating layer of a thickness of the order of magnitude of 10^{-4} mm., and a superposed stratum of solid material integral therewith, of substantially greater conductivity and insulated from the conducting solid material by the said insulating layer.

2. An electrical device comprising a conducting solid material having on one surface an inorganic insulating layer of a thickness of the order of magnitude of 10^{-4} mm., and a superposed stratum of solid material integral therewith, of substantially greater conductivity and insulated from the conducting solid material by the said insulating layer.

3. An electrical device comprising a conducting solid material having on one surface an insulating layer of minute thickness and chemically formed of and on said underlying material, and a superposed stratum of solid material integral therewith, of substantially greater conductivity and insulated

Figure B.13: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,900,018 (filed in 1928).

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from the conducting solid material by the said insulating layer.

4. An electrical device embodying an integral strip of two strata of conducting solid material and an intermediate dielectric stratum of minute thickness and constituted as a compound of one of the two said strata, said dielectric stratum insulating the two strata of conducting materials from each other.

5. An electrical device comprising a metal body having a surface provided with a layer of a non-conducting compound of said metal chemically formed thereon, and a stratum including copper superposed thereover and insulated from the metal body by the said non-conducting compound.

6. An electrical device comprising a metal body having a surface provided with a layer of a non-conducting compound of said metal chemically formed thereon, a stratum of substantially greater conductivity superposed thereover and insulated from the metal body by the said non-conducting compound, and a metal foil making contact with the latter and insulated by the layer of non-conducting compound from the metal body.

7. An electrical device embodying an integral strip of two strata of conducting solid material and an intermediate dielectric stratum, and a coating of a non-tarnishing metal over an outer stratum.

8. An electrical device comprising a strip of aluminum having a surface provided with a layer of the said aluminum formed thereon as oxide, and a stratum of substantially greater conductivity superposed over the latter and insulated by the layer of oxide from the strip of aluminum.

9. A dry aluminum strip having a layer of oxide of aluminum of a thickness of the order of magnitude of 10^{-4} mm., and a solid conductive stratum thereover, integrally associated therewith and insulated by a layer of oxide from the strip of aluminum.

10. An electrical device comprising a strip of aluminum having a surface provided with a layer of aluminum oxide, and a stratum including copper superposed thereover and integral therewith.

11. An electrical device comprising a metal body, an insulating layer of a compound of said metal chemically formed of said metal over a surface thereof, and a conducting stratum of substantially greater conductivity provided thereon by cathodically spattering a metal.

12. An electrical device comprising a metal body having a projecting conducting tongue, and on a surface an insulating layer of minute thickness whose outer face has a superposed stratum of solid material of relatively greater conductivity, a coating of non-tarnishing metal over the latter, and a metal foil covering about the last-named coating affording contact means thereto.

13. An amplifier for electric current, comprising a conducting solid material, an insulating layer on a surface thereof, and a conducting stratum over the latter including a portion approaching molecular thickness.

14. An amplifier for electric current, comprising a conducting solid material, an insulating layer on a surface thereof, and a conducting stratum over the latter having a portion reduced to a degree approaching molecular thickness and affording a line of complete demarcation between two portions of said stratum.

15. An amplifier for electric current, comprising a conducting solid material, an insulating layer on a surface thereof, and a conducting stratum over the latter and having a narrow portion across the same approaching molecular thickness.

16. An amplifier for electric current, comprising a conducting solid material, an insulating layer on a surface thereof, a conducting stratum over the latter including a portion approaching molecular thickness, and means to apply a difference of potential across said portion.

17. An amplifier for electric current, comprising a conducting solid material, an insulating layer on a surface thereof, a conducting stratum over the latter including a portion approaching molecular thickness, means to apply a potential to the conducting solid material, and means to apply a difference of potential across said portion.

18. An amplifier for electric current, comprising a conducting material, an insulating layer on a surface thereof, a conducting stratum over the latter having a transverse depression therein of molecular thickness, and means to apply a difference of potential to the coating upon opposite sides of the depression.

19. An amplifier for electric current, comprising a conducting material, an insulating layer on a surface thereof, a conducting stratum over the latter having a transverse depression therein of molecular thickness, means to apply a difference of potential to the conducting stratum upon opposite sides of the depression, and means to apply a third potential to the conducting base material.

20. An amplifier for electric current, comprising a conducting solid material, an insulating layer on a surface thereof of minute thickness, and a conducting stratum over the insulating layer having a narrow portion approaching molecular thickness.

21. An amplifier for electric current, comprising a conducting solid material, an insulating layer on a surface thereof having a narrow portion of minute thickness, and a conducting stratum over the insulating layer having a narrow portion approaching molecular thickness and coinciding with part of

Figure B.14: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,900,018 (filed in 1928).

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the said narrow portion of the insulating cover.

22. The method of forming an electrical device of the character set forth, which comprises chemically forming upon a strip of metal an insulating layer thereof to a minute thickness only, and providing a substantially greater conductive stratum over the latter by cathodically spattering a metal thereon.

23. The method of forming an electrical device of the character set forth, which comprises chemically forming upon a strip of metal an insulating coating thereof to a minute thickness only, providing a substantially greater conductive stratum over the latter by cathodically spattering a metal thereon, and subsequently treating the spattered coating.

24. The method of forming an electrical device of the character set forth, which comprises electrolytically forming upon a strip of aluminum an insulating coating of aluminum oxide to a minute thickness only, and providing a substantially greater conductive stratum over the latter by cathodically spattering copper thereon.

25. In the method of forming an amplifier element of the nature set forth, the step of cathodically applying from a metal a graduated coating to a metal strip by directing a stream from said metal thereto at an angle and intercepting said stream over a portion of the strip.

26. The method of forming an amplifier element of the nature set forth, which includes cathodically applying from a metal a graduated coating to the element by directing two streams from said metal substantially parallel to the element to be coated and on opposite sides thereof.

27. The method of forming of a metal foil an amplifier element of the nature set forth, which embodies directing two streams of cathodically spattered conducting matter thereto and from opposite sides of the said foil.

28. A metal strip having a dielectric coating over its surface and a graduated metal coating thereover, integrally associated therewith and insulated by said dielectric coating from the metal strip.

In testimony whereof I affix my signature.

JULIUS EDGAR LILIENFELD.

Figure B.15: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,900,018 (filed in 1928).

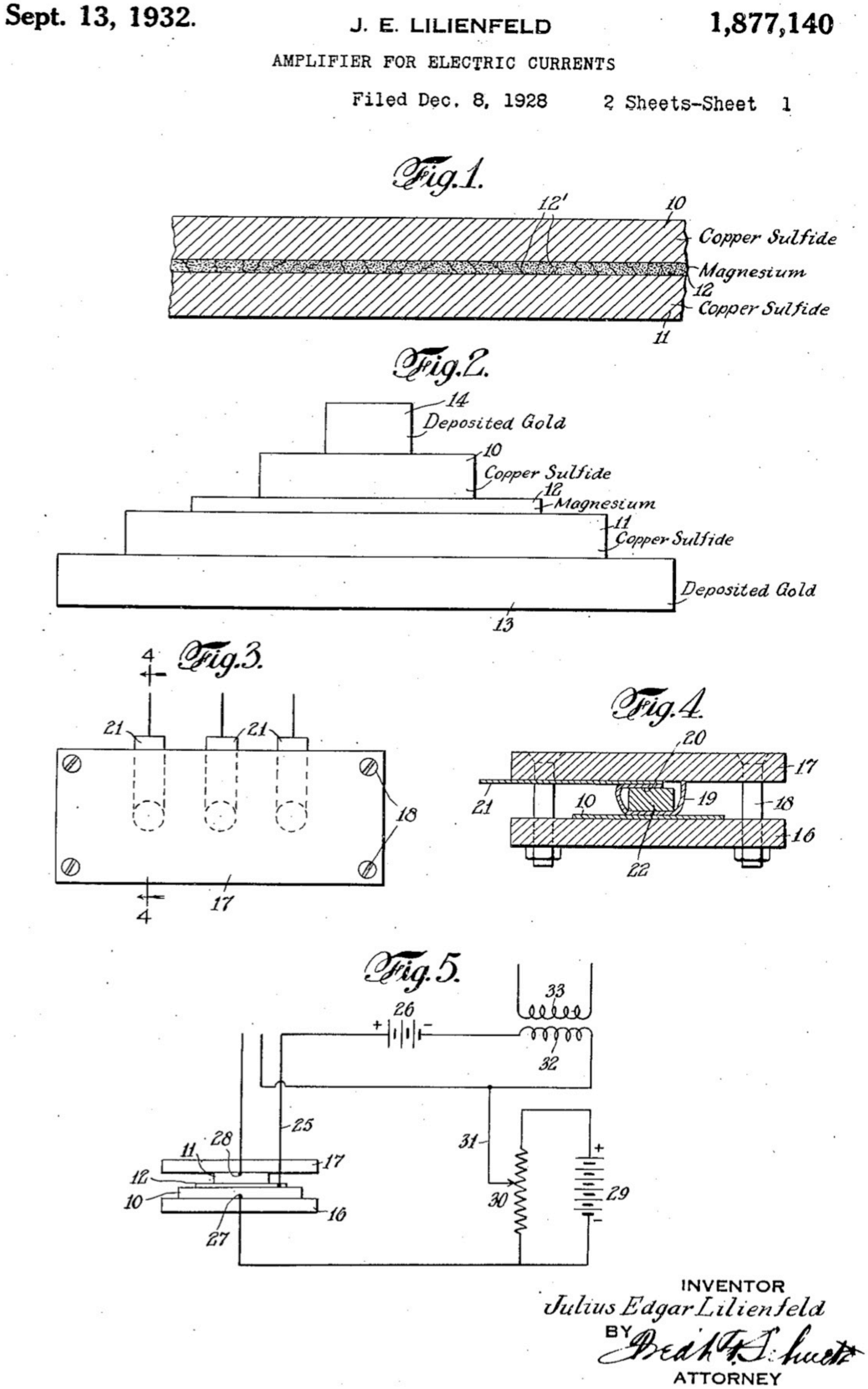

Figure B.16: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,877,140 (filed in 1928).

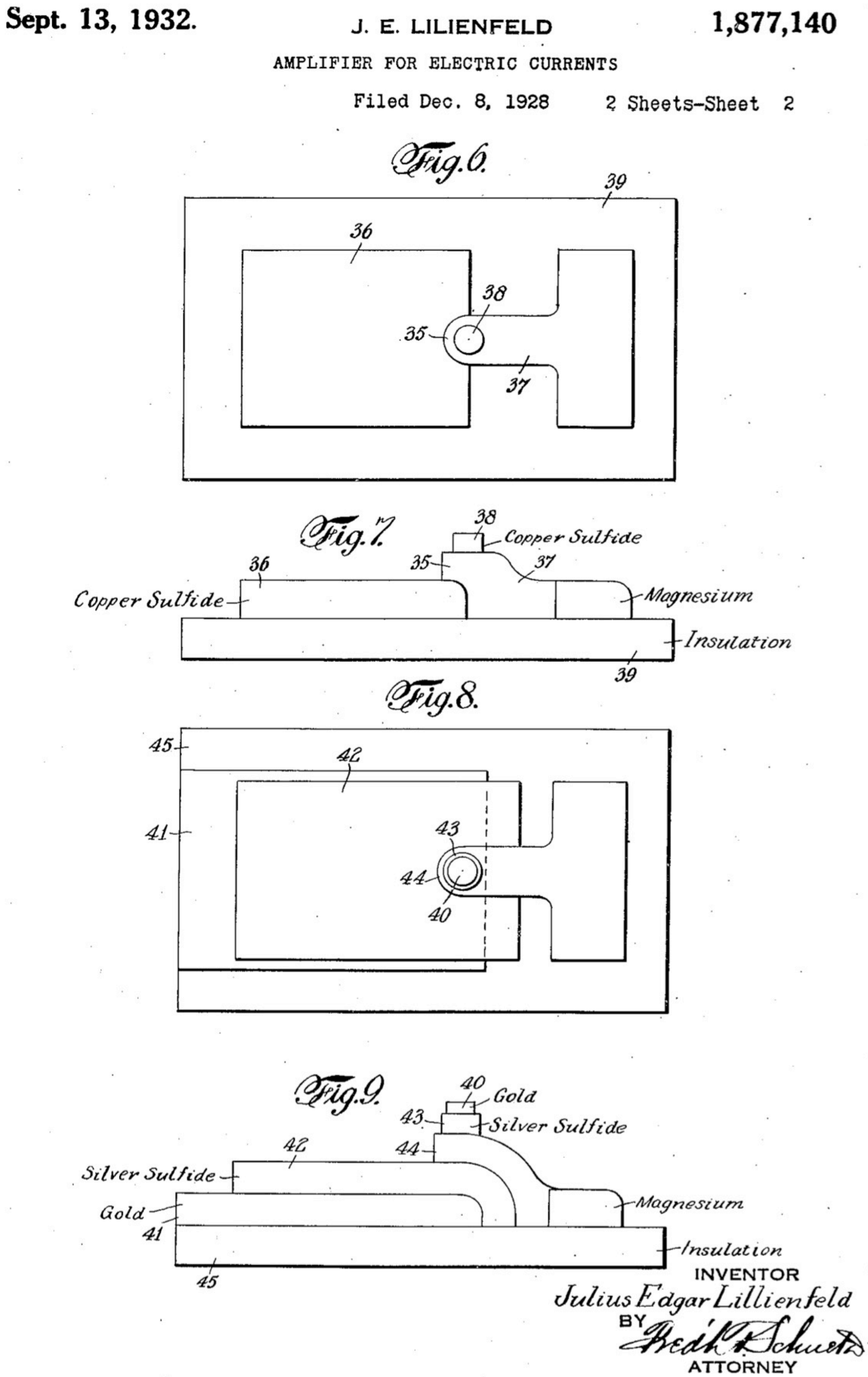

Figure B.17: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,877,140 (filed in 1928).

Patented Sept. 13, 1932 **1,877,140**

UNITED STATES PATENT OFFICE

JULIUS EDGAR LILIENFELD, OF CEDARHURST, NEW YORK

AMPLIFIER FOR ELECTRIC CURRENTS

Application filed December 8, 1928. Serial No. 324,794.

The invention relates to means for controlling the flow of an electric current, more especially in relation to the amplification of the same. Various devices such as relays, thermionic and otherwise, have been utilized for this purpose; and it is the object of the present invention to afford an extremely compact, simple and durable amplifying member which will be particularly efficient for the purpose intended and which, withal, may be constructed at small expense and have extremely long life. A further object of the invention is to construct a member of this character so that the same shall have but a minimum electrostatic capacity.

More particularly, the invention consists of an amplifier comprising two outer layers and an intermediate layer in intimate contact therewith, the materials constituting the said layers being such that the two outer layers form couples, preferably asymmetric couples, with the opposite faces of the intermediate layer. The latter, moreover, is made of minute thickness, of the order of magnitude of $200\mu\mu$, such that by reason of its porosity, or suitable treatment, the same will offer minute passages between the outer layers for the flow of electric current therebetween.

Provision is made, also, to maintain the outer layers at potentials different from each other and also different from that of the intermediate layer, which is preferably at a potential opposite to the potential of the said outer layers. The intermediate layer then constitutes a blocking layer biased to vary the resistance to the flow of electric current between the outer layers; and is also adapted to have impressed thereon a source of varying potential, such as the input current to be amplified, the output current then being taken from the outer layers with the circuit thereof including a local source of potential.

The nature of the invention, however, will best be understood when described in connection with the accompanying drawings, in which:

Fig. 1 is a fragmentary vertical section through the novel amplifier and on a greatly exaggerated scale.

Fig. 2 is an elevation, on an enlarged and exaggerated scale, illustrating a modification.

Fig. 3 is a plan view and Fig. 4 a transverse vertical section, taken on the line 4—4, Fig. 3, illustrating one means of effecting electrical contact with the respective elements of the amplifier.

Fig. 5 is a diagrammatic view illustrating the electrical connections involved.

Fig. 6 and 7 are respectively a plan and a front elevation, on a greatly exaggerated scale, of an amplifier constructed in manner to reduce the electrostatic capacity thereof to a minimum; and Figs. 8 and 9 are similar views illustrating the construction applied to a modified form of the amplifier.

Referring to the drawings, the amplifier is indicated as constructed of a plurality of relatively thin layers of metal and compounds, the underlying principle of the amplifier being the couple—i. e., two conductors in contact with each other and of such a kind that a very high resistance is opposed to current at the transition over from one conductor to the other—and preferably the asymmetric couple. It is known that certain metals, for example magnesium, aluminum, tungsten, tantalum, etc., if brought into contact with certain compounds such as sulfides, selinides, oxides, for example, copper sulfide, silver sulfide, copper selinide, lead peroxide, etc., provide couples of a high resistance when the metal is at a positive potential and the compound negative. Asymmetric couples are also known consisting solely of compounds such as sulfides, oxides, etc. no pure metal being then involved.

In the present instance, two asymmetric couples of the aforesaid character are utilized, an element common to both being pro-

Figure B.18: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,877,140 (filed in 1928).

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vided. For example, as shown in Fig. 1, the amplifier is constructed of three layers, the two outer layers 10 and 11 comprising a conducting polarizing compound such as copper sulfide, or copper bisulphide, silver sulfide, lead peroxide, magnesium sulfide, etc., while the intermediate layer 12 is of metal such as magnesium, or aluminum, tungsten, tantalum, etc. I have found that a very satisfactory amplifier may be constructed with the intermediate layer 12 consisting of magnesium, which may be spattered, condensed or otherwise deposited in a layer upon the surface of one of the outer layers of conducting polarizing compound such as of copper sulfide, and the other outer layer of conducting polarizing compound then spattered or deposited on the opposite uncovered surface of the layer 12.

In applying the intermediate layer 12, this operation should be so conducted that at least certain portions thereof will be of minute thickness, for example, of the order of magnitude of 200$\mu\mu$, in order that these portions may be porus or contain breaks 12′ which will be filled out by the material of the outer layers and offer passageways between the said outer layers for the flow of electric current therebetween. The degree of porosity may be increased or a porus break established in the layer by exerting pressure thereon sufficient to force the enclosing material therethrough.

In order to allow for convenient connection with the said outer layers, additional layers 13 and 14, Fig. 2, affording suitable bases as of a conducting material of a non-polarizable character, such as nickel, platinum, gold, etc., may be provided over the respective layers 10 and 11. However, if the enclosing layers are especially thin, then one at least must be applied to a substantial base which may be of conducting or of insulating material.

More particularly, a conducting material is to be used for the base if the bottom layer is made of a material of comparatively low conductivity (silver sulfide). A very good base may consist of an electrolytically oxide-coated aluminum foil of 0.001 inch thickness. A foil of this character has the advantage of flexibility; and, moreover, further coatings adhere to it very well. Of course, an insulating base is formed thereby, considering the oxide coating; but, if a conducting base be required, an inert conducting layer, as of gold, must be applied over the oxide.

In the construction of the amplifier, the application of the various layers may conveniently be accomplished by beginning with the lowermost layer 13, which, in this case, would be a metal, then spattering the layer 11 thereon upon which in turn is spattered the layer 12 and over the latter the layer 10, while the final outer and upper layer 14 may be deposited, for example, electrolytically, upon the layer 10. This will afford a substantial and rugged construction of the amplifier; and it will be appreciated that the completed amplifier will occupy but very small space and a great number thereof may be connected in series in the usual and well-known manner.

Electrical contact to the layer 12 and the layers 13 and 14, or directly to the aforesaid layers 10 and 11, may be effected in any suitable manner, it being understood, however, that because of the minute thickness of these layers it is not feasible to provide the usual soldered connection. Means for exerting a pressure contact, preferably of a yielding nature, are therefore arranged to engage the exposed surfaces of the respective layers.

For example, and as illustrated in Figs. 3 and 4, the amplifier may be supported upon a rigid base plate 16 of insulating material and over said amplifier placed a further or top plate 17, also of insulating material, the two said plates being arranged to be drawn together as by means of the threaded bolts 18 at the four corners thereof. In addition, contact cups 19 are provided between the bottom and top plates, one for each of the layers of the amplifier to which contact is to be made. These cups consist, for example, of flexible or pliable metal provided with an inwardly directed tab 20, designed to hold between itself and the corresponding base a terminal strip 21 as of metal foil. The bottom of the cup rests against the particular layer, as the layer 10, with which contact is desired; and a block of resilient rubber 22 contained by the cup affords ample pressure, when the base and top plates are clamped down, to insure a positive and reliable contact.

In the operation of these amplifiers, connection is made from the intermediate or common layer to a biasing voltage, for example, in the specific illustration hereinbefore set forth, to a positive voltage through the lead 25 to a source 26. The terminals 27 and 28 of the amplifier, moreover, are so connected that the other layers 10 and 11 will be maintained at a potential of the same sign, in the present instance negative; and this is effected by connecting the one terminal 28 through the output circuit with the negative side of the source of potential 26 while the terminal 27 of the layer 10 is connected to the negative side of a further source of potential 29.

A potentiometer 30 is provided across the source of potential 29 and is connected through lead 31 also with the negative side of the source of potential 26. In the circuit of the latter, furthermore, is provided a transformer 32 or other suitable coupling by which the input circuit 33 may be coupled

Figure B.19: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,877,140 (filed in 1928).

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to the amplifier; and it will be noted that variations produced in this input circuit will correspondingly affect the potential of the layer 12 with respect to the layer 10 and also to the layer 11.

In the initial formation of the amplifier, this layer is to be polarized by impressing a sufficiently high voltage between the same and the outer layers 10 and 11. When this is once effected, a high resistance will be established between 10 and 12 and also between 11 and 12. Therefore, current flowing from the intermediate layer to the respective outer layers will be negligible; while, on the other hand, as the normal biasing potential of layer 12 is changed with each impulse derived from the input circuit, the resistance between the layers 10 and 11 will be changed correspondingly and a greatly magnified effect results with respect to the current flowing between the said outer layers. The flow of current between layers 10 and 11 will, therefore, change with the bias of the intermediate layer 12 becoming more positive or more negative.

The amplifier may be operative also if the outer layers be constituted by the polarizable metal and the intermediate layer by a conducting polarizing compound. In such case, however, the bias of the intermediate layer should be negative, while in the previous case it was positive.

These biasing voltages, moreover, may be of any value so long as they do not destroy the positive (or negative) insulating property of the intermediate layer; and with magnesium and copper sulfide as the materials constituting the amplifier, the biasing voltage may vary between +15 volts and zero volts. As a limiting case, however, a slightly negative bias (or positive) may be admissible so long as it does not break down the insulation effect of layer 12 against the layers 10 and 11 which requires a slight voltage, for example, of the order of magnitude of a few tenths of a volt.

Where the requirements are such that electrostatic capacity should be low, this may readily be attained by reducing the actual contacting areas to a minimum. For example, reference being had to Figs. 6 and 7, the intermediate layer 35, as of magnesium, is made to cover only a small portion of the underlying layer 36 consisting of copper sulfide, as by means of an arm 37 thereof overhanging an edge portion of the sulfide layer, while the uppermost layer 38 is merely in the nature of a small spot. A base 39 of insulation material supports the entire device; and contact may be made to the various layers as in the manner hereinbefore described.

Figs. 8 and 9 show a similar arrangement but wherein additional outer or terminal layers 40 and 41, as of gold, are provided over the respective outer layers 42 and 43, of silver sulfide in this instance, with intermediate layer 44 of magnesium—all being mounted on an insulation base 45. In this embodiment, the respective layers are likewise of progressively less contacting area, whereby capacity is reduced to inappreciable amounts.

I claim:

1. An amplifier for electric currents, comprising two outer layers and an intermediate layer in intimate contact therewith, the layers being of material such that asymmetric couples are formed by the respective outer layers with the opposite faces of the intermediate layers and being interconnected in part thereby, means to apply potentials of same sign to the outer layers, and means to apply a potential of the opposite sign to the intermediate layer.

2. An amplifier for electric currents, comprising two outer layers and an intermediate layer in intimate contact therewith, the layers being of material such that asymmetric couples are formed by the respective outer layers with the opposite faces of the intermediate layer, the latter offering minute passageways between the outer layers for the flow of electric current therebetween, means to apply potentials of same sign to the outer layers, and means to apply a potential of the opposite sign to the intermediate layer.

3. An amplifier for electric currents, comprising two outer layers and an intermediate layer in intimate contact therewith, the layers being of material such that asymmetric couples are formed by the respective outer layers with the opposite faces of the intermediate layer and being interconnected in part thereby, and means to maintain the outer layers at a potential of same sign and the intermediate layer at the opposite sign.

4. An amplifier for electric currents, comprising two outer layers and an intermediate layer in intimate contact therewith, the layers being of material such that asymmetric couples are formed by the respective outer layers with the opposite faces of the intermediate layer, the latter offering minute passageways between the outer layers for the flow of electric current therebetween, means to maintain the outer layers at a potential of same sign and the intermediate layer at the opposite sign, and means to impress upon the intermediate layer a potential varying with respect to the two outer layers.

5. An amplifier for electric currents, comprising two outer layers of polarizing conducting elements and an intermediate polarizable conducting element, the latter being in intimate contact with the former and having portions of sub-microscopic thickness, means to maintain the outer elements at a potential of same sign and the intermediate element at the opposite sign, and means to

Figure B.20: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,877,140 (filed in 1928).

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impress a varying potential upon the intermediate element.

6. An amplifier for electric currents, comprising two outer layers of like polarizing conducting compound and an intermediate polarizable conducting element, the latter being in intimate contact with the former and having portions of sub-microscopic thickness, means to maintain the outer elements at a potential of same sign and the intermediate element at the opposite sign, and means to impress a varying potential upon the intermediate element.

7. An amplifier for electric currents, comprising two outer layers of like polarizing conducting compound and an intermediate polarizable metal, the latter being in intimate contact with the former and having portions of sub-microscopic thickness, means to maintain the outer elements at a potential of same sign and the intermediate element at the opposite sign, and means to impress a varying potential upon the intermediate element.

8. An amplifier for electric currents, comprising two outer layers of polarizing conducting elements, an intermediate blocking layer having portions of sub-microscopic thickness and interconnecting in part said outer layers, the said intermediate layer being permanently positively biased to vary resistance to flow of electric current between the outer layers, means to apply potentials of same sign to the outer layers, and means to apply a potential of the opposite sign to the intermediate layer.

9. An amplifier for electric currents, comprising two outer layers of polarizing conducting elements and an intermediate polarizable conducting element, the latter being in intimate contact with the former and having portions of sub-microscopic thickness, means to maintain the outer elements at a potential of same sign and the intermediate element at the opposite sign, means to impress a varying potential upon the intermediate element, and terminal members associated with the respective outer elements.

10. An amplifier for electric currents, comprising two outer layers of polarizing conducting elements and an intermediate polarizable conducting element, the latter being in intimate contact with the former and having portions of sub-microscopic thickness, a source of potential, a potentiometer connected across the same, the negative terminal thereof being connected to one of the outer elements, a second source of potential, the positive terminal thereof being connected to the intermediate element and its negative terminal to the other of the outer elements and also to the other terminal of the said potentiometer.

11. An amplifier for electric currents, comprising two outer layers of polarizing conducting elements and an intermediate polarizable conducting element, the latter being in intimate contact with the former and having portions of sub-microscopic thickness, a source of potential, a potentiometer connected across the same, the negative terminal thereof being connected to one of the outer elements, a second source of potential, the positive terminal thereof being connected to the intermediate element and its negative terminal to the oth?r of the outer elements and also to the other terminal of the said potentiometer, and means to impress a voltage upon the circuit of the second-named source of potential.

12. An amplifier for electric currents, comprising a strip of magnesium of minute thickness, layers of copper sulfide in intimate contact with opposite faces of the magnesium, means to positively bias the said magnesium strip, means to maintain the copper sulfide layers at a negative potential, and means to impress a varying potential to the magnesium.

13. An amplifier of the nature set forth and embodying a plurality of superposed layers forming couples, characterized by having an intermediate layer make contact with adjacent opposite layers over a small portion of its total superficial area only, to interconnect in part said layers, means to apply potentials of same sign to the outer of the superposed layers, and means to apply a potential of the opposite sign to the intermediate layer.

14. An amplifier of the nature set forth and embodying a plurality of superposed layers forming couples, characterized by having the respective layers of progressively smaller contact area, an intermediate layer interconnecting in part the adjacent layers, means to apply potentials of same sign to the adjacent layers, and means to apply a potential of the opposite sign to the intermediate layer.

15. In an amplifier for electric currents, comprising couples in the form of superposed layers: means for making electrical contact with the respective layers, comprising a metallic cup-shaped element, the bottom of which is adapted to rest upon a corresponding layer and having a tab directed inwardly over the mouth of the cup, a terminal strip extending over said tab and outwardly therefrom, resilient means contained within the cup between the bottom thereof and said tab, and means upon opposite sides of the cup pressing respectively against the said layer and terminal strip to exert pressure upon the resilient means.

16. In an amplifier for electric currents, comprising couples in the form of superposed layers: means for making electrical contact with the respective layers, comprising a metallic cup-shaped flexible element, the bottom of which is adapted to rest upon

Figure B.21: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,877,140 (filed in 1928).

1,877,140 **5**

a corresponding layer and having a flexible tab directed inwardly over the mouth of the cup, a terminal strip extending over said tab and outwardly therefrom, resilient means contained within the cup between the bottom thereof and said tab, and insulating means upon opposite sides of the cup pressing respectively against the said layer and terminal strip to exert pressure upon the resilient means.

In testimony whereof I affix my signature.

JULIUS EDGAR LILIENFELD.

Figure B.22: Julius Edgar Lilienfeld filed a number of highly detailed patent applications on field effect transistors, including U.S. Patent 1,877,140 (filed in 1928).

[**2. Oskar Heil (German, 1908–1994)** filed detailed patent applications on field effect transistors in 1934 in several countries, such as:

> Oskar Heil. Filed 1934. Swiss patent CH184,396. Verfahren zum Steuern oder Verstärken elektrischer Ströme. [Method for Controlling or Amplifying Electrical Currents.]
>
> Oskar Heil. Filed 1934. U.K. patent GB439,457. Improvements in or Relating to Electrical Amplifiers and Other Control Arrangements and Devices.

See pp. 2679–2685.

Currently it is unclear just what experimental work Heil may have done on the concept either before or after filing the patent application, or whether other German-speaking scientists may have taken up the ideas proposed in the application.

During World War II, Heil conducted electronics and physics research at C. Lorenz AG in Germany. After the war, he moved to the United States, where he continued his research for several decades, working for the U.S. government as well as several electronics companies.

Much more archival research should be conducted to elucidate the history and impact of Heil's ideas and projects both in Europe and in the United States.

Nr. 184396 **Klasse 112**

SCHWEIZERISCHE EIDGENOSSENSCHAFT

EIDGEN. AMT FÜR GEISTIGES EIGENTUM

PATENTSCHRIFT

Veröffentlicht am 1. August 1936

Gesuch eingereicht: 25. Februar 1935, 20 Uhr. — Patent eingetragen: 31. Mai 1936.
(Priorität: Deutschland, 2. März 1934.)

HAUPTPATENT

Dr. Oskar HEIL, Berlin-Grunewald (Deutschland).

Verfahren zum Steuern oder Verstärken elektrischer Ströme.

Die vorliegende Erfindung betrifft ein Verfahren und eine Vorrichtung zum Steuern oder Verstärken elektrischer Ströme.

Während man bisher zu diesem Zweck fast ausschließlich Elektronenröhren verwendet hat, beruht das erfindungsgemäß beanspruchte Verfahren auf einem ganz neuen Effekt, der zum ersten Mal beobachtet wurde.

Es wurde festgestellt, daß dünne Schichten von Halbleitern ihren Widerstand für den elektrischen Strom in weiten Grenzen ändern, wenn man diese Schichten als Elektroden von Kondensatoren ausbildet und die Elektroden auf verschiedene Spannung auflädt.

Zur näheren Erläuterung diene die schematische beispielsweise Darstellung in Fig. 1. Zwischen den Metallelektroden 1 und 2 befindet sich die dünne Schicht des Halbleiters 3. Die Batterie 4 schickt einen Strom durch die dünne Halbleiterschicht, der mittels Amperemeter 5 gemessen wird. Lädt man nun die Elektrode 6 positiv oder negativ gegenüber der Schicht 3 auf, so ändert sich der elektrische Widerstand dieser Schicht und damit auch die am Amperemeter 5 gemessene Stromstärke. Es ist also möglich, durch Anlegen einer irgendwie geformten Wechselspannung an die Klemmen 7 den Strom in 5 zu steuern. Mit solchen Anordnungen lassen sich in ähnlicher Weise wie mit Elektronenröhren Verstärker bauen. Es ist vorteilhaft, den Abstand zwischen der Elektrode 6 und dem Halbleiter 3 möglichst gering zu machen, etwa durch Verwendung einer dünnen Isolierschicht von weniger als $^{1}/_{100}$ mm Dicke zwischen beiden. Zweckmäßigerweise findet dabei ein Isoliermaterial von hoher Dielektrizitätskonstante Anwendung (mit einem Zahlenwert von 10 oder darüber).

Statt eine Steuerelektrode 6 kann man auch zwei Steuerelektroden 6 zu beiden Seiten der Schicht 3 anordnen; statt dessen können solche auch nur auf einer Seite angebracht werden. Man kann sie in diesem Falle nebeneinander oder hintereinander, bezogen auf die Stromrichtung im Halbleiter,

Figure B.23: Oskar Heil filed patent applications on field effect transistors in Germany and other countries in 1934.

anbringen. Sie können getrennt betrieben werden, zum Beispiel um zwei Wechselspannungen zu überlagern. Es können auch noch mehr als zwei Steuerelektroden vorgesehen werden.

Verstärkerelemente gemäß vorliegender Erfindung kann man herstellen, indem man auf isolierende Platten die Halbleiterschichten, sämtliche Elektroden und die Isolierschichten nacheinander aufdampft oder durch Kathodenzerstäubung aufträgt. Die für die Durchführung des Verfahrens optimale Schichtdicke des Halbleiters hängt von der Leitfähigkeit des Halbleiters ab. Offenbar ist es die Dicke, die gleich der Summe der Eindringtiefen eines elektrischen Feldes ist, das von beiden Seiten in die Schicht eindringt, denn dann wird gerade die ganze Schicht durchgesteuert, ohne daß sich die Steuerfelder überschneiden, oder ohne daß eine unbeeinflußte Restschicht im Halbleiter übrig bleibt. Diese Dicke muß durch Vorversuche für jedes Material zunächst erst ermittelt werden. Je größer die Leitfähigkeit ist, desto dünner wird man die Schicht auftragen.

Eine beispielsweise Vorrichtung zur Ausführung des neuen Verfahrens ist aus Fig. 2 zu ersehen. Die Lage der Einzelteile ist in Fig. 2^a im vergrößerten Schnitt dargestellt, während dieselben in Fig. 2^b zur besseren Sichtbarmachung perspektivisch und auseinandergezogen abgebildet sind. Die Halbleiterschicht 3 ist mit den beiden Metallelektroden 1 und 2, die zum Anschluß des Stromes dienen, verbunden und von den Steuerelektroden 6 durch Schichten 8 aus Isoliermaterial getrennt.

Für ein Ausführungsbeispiel kommen etwa folgende Maße in Frage:

Ausdehnung der Halbleiterschicht 3 (Abb. 2): in Stromrichtung 15 mm, quer zur Stromrichtung 30 mm. Dicke der Schicht 3 (und der Metallschichten 1 und 2) von 0,001 bis 0,01 mm. Dicke der Glimmerschichten 8 von 0,01 bis 0,1 mm. Die Metallplatten 6 seien etwa 1 mm stark und dienen gleichzeitig zur Halterung.

An die Stelle von Isoliermaterial kann auch Luft- bezw. Vakuumisolation treten. Dabei geht man so nahe an die Schicht heran, daß gerade mechanisch und elektrisch eine sichere Isolation gewährleistet ist.

Es sei ausdrücklich darauf hingewiesen, daß der Begriff Halbleiter heute ein wohldefinierter Begriff ist und daß beispielsweise Stoffe wie Tellur, Jod, Kupferoxydul, Vanadinpentoxyd und dergleichen, ferner aber auch die sogenannten Lückenleiter, die durch verkehrten Halleffekt ausgezeichnet sind, dazu zählen. Charakteristisch für Halbleiter ist der negative Temperaturkoeffizient des Widerstandes.

PATENTANSPRUCH I:

Verfahren zum Steuern oder Verstärken elektrischer Ströme, dadurch gekennzeichnet, daß man mittels einer oder mehrerer Elektroden, an die man Steuerspannungen anlegt, den Widerstand einer oder mehrerer stromdurchflossener, dünner Halbleiterschichten ändert, wobei man die Steuerelektroden isoliert von den Halbleiterschichten in solcher Nähe von den letzteren anordnet, daß gerade mechanisch und elektrisch eine sichere Isolation gewährleistet ist.

PATENTANSPRUCH II:

Vorrichtung zur Ausführung des Verfahrens nach Patentanspruch I, dadurch gekennzeichnet, daß eine streifenförmige, dünne Halbleiterschicht an den beiden Längsseiten mit Elektroden zum Anschluß des elektrischen Stromes versehen ist und auf den Flächen des Halbleiters, isoliert davon, eine oder mehrere Steuerelektroden angeordnet sind.

UNTERANSPRUCH:

Vorrichtung nach Patentanspruch II, dadurch gekennzeichnet, daß zwischen der Halbleiterschicht und den Steuerelektroden Isolationsschichten mit hoher Dielektrizitätskonstante angeordnet sind.

Dr. Oskar HEIL.

Vertreter:
IMER, de WURSTEMBERGER & Cie., Genf.

Figure B.24: Oskar Heil filed patent applications on field effect transistors in Germany and other countries in 1934.

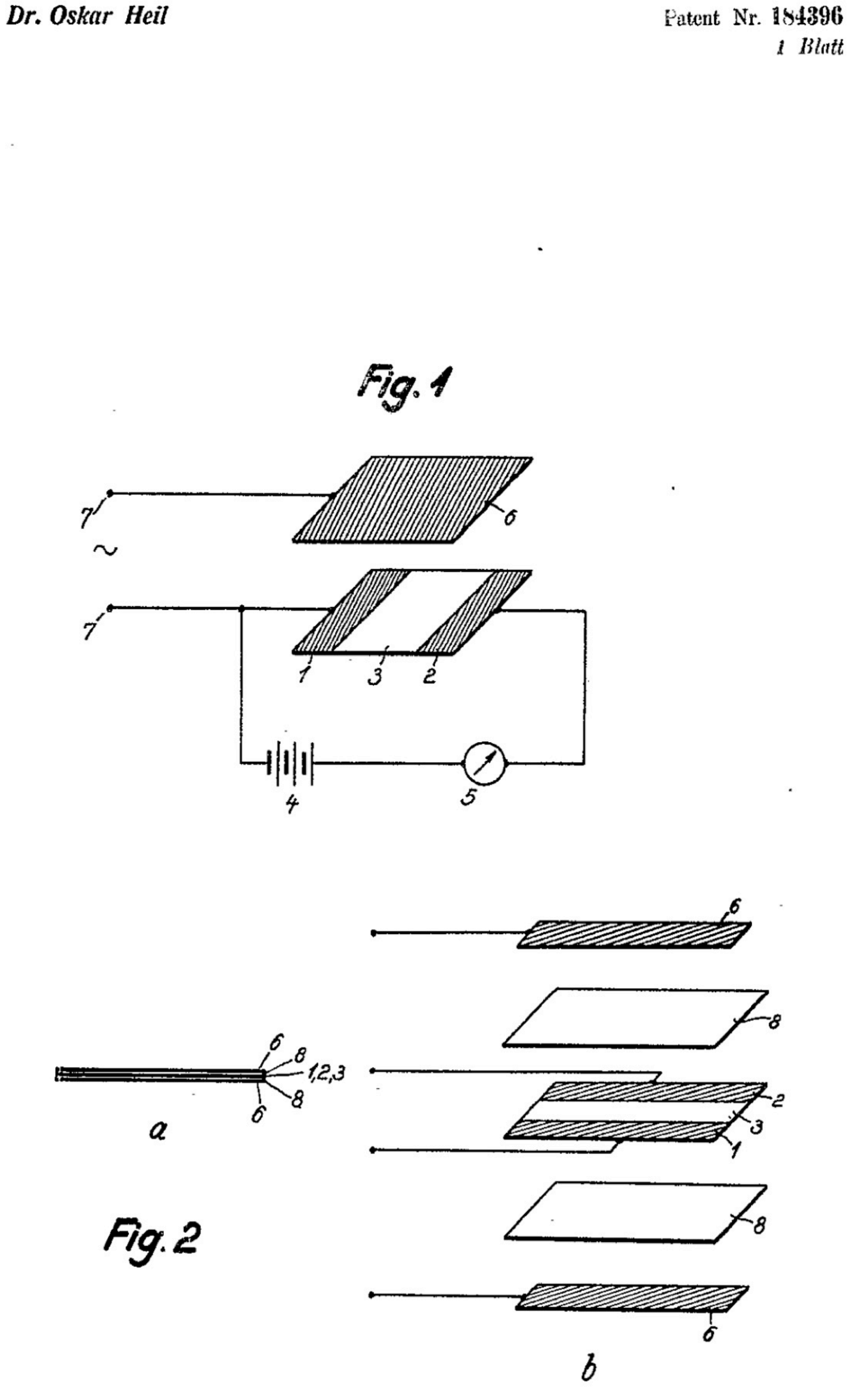


Figure B.25: Oskar Heil filed patent applications on field effect transistors in Germany and other countries in 1934.

PATENT SPECIFICATION

Convention Date (Germany): March 2, 1934.
Application Date (in United Kingdom): March 4, 1935.
Complete Specification Accepted: Dec. 6, 1935.

439,457
No. 6815/35.

COMPLETE SPECIFICATION

Improvements in or relating to Electrical Amplifiers and other Control Arrangements and Devices

I, OSKAR HEIL, German citizen, of 21 Jagowstrasse, Berlin-Grunewald, Germany, do hereby declare the nature of this invention and in what manner the same is to be performed, to be particularly described and ascertained in and by the following statement:—

This invention relates to electrical amplifiers and the like and provides novel apparatus adapted to effect alternating current amplification and to perform other functions e.g. general control functions such as have usually been performed hitherto by thermionic valves. In general terms the present invention—which, as will be seen later, embodies a principle which is believed to be new and is based upon a discovery believed to be new—may be stated to provide a substitute for thermionic valves.

The discovery upon which this invention is based is that if a semi-conductor be arranged as to form part of a condenser which is subjected to a varying voltage charge the resistance thereof will vary as a function of said varying voltage and according to this invention this phenomenon or effect is utilised for amplifying or other control purposes.

It has been discovered that a thin layer of semi-conductor will fluctuate within wide limits in its resistance to an electric current if the said layer be arranged to act as an electrode of a condenser which is charged to a varying voltage.

The invention is illustrated in and further explained in connection with the accompanying diagrammatic drawings.

Referring to fig. 1 which serves to illustrate the essential principle of the invention 1 and 2 are metal electrodes between which is a thin layer 3 of a semi-conductor. A battery 4 sends a current through the thin layer of semi-conductor and this current is measured by the ammeter 5. If, now, an electrode 6 in electro-static association with the layer 3 is charged positively or negatively in relation to the said layer 3, the electrical resistance of this layer is found to vary and the current strength as measured by the ammeter 5 also to vary. Thus it is possible by the application of an alternating voltage of any wave form to the terminals 7 to produce a corresponding variation in the current through 5. This principle may be utilised to provide amplifiers which act in a way analogous to thermionic valve amplifiers. It is advantageous to make the distance between the electrode 6 and the semi-conductor 3 as small as possible, e.g. by providing a thin layer of insulation—preferably one having a high dielectric constant—between them.

Control electrodes playing a function like that of electrode 6 of fig. 1 can be provided on both sides of the layer 3. Again a plurality of control electrodes may be arranged next each other or one behind the other on one or both sides of the layer 3 and these electrodes may be operated separately, e.g. for the purpose of effecting simultaneous control by a plurality of alternating voltages.

Amplifier devices in accordance with the present invention can be made in various ways a preferred way being by applying the layers of semi-conductor, all the required electrodes and the insulating layers in succession to insulating plates the metal members being applied either by vaporizing metal or by depositing metal by cathode dispersion. The best thickness of semi-conductor layer to be used in any case depends on the conductivity of the semi-conductor employed and should be first ascertained by experiment for each semi-conductor material. In general, the greater the conductivity of the semi-conductor the more thin must be the layer thereof for best results.

One arrangement in accordance with this invention is shown in figure 2, the separate points embodied in figure 2 being shown assembled at *a* and enlarged and in exploded perspective view at *b*. In figure 2, 3 is a layer of semi-conductor which is connected to two metallic electrodes 1 and 2 via which the current to be controlled is passed through the layer 3. 6 are the control electrodes and these are separated from the construction 1 3 2 by layers 8 of insulating material. One controlling potential may be applied between the terminal 7′ and the terminal

Figure B.26: Oskar Heil filed patent applications on field effect transistors in Germany and other countries in 1934.

of the battery 4 connected to the electrode 2 to control the current from the battery 4 through the semi-conducting layer 3 while a second controlling potential may be applied between the terminal 7″ and the other terminal of the battery 4 or alternatively (as shown dotted) to the same terminal of the battery 4. In place of insulating material air or vacuum insulation may be used, i.e. the parts 6 may be spaced from the construction 1 3 2 by air or, by using an evacuated enclosing envelope, by vacuum.

The term semi-conductor is used in the present specification in its present day well understood sense to include such substances as tellurium, iodine, cuprous oxide, vanadium pentoxide in which conduction is effected by a displacement of electrons as in the case of metals and does not include substances wherein conduction depends upon ionisation or electrolytic action in which case conduction takes place by a transfer of atoms or molecules.

As regards elements which are semi-conductors, these fall in the periodic system on the border line between metals and metalloids and these materials generally exist in at least one form which possesses a metallic character. As regards other materials which are semi-conductors, these possess a similarity to metals either in respect of a metallic sheen or in respect of their high absorption of light.

The term semi-conductor is also used in the present specification to include what may be termed " gap " conductors, i.e. conductors which exhibit an inverted Hall effect. As is known, if a flat plate-like conductor is traversed longitudinally by an electric current and is subjected to a magnetic field whose lines of force are perpendicular to the plane of the conductor, there is set up in the conductor a potential difference transverse to the direction of current flow. This is known as the Hall effect and normally the potential difference is of a sense corresponding to a negative Hall coefficient. Most metals possess such a negative Hall coefficient but there exist certain materials which possess a positive Hall coefficient, the potential difference set up being of the opposite sense. These materials may be said therefore to exhibit an inverted Hall effect. A general characteristic of semi-conductors is a negative temperature coefficient of resistance.

Having now particularly described and ascertained the nature of our said invention and in what manner the same is to performed I declare that what I claim is:—

1. An electrical amplifier or other control arrangement or device wherein one or more thin layers of semi-conductor traversed by current is or are varied in resistance in accordance with control voltage applied to one or more control electrodes arranged close to and insulated from said semi-conductor layer or layers so as to be in electrostatic association therewith.

2. An arrangement or device in accordance with claim 1 and comprising at least one narrow strip-shaped thin layer of semi-conductor provided on its two longer edges with electrodes which serve to lead electric current into and from said layer, there being at least one control electrode arranged close to a face of the semi-conductor layer and insulated therefrom.

3. An arrangement or device in accordance with any of claim 1 or 2 and comprising at least one thin semi-conductive layer and at least one control electrode in electro-static association therewith said layer and electrode being insulated from one another by insulation of high dielectric constant.

4. An arrangement or device in accordance with any of claim 1 or 2 and comprising at least one thin semi-conductive layer and at least one control electrode in electro-static association therewith said layer and electrode being insulated from one another by air insulation.

5. An arrangement or device in accordance with any of claim 1 or 2 and comprising at least one thin semi-conductive layer and at least one control electrode in electro-static association therewith said layer and electrode being insulated from one another by vacuum insulation.

6. An arrangement or device in accordance with any of the preceding claims and comprising a thin layer of semi-conductor, electrodes on opposite edges thereof, an output circuit including a source of potential said electrodes and said layer in series, a control electrode adjacent one face of said layer and insulated therefrom, and means for applying control potentials between said control electrode and one of said other electrodes.

7. An arrangement or device in accordance with any of claims 1 to 5 and comprising a thin layer of semi-conductor, electrodes on opposite edges thereof, an output circuit including a source of potential said electrodes and said layer in series, a control electrode adjacent one face of said layer and insulated therefrom, a second control electrode adjacent the opposite face of said layer and insulated therefrom, said layer being thus sandwiched between said control electrodes, and means for applying control

Figure B.27: Oskar Heil filed patent applications on field effect transistors in Germany and other countries in 1934.

potentials between said control electrodes.

8. An arrangement or device in accordance with claim 6 or 7 and wherein the control electrode or electrodes (as the case may be) is or are spaced from the adjacent layer face or faces by an interposed sheet or sheets of solid dielectric.

9. An arrangement or device in accordance with any of claims 6 to 8 mounted in an evacuated envelope.

10. An arrangement or device in accordance with any of the preceding claims and wherein the semi-conductor is tellurium, iodine, cuprous oxide, vanadium pentoxide or a so-called " gap " conductor.

11. An electrical amplifier or other control arrangement or device utilising the phenomenon of varying semi-conductor resistance substantially as herein described with referance to the accompanying drawings.

Dated this 4th day of March, 1935.

CARPMAELS & RANSFORD,
Agents for Applicant,
24, Southampton Buildings,
London, W.C.2.

Leamington Spa: Printed for His Majesty's Stationery Office, by the Courier Press.—1936.

Figure B.28: Oskar Heil filed patent applications on field effect transistors in Germany and other countries in 1934.

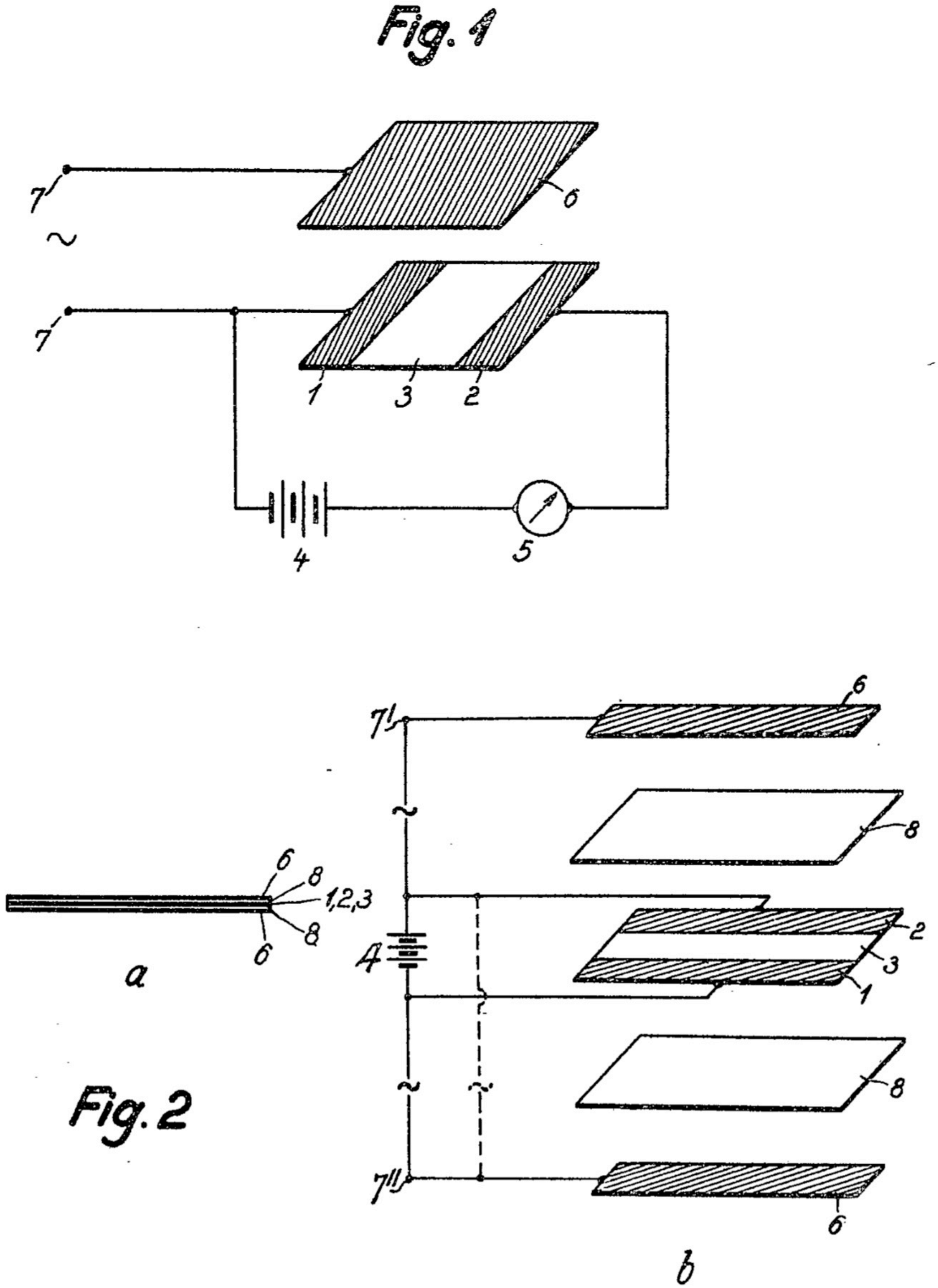


Figure B.29: Oskar Heil filed patent applications on field effect transistors in Germany and other countries in 1934.

3. Gilles Holst (Dutch, 1886–1968) and Willem Christiaan van Geel (Dutch, 1895–1967) filed a patent application on transistors in 1935 [Van Delft 2014]:

> Gilles Holst and Willem Christiaan van Geel. Filed in Germany in 1935 and subsequently in other countries. U.S. patent 2,173,904. Electrode System of Unsymmetrical Conductivity.

See pp. 2687–2689.

Holst was the research director at the Philips Eindhoven laboratory, and van Geel was an expert there on metal and semiconductor materials. Both were nominated for the Nobel Prize in Physics but never won.[1]

Holst was also one of the inventors of the sodium vapor lamp in 1932 (p. 971).

Philips Eindhoven was closely tied to the rest of the predominantly German-speaking research world from the late nineteenth century through World War II, including work on electronics, communications, and directed energy beams.[2]

To what extent was the work by Holst and van Geel based on the earlier patents of Julius Lilienfeld and Oscar Heil?

How much did they interact with other groups in the greater German-speaking world that were trying to develop transistors in the 1930s and early 1940s?

How far did the transistor-related work of Holst and van Geel get by 1945?

Did their work influence postwar projects at Bell Laboratories?

Much more archival research is needed.]

[1] https://www.nobelprize.org/nomination/archive/show.php?id=4874
https://www.nobelprize.org/nomination/archive/show.php?id=4936

[2] See for example: CIOS III-1; CIOS VI-26, 27; CIOS X-13; CIOS XI-10; CIOS XII-22.

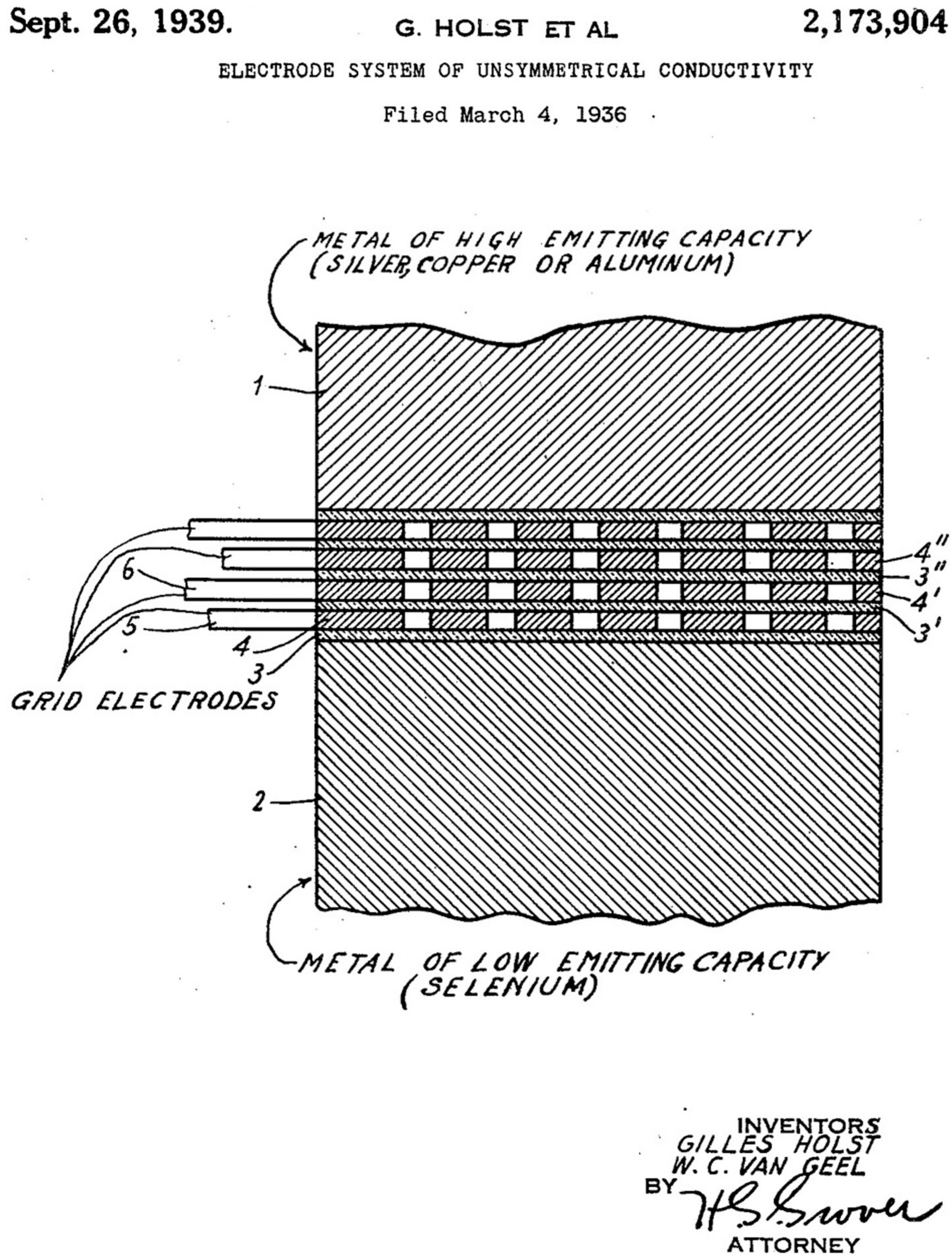


Figure B.30: Gilles Holst and Willem Christiaan van Geel filed a patent application on transistors in 1935.

Patented Sept. 26, 1939 **2,173,904**

UNITED STATES PATENT OFFICE

2,173,904

ELECTRODE SYSTEM OF UNSYMMETRICAL CONDUCTIVITY

Gilles Holst and Willem Christiaan van Geel, Eindhoven, Netherlands, assignors to N. V. Philips' Gloeilampenfabrieken, Eindhoven, Netherlands

Application March 4, 1936, Serial No. 67,052
In Germany March 9, 1935

3 Claims. (Cl. 179—171)

The invention relates to an electrode system of unsymmetrical conductivity formed by two layers of different emitting capacity which are separated from one another by a layer of insulating material.

It is known already that if cuprous oxide rectifiers form the starting point, a three-electrode system may be produced by providing in the semi-conductive oxide layer a grid to which an auxiliary voltage is applied in order to act upon the electron current flowing from the copper electrode to the semi-conductor. Experiments have shown, however, that a detector thus produced does not function satisfactorily.

Furthermore, it has previously been proposed to form a detector as a dry rectifier in which the electron current between the metallic electrode and the semi-conductor is acted upon by the field variation of a magnetic circuit of which the rectifier forms a part. This form of construction has the drawback that it takes up much room and cannot be operated in a simple manner.

The invention has for its object to provide a detector or amplifier capable of taking the place of the present valves with thermal emission which are complicated and expensive in initial cost as well as in operation, for example, due to the current consumption for heating the cathode.

According to the invention, an electrode system of unsymmetrical conductivity is formed by two layers of different emitting capacity which are separated from one another by a layer of insulating material, and embedded in the insulating intermediate layer is a grid provided with a supply conductor for applying potentials for the control of the electron current and/or for screening purposes.

A detector of this kind may consequently take the place of a usual detector or three-electrode-amplifying valve for it likewise comprises both an emitting electrode and an electrode which does not or substantially does not emit and, between these two electrodes, a grid which corresponds to a grid arranged in a valve in the vacuum between the cathode and the anode. In accordance with the invention, the grid is located in the insulating layer, which, as has been found, has the most favorable result. It is clear that the number of grids need not be limited to one.

A favorable form of execution of an electrode system according to the invention is that which follows:

The grids are constituted by perforated layers of conductive material which are contained in the insulating intermediate layer, said perforated layers being obtained, for example, by applying to one of the electrodes alternately an insulating layer and a perforated conductive layer and finally to the last conductive layer again an insulating layer. It is consequently possible to form electrode systems which correspond to the present radio valves having three or more electrodes such as, for example, the triodes, tetrodes, pentodes, hexodes, etc.

It is particularly important and advantageous that the insulating intermediate layer which contains the grids be formed independently of the adjacent electrode layers, for this renders it possible to control at will both the thickness of the layer and the position of the grids. The intermediate layer may be constituted of, for example, artificial resin which is applied in liquid condition to one of the electrodes. It is thus possible to apply a perfectly homogeneous layer.

It is of course very desirable to make the intermediate layer as thin as possible in order to raise as much as possible the electrical field strength between the main electrodes, as this has a great effect on the favorable operation. Due to the presence of a conductive grid there arises however the possibility that due to the too slight thickness of the insulating layer at a single, for example, accidentally projecting point, said grid may short-circuit one of the electrodes. In one favorable form of execution the risk of a short circuit is avoided by providing the grids with an insulating coating before they are applied to the insulating layer.

When choosing a grid material it should be considered that on account of its own emission a grid of emitting material acts upon the electron current between the anode and the cathode.

According to a favorable mode of execution use is therefore made of a grid material being a semi- or bad conductor and having a slight emitting capacity.

The invention will be explained more fully with reference to the accompanying drawing which represents, by way of example, one embodiment thereof.

The main electrodes 1 and 2 are formed, respectively, by a conductor consisting of a metal of high emitting capacity such as aluminum, copper or silver and by a semi-conductor as is usual in dry rectifiers. Selenium is a very suitable material for the semi-conductor.

The drawing represents, by way of example, a six-electrode-system. Besides the main electrodes 1 and 2 there are consequently four further

Figure B.31: Gilles Holst and Willem Christiaan van Geel filed a patent application on transistors in 1935.

2 2,173,904

electrodes (screen and control grids and the like). The main electrodes are separated from one another by means of an insulating material 3. In the example shown there are a plurality of grids which have been applied so as to alternate with the insulating layers.

In producing such an electrode system one starts, for example, with a main electrode 2 with smooth contact surface. To this electrode is applied, for example, by spraying, an insulating layer 3 to which is applied a grid 4 which is provided with a supply conductor 5 in order to apply potentials. Then an insulating layer 3' is applied again and subsequently again a grid 4' provided with a supply conductor 6. Thus one proceeds until the required number of grids is present and lastly an insulating layer is applied to the last grid.

The grids consist of perforated plates which before being applied to the insulating layers may be provided with an insulating coating. They may be constituted, for example, by a perforated and electrolytically oxidized plate of aluminum or by a perforated plate coated with a thin layer of artificial resin. Alternatively, the grids may be formed as wire gauze.

What we claim is:

1. An electrode system for the detection or amplification of electric currents comprising a pair of main electrodes in spaced relation, one of which has a high emitting capacity and is made of a metal from the group including silver, copper and aluminum, and the other of which has a low emitting capacity and is made from selenium, a plurality of control electrodes also in spaced relation interposed between the main electrodes, and thin layers of insulating material interposed between and contacting with the surfaces of adjacent control electrodes and the surfaces of adjacent main and control electrodes.

2. An electrode system as defined in claim 1, wherein an artificial resin constitutes the layers of insulating material between the several electrodes.

3. An electrode system as defined in claim 1 wherein the control electrodes are made from aluminum, the surfaces of which have been oxidized.

GILLES HOLST.
WILLEM CHRISTIAAN VAN GEEL.

Figure B.32: Gilles Holst and Willem Christiaan van Geel filed a patent application on transistors in 1935.

[**4. Rudolf Hilsch (German, 1903–1972) and Robert Pohl (German, 1884–1976)** demonstrated a proof-of-concept point-contact transistor in 1938:

> Rudolf Hilsch and Robert Pohl. 1938. Steuerung von Elektronenströmen mit einem Dreielektrodenkristall und ein Modell einer Sperrschicht. *Zeitschrift für Physik* 111:399–408.

Like a modern transistor, this solid-state semiconductor device had three electrodes, with the current flow into the middle electrode (the base, in modern terminology) controlling and greatly amplified by the much larger current flow between the other two electrodes (see pp. 2691–2692). For the 1938 experiments, that signal amplification was approximately a factor of 20. These results were extremely impressive, but the reason they are best described as "proof of concept" is that they were obtained in a material (a potassium bromide crystal) that became a good semiconductor only at a very high temperature (490^oC) and high voltages (100–150 Volts), which would not be practical for use in normal electronic circuits.

Hilsch recognized those limitations and promptly proposed that the results be replicated by modifying existing room-temperature semiconductor diodes to add a third electrode for the base (see below and p. 2693):

> Rudolf Hilsch. 1939. Elektronenleitung in Kristallen. *Die Naturwissenschaften* 27:489–492.

From available documentation, it is unclear exactly what projects Hilsch worked on between 1939 and the postwar period. Given his determination to replicate the transistor amplifier results in a more practical semiconductor device, and given the extensive wartime work on new and improved semiconductor devices, it seems likely that he would have carried his transistor work further, or collaborated with other scientists to do so.

In any event, the 1938 Hilsch and Pohl paper and the 1939 Hilsch paper were published in physics journals that were highly regarded and widely read in the German-speaking world, so they would have encouraged many other scientists (such as those mentioned in this appendix) to try to replicate, extend, and apply that work.

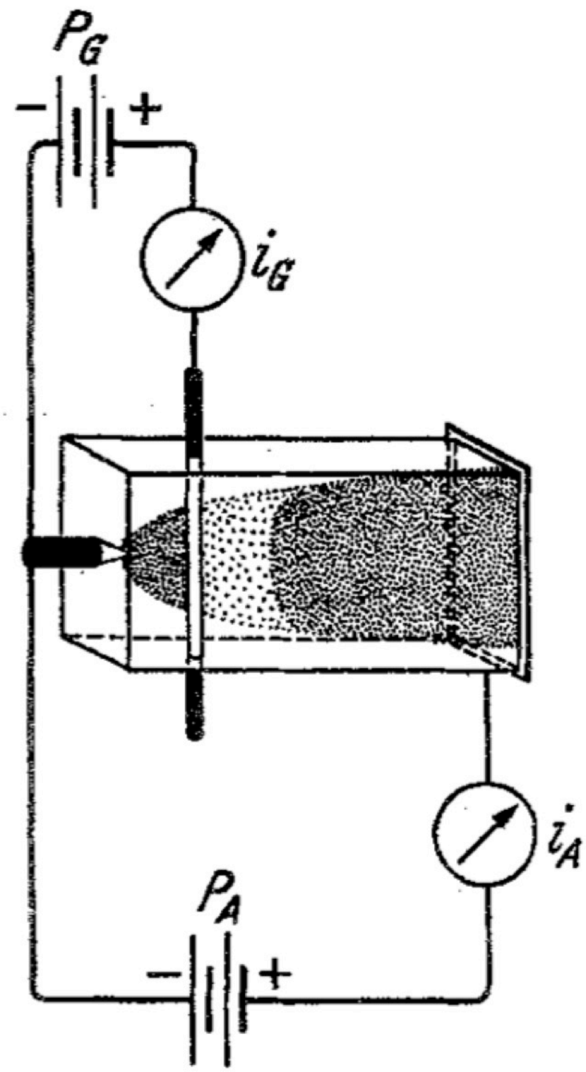
At the end of World War II, both Hilsch and Pohl were extensively interrogated by scientists and officials from Allied countries in order to aid postwar electronics programs in those countries (see for example pp. 2997 and 3005).]

Rudolf Hilsch. 1939. Elektronenleitung in Kristallen. *Die Naturwissenschaften* 27:489–492.

> Durch diese Messung ist zum erstenmal gezeigt worden, daß man auch in festen Körpern Ströme steuern kann. Die Trägheit der Ströme in diesem "großen" Modell ist naturgemäß groß. Es ist jetzt nur eine Aufgabe der Technik, auch in den dünnen Sperrschichten der technischen Gleichrichter das Steuergitter unterzubringen. Wenn die Lösung dieser Aufgabe gelingt, kann der Dreielektroden-Kristall auch technisch neben dem Dreielektroden-Rohr seine Bedeutung erhalten.

> This measurement has shown for the first time that it is also possible to control currents in solid bodies. The inertia of the currents in this "large" model is naturally large. It is now only a technical task to add the control grid in the thin barrier layers of engineering rectifiers. If the solution to this problem is successful, the three-electrode crystal can also gain technical significance alongside the three-electrode tube.

Rudolf Hilsch (1903–1972) and Robert Pohl (1884–1976) demonstrated a prototype point-contact transistor (1938)



Rudolf Hilsch and Robert Pohl. 1938. Steuerung von Elektronenströmen mit einem Dreielektrodenkristall und ein Modell einer Sperrschicht. *Zeitschrift für Physik* 111:399.

Fig. 6. Schema und Schaltung eines Dreielektrodenkristalles. Gezeichnet ist die durch Farbzentren sichtbar gemachte Elektronenverteilung während einer Abnahme des Anodenstromes. Die negative Aufladung des Gitters ist vergrößert worden, der Anodenstrom hat aber noch nicht seinen stationären Wert erreicht. (Kristallabmessungen $2 \times 5 \times 10$ mm).

Figure B.33: Rudolf Hilsch and Robert Pohl demonstrated a prototype point-contact transistor in 1938.

Rudolf Hilsch (1903–1972) and Robert Pohl (1884–1976) demonstrated a prototype point-contact transistor (1938)

Fig. 7.

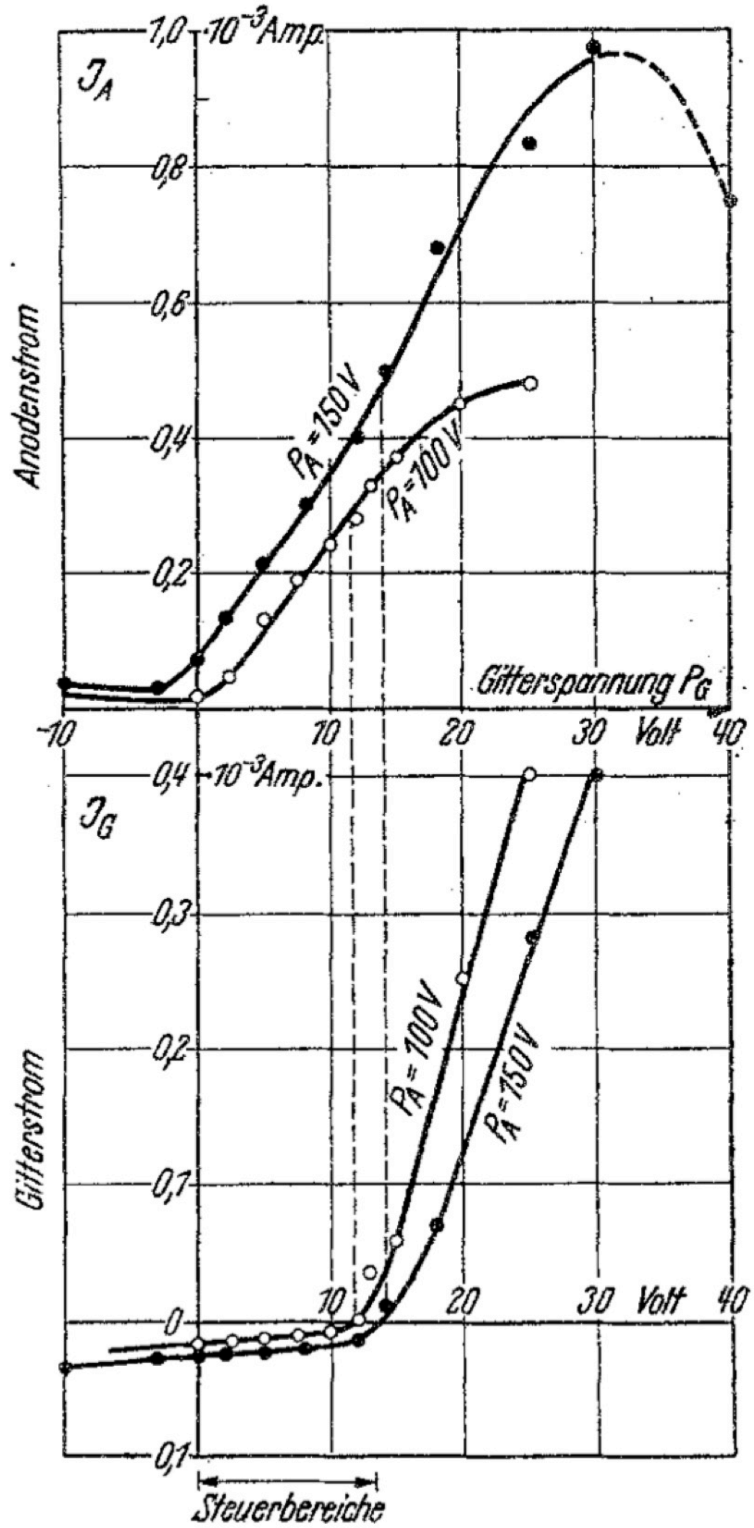


Fig. 8.

Rudolf Hilsch and Robert Pohl. 1938. Steuerung von Elektronenströmen mit einem Dreielektrodenkristall und ein Modell einer Sperrschicht. *Zeitschrift für Physik* 111:399.

Fig. 7 und 8. Die beiden Kennlinien eines Dreielektrodenkristalles mit 20facher Verstärkung. $T = 490^0$ C.

Figure B.34: Rudolf Hilsch and Robert Pohl demonstrated a prototype point-contact transistor in 1938.

Rudolf Hilsch (1903–1972) and Robert Pohl (1884–1976) demonstrated a prototype point-contact transistor (1938)

Rudolf Hilsch. 1939. Elektronenleitung in Kristallen. *Die Naturwissenschaften* 27:489–492.

Die Steuerung von Elektronenströmen in Kristallen.

Im Besitze der Modell-Sperrschicht mit großer Dicke erhält man einen besonderen Vorteil. Es gelingt, die im *Kristall* fließenden Elektronenströme mit einem *Gitter* ebenso zu steuern wie in einem *Elektronenrohr*. In Fig. 2 ist im Schema zwischen der Calcium- und Platinelektrode eine dritte Elektrode, das Gitter, in Form eines Platindrahtes eingeschmolzen. Das Einschmelzen gelingt ohne Zerstörung des Einkristalls ebenso leicht wie das Einschmelzen eines warmen Drahtes in einen Eisblock. Es ist wichtig, daß der Pt-Draht selbst keine Elektronen in den Kristall abgeben kann. Durch eine negative Aufladung mit einer Gitterbatterie kann ein vom Calcium-Blech ausgehender Elektronenstrom gesteuert werden. Die Wirksamkeit dieser Anordnung ist aus dem Meßbeispiel der Fig. 3 ersichtlich. Die in der Röhrentechnik üblichen Bezeichnungen können beibehalten werden.

Durch diese Messung ist zum erstenmal gezeigt worden, daß man auch in festen Körpern Ströme steuern kann. Die Trägheit der Ströme in diesem „großen" Modell ist naturgemäß groß. Es ist jetzt nur eine Aufgabe der Technik, auch in den dünnen Sperrschichten der technischen Gleichrichter das Steuergitter unterzubringen. Wenn die Lösung dieser Aufgabe gelingt, kann der Dreielektroden-Kristall auch technisch neben dem Dreielektroden-Rohr seine Bedeutung erhalten.

Figure B.35: Rudolf Hilsch and Robert Pohl demonstrated a prototype point-contact transistor in 1938.

[**5. Erich Habann (German, 1892–1968)** filed a very detailed patent application on point-contact transistors, their fabrication, and use:

> Erich Habann. Filed in 1942. German patent DE 971,775. Einrichtung zur Verstärkung elektrischer Ströme und Spannungen. [Device for Amplifying Electrical Currents and Voltages.] (pp. 2695–2698)

The level of detail in the patent application suggests that by 1942, Habann may well have already produced and demonstrated such transistors at his Hessenwinkel laboratory (p. 2699).

Although documentation on his transistor results is not currently available, it is known that Habann worked on a number of secretive research projects involving electronics, rockets, and nuclear physics during the war, and that he was well funded by the German military. After the war, he continued his research for the Soviet Union.

If Habann indeed had a working prototype transistor by 1942, it is possible that such transistors may have been mass-produced for use in rocket guidance systems or other applications before the end of the war.

It is also quite possible that Habann, his hardware, and his information directly or indirectly aided the development of microelectronics technologies in Allied countries after the war.

It appears that thus far only the German historian Günter Nagel has investigated and briefly written about Erich Habann and his inventions:

> Günter Nagel. 2006. Pionier der Funktechnik. *Brandenburger Blätter*. 15 December 2006 p. 9.
>
> Günter Nagel. 2011. *Himmlers Waffenforscher: Physiker, Chemiker, Mathematiker und Techniker im Dienste der SS*. Aachen: Helios.
>
> Günter Nagel. 2012a. *Wissenschaft für den Krieg: Die geheimen Arbeiten der Abteilung Forschung des Heereswaffenamtes*. Stuttgart: Franz Steiner.

Much more archival research should be conducted to investigate Habann's technical accomplishments, as well as their direct and indirect impacts on other research programs.]

Erteilt auf Grund des Ersten Überleitungsgesetzes vom 8. Juli 1949
(WiGBl. S. 175)

BUNDESREPUBLIK DEUTSCHLAND

AUSGEGEBEN AM
26. MÄRZ 1959

DEUTSCHES PATENTAMT

PATENTSCHRIFT

№ 971 775

KLASSE 21g GRUPPE 11 02

INTERNAT. KLASSE H 01 l ———

H 11624 VIII c/21g

Dr. Erich Habann, Berlin-Hessenwinkel
ist als Erfinder genannt worden

Dr. Hildegard Koepke, Berlin-Zehlendorf

Einrichtung zur Verstärkung elektrischer Ströme und Spannungen

Patentiert im Gebiet der Bundesrepublik Deutschland vom 22. September 1942 an
Der Zeitraum vom 8. Mai 1945 bis einschließlich 7. Mai 1950 wird auf die Patentdauer nicht angerechnet
(Ges. v. 15. 7. 1951)
Patentanmeldung bekanntgemacht am 20. August 1953
Patenterteilung bekanntgemacht am 12. März 1959

Die Erfindung benutzt zur Verstärkung elektrischer Ströme oder Spannungen einen Trockengleichrichter. Dieser besteht z. B. beim Selentrockengleichrichter aus Selen in kristallisiertem Zustande als Halbleiter, das sich als dünne Schicht zwischen zwei Elektroden befindet, die bei gleicher Feldstärke als Kathoden verschieden große Elektronenströme in das Selen hineinzusenden vermögen. Je unterschiedlicher die beiden Elektroden in ihrer Emissionsfähigkeit sind, desto besser arbeitet der Gleichrichter. In der Praxis wird Selen bei so hoher Temperatur auf einer Nickelunterlage geschmolzen, daß sich zwischen dem Nickel und dem Selen eine dünne Schicht von Nickelselenid bildet. Dieses Nickelselenid vermag als Kathode nur sehr geringe Elektronenmengen in das Selen zu emittieren, im Gegensatz zu den Metallen wie Cadmium, Blei, die als Kathoden bei gleich großer Feldstärke erheblich größere Elektronenmengen in das Selen hineinzusenden vermögen. Die Metalle selbst unterscheiden sich im übrigen nur wenig in ihrem Emissionsvermögen untereinander. Eine Selenschicht, die sich zwischen einer Nickelselenidelektrode auf der einen Seite

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Figure B.36: In 1942, Erich Habann filed a detailed patent application on point-contact transistors, their fabrication, and use.

2 **971 775**

und einer Metallelektrode auf der andern Seite befindet, wird große Ströme hindurchlassen, wenn die Metallelektrode Kathode ist, und nur sehr geringe Ströme hindurchlassen, wenn die Nickelselenidelektrode Kathode ist.

Die Erfindung geht von diesen Erkenntnissen aus. Sie geht ferner von der Erkenntnis aus, daß der Strom in der Selenschicht ein reiner Elektronenstrom ist, daß dieser außer von der Elektronenemissionsfähigkeit der anliegenden Kathode von der elektrischen Feldstärke abhängt, die an dieser Kathode herrscht, und daß demgemäß die Verhältnisse ähnlich liegen wie bei Hochvakuumröhren mit Glühkathode. Infolgedessen muß sich mit dem Trockengleichrichter auch ein Verstärker analog den Glühkathoden-Verstärkerröhren zusammenbauen lassen. Da wegen der dünnen Selenschicht der an sich bekannte Einbau eines Gitters nicht zum gewünschten Ziel führt, wird die eine Elektrode erfindungsgemäß unterteilt, derart, daß der eine Teil als Steuerorgan dient und aus einem Metall besteht, das mit der Gleichrichterschicht durch chemische Reaktion eine Übergangsschicht bildet. Grundsätzlich ist es möglich, dieses Steuerorgan entweder auf der Anodenseite unterzubringen oder, wie in der Zeichnung, auf der Kathodenseite. Die beiden Elektroden *a* und *b* liegen hier in einer Ebene auf derselben Seite der Selenschicht, während auf der andern Seite der Selenschicht die Anode *A* anhaftet. *a* ist die Steuerelektrode und entspricht dem Gitter in den Verstärkerröhren, *b* ist die Emissionskathode und entspricht dem Glühfaden in Verstärkerröhren. Damit die von der Steuerelektrode ausgehenden elektrischen Kraftlinien sich möglichst zwischen Emissionskathode *b* und Steuerelektrode *a* ausbilden und weniger zwischen Steuerelektrode *a* und Anode *A*, verdient die Anordnung gemäß der Zeichnung den Vorzug vor einer Anordnung des Steuerorgans auf der Anodenseite. Außerdem werden in der Zeichnung die Steuerelektrode *a* und die Emissionskathode *b* in Streifen rasterartig ineinandergeschachtelt, wobei möglichst keiner der Streifen breiter gehalten wird, als die Selenschicht dick ist. Die Streifen *a* werden unter sich elektrisch verbunden, und ebenso sind die Streifen *b* unter sich elektrisch verbunden. Die Streifen sind durch dünne Isolationsblättchen (Glimmer) voneinander gegen seitliche Berührung isoliert. Die Anode *A* stellt in üblicher Weise eine zusammenhängende Fläche aus einem aufgespritzten oder angepreßten Metall dar.

Die Verstärkung hängt hauptsächlich von dem Verhältnis der Oberflächen der Streifen der Emissionskathode zu denen des Steuerorgans ab. Natürlich kommen die Oberflächen nur so weit in Betracht, als die Emissionskathode und die Steuerelektrode die Selenschicht tatsächlich berühren. Das Verhältnis spielt eine ähnliche Rolle wie der Durchgriff bei Verstärkerröhren: je kleiner das angegebene Verhältnis ist, desto größer ist der Verstärkungsgrad. Die Schaltung ist der der Verstärkerröhren analog: Der zu verstärkende Strom wird zwischen Emissionskathode *b* und Steuerelektrode *a* gelegt. Der verstärkte Strom wird zwischen Emissionskathode *b* und Anode *A* abgenommen. Zwischen der Kathode *b* und der Anode *A* liegt ständig eine entsprechend bemessene Gleichspannung, und zwar mit dem negativen Pol an der Emissionskathode *b* und mit dem positiven Pol an der Anode *A*. Die Steuerelektrode *a* muß eine negative Gleichspannung vorgespannt erhalten, ähnlich der negativen Vorspannung der Gitter bei Verstärkerröhren. Diese Gleichspannung — ebenfalls optimal bemessen — liegt also mit dem negativen Pol an der Steuerelektrode *a* und mit dem positiven Pol an der Emissionskathode *b*.

Eine solche Einrichtung würde auf der Steuerseite noch zuviel Energie verbrauchen, als Verstärker also noch wenig oder gar nicht funktionieren. Die Steuerelektrode *a* wird nun aus einem Material angefertigt, das möglichst schlecht Elektronen in die Gleichrichterschicht (Se) emittiert, z. B. Nickelselenid, während die Emissionskathode *b* aus einem Material hergestellt wird, das möglichst gut und reichlich Elektronen in die Gleichrichterschicht emittiert (praktisch alle Metalle). Unter den hier möglichen Metallen kommen besonders diejenigen in Betracht, die sich nicht mit Selen verbinden. Dies sind außer Graphit Chrom und Aluminium. Das Material der Anode ist gleichgültig. Zweckmäßig besteht es aus Blei oder Cadmium oder Zinn oder einer leicht aufspritzbaren Metallegierung.

Der Raster wird aus entsprechend geschnittenen Streifen, aus dünnem Nickelblech für die Steuerelektrode *a* und aus dünnen Aluminiumfolien für die Emissionskatode *b*, gebildet. Die der Selenschicht zugekehrte Fläche der Streifen wird möglichst eben gemacht. Auf ihr wird Selen in etwa $^1/_{10}$ bis $^2/_{10}$ mm dicker Schicht zum Schmelzen gebracht. Die Fläche mit der Selenschicht wird dann so hoch erhitzt, bis das Nickel mit dem Selen reagiert und eine oberflächliche Nickelselenidschicht bildet, aber nicht so hoch erhitzt, daß auch das Aluminium reagiert (300° C genügen). Die Erhitzung erfolgt so lange, bis sich die Nickeloberfläche vollständig mit der Nickelselenidschicht von ausreicher Dicke bedeckt hat. Darauf wird die Schicht bei 200° C oder besser durch Abschrecken zum Erstarren gebracht. Dann wird zweckmäßig mit einem Graphit- oder Aluminiumstempel die Selenschicht fest an ihre gerasterte Unterlage gepreßt und mehrere Stunden unter diesem Preßdruck bei etwa 120° C und dann bei 210° C angelassen. Schließlich wird auf die fertige und abgekühlte Schicht nach Entfernung des Druckstempels eine leicht schmelzende Metallegierung, z. B. aus Cadmium und Zinn, als Anode *A* aufgesprizt oder auch nur eine Bleiplatte als Anode *A* gegen die Selenschicht gepreßt. Für die Selenschicht ist eine bestimmte Dicke optimal. Ist sie zu dick, so spielen die Unterschiede in der Elektronenemissionsfähigkeit der anliegenden Elektroden nicht mehr die entscheidende Rolle. Der Strom wird dann hauptsächlich von der Eigenleitfähigkeit des Selens bestimmt. Bei zu dünner Schicht leidet die Durch-

Figure B.37: In 1942, Erich Habann filed a detailed patent application on point-contact transistors, their fabrication, and use.

schlagsfestigkeit, und die konstruktiven Schwierigkeiten werden zu groß. Die optimale Schichtdicke liegt beim Selen zwischen $^1/_{10}$ und $^2/_{10}$ mm.

Es besteht ein Interesse, zur Verringerung ihrer Kapazität die Streifen *a* und *b* möglichst klein zu machen. An Stelle der Streifen werden besser dünne Drähte aus Nickel und Aluminium verwendet, die gemeinsam über eine Porzellanunterlage, die entsprechende Rillen hat, gewickelt werden, und zwar derart, daß die Drähte einlagig und abwechselnd, lediglich durch die Porzellanrillen isoliert, dicht nebeneinander auf der Porzellanfläche liegen.

Der Verstärker arbeitet trägheitslos. Er kann, wenn der Anodenkreis mit dem Steuerkreis rückgekoppelt wird, als Generator dienen, oder er kann mit weiteren Verstärkern in Reihe geschaltet werden, indem der aus dem Anodenkreis des ersten Verstärkers resultierende Strom über einen Transformator oder ein sonstiges geeignetes Kopplungsglied dem Steuerkreis des zweiten Verstärkers zugeleitet wird usw. Es können so hohe Verstärkungen erzielt werden. Andererseits können mehrere Verstärker auch parallel geschaltet und so der Aufnahme und der verstärkten Wiedergabe auch größerer Leistungen angepaßt werden. Es besteht die Möglichkeit, diese Anpassung von vornherein durch Bemessung der gesamten Selenfläche vorzunehmen.

Eine höhere Anodenspannung liefert ohne weiteres eine größere Leistung. Die positive Anodenspannung wird aber dadurch begrenzt, daß von der Steuerelektrode *a*, die ja gegenüber allen andern Elektroden, insbesondere gegenüber der Anode *A* negativ ist, nicht nur kein größerer Strom zur Emissionskathode *b*, sondern auch nicht zur Anode *A* hinüberfließen darf. Insofern müssen Anodenspannung und Vorspannung des Steuergitters einander optimal angepaßt sein. Die Leistung des Verstärkers kann weiterhin durch Kühlflächen, welche die Temperatur der Selenschicht beim Betriebe niedrig halten, gesteigert werden.

Die Erfindung ist nicht auf den Selengleichrichter beschränkt. In gleicher Weise können andere Gleichrichtertypen verwendet werden. Beim Kupferoxydulgleichrichter beispielsweise entspricht das Kupferoxydul der Selenschicht und das Kupferoxyd der Nickelselenidschicht. Die Steuerelektrode wird daher hier einen dünnen Überzug von Kupferoxyd erhalten müssen und erst mit diesem die Kupferoxydulschicht berühren dürfen. Das Material der Anode ist auch hier gleichgültig, während die Emissionskathode zweckmäßig aus reinem Kupfer besteht.

PATENTANSPRÜCHE:

1. Einrichtung zur Verstärkung elektrischer Ströme und Spannungen mittels einer von drei Elektroden oberflächlich berührten Gleichrichterschicht, bei der eine Elektrode als Steuerelektrode dient, dadurch gekennzeichnet, daß auf der einen Seite der Gleichrichterschicht eine zusammenhängende Elektrode anliegt, während die auf der anderen Seite liegende Elektrode unterteilt ist, derart, daß der eine Teil als Steuerelektrode dient und aus einem Metall besteht, das mit der Gleichrichterschicht durch chemische Reaktion eine Übergangsschicht bildet.

2. Einrichtung nach Anspruch 1, dadurch gekennzeichnet, daß bei einer aus einer Verbindung bestehenden Gleichrichterschicht, wie Kupferoxydul, die Übergangsschicht statt durch Reaktion des Metalls der Steuerelektrode mit der Gleichrichterschicht durch Reaktion eines Metalloides (Sauerstoff) mit der Gleichrichterschicht gebildet ist.

3. Einrichtung nach Anspruch 1 oder 2, dadurch gekennzeichnet, daß die beiden auf derselben Seite der Gleichrichterschicht benachbarten Elektroden rasterartig oder rostartig ineinander verschachtelt sind, derart, daß die ineinandergreifenden Teile eng nebeneinander liegen und eine Breite besitzen, die vorzugsweise kleiner als die Stärke der Gleichrichterschicht ist.

4. Einrichtung nach den Ansprüchen 1 bis 3, dadurch gekennzeichnet, daß die Steuerelektrode von größerer Flächenausdehnung als die neben ihr angeordnete Elektrode ist.

5. Einrichtung nach den Ansprüchen 1 bis 4, dadurch gekennzeichnet, daß die Veränderung der von der Steuerelektrode beaufschlagten Flächenteile der Gleichrichterschicht als kontinuierlicher Übergang durch thermische Behandlung erzielt ist.

6. Einrichtung nach Anspruch 5, dadurch gekennzeichnet, daß die optimale Stärke der Übergangsschicht durch die Höhe der angewandten Temperatur und die Dauer der Erhitzung bestimmt ist.

7. Einrichtung nach den Ansprüchen 1 bis 7, dadurch gekennzeichnet, daß die anderen Elektroden aus einem Material bestehen, das sich nicht mit der Gleichrichterschicht verbindet.

8. Einrichtung nach den Ansprüchen 1 bis 7, dadurch gekennzeichnet, daß die der Steuerelektrode benachbarte Elektrode die Anode darstellt.

9. Einrichtung nach den Ansprüchen 1 bis 7, dadurch gekennzeichnet, daß die der Steuerelektrode benachbarte Elektrode die Kathode darstellt.

10. Einrichtung nach den Ansprüchen 1 bis 9, dadurch gekennzeichnet, daß Mittel zur Kühlung (Kühlflächen) vorgesehen sind.

In Betracht gezogene Druckschriften:

Deutsche Patentschriften Nr. 450 091, 519 161, 684 522;

österreichische Patentschrift Nr. 130 102;

Figure B.38: In 1942, Erich Habann filed a detailed patent application on point-contact transistors, their fabrication, and use.

schweizerische Patentschriften Nr. 184 396, 215 504;
französische Patentschrift Nr. 786 454;
britische Patentschriften Nr. 349 584, 500 342, 500 344, 529 754;
USA.-Patentschriften Nr. 1 745 175, 1 900 018, 2 160 383, 2 173 904;
Zeitschrift für Physik, 111 (1938/39), S. 399, 406 bis 408;
Zeitschrift für Elektrochemie und angewandte physikalische Chemie, 1943, S. 274ff., 284;
Physikalisches Taschenbuch von Hermann Ebert, Braunschweig, 1951, S. 346;
D'Ans-Lax: »Taschenbuch für Chemiker und Physiker«, Springer-Verlag, 1949, S. 1218;
Berichte der Sächsischen Akademie der Wissenschaften, Leipzig, Bd. 82, 1930, S. 133;
Gmelin: »Handbuch für anorganische Chemie«, Bd. 10, »Selen«, S. 417;
Proc. I.R.E., Bd. 40, S. 1512ff. (1952);
Transact. Electrochem. Soc., 79 (1941), S. 359/360.

Hierzu 1 Blatt Zeichnungen

Zu der Patentschrift **971 775**
Kl. **21 g** Gr. 11 02
Internat. Kl. **H 01 l** ——

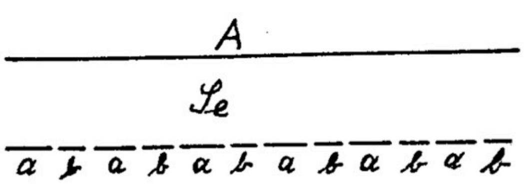


Figure B.39: In 1942, Erich Habann filed a detailed patent application on point-contact transistors, their fabrication, and use.

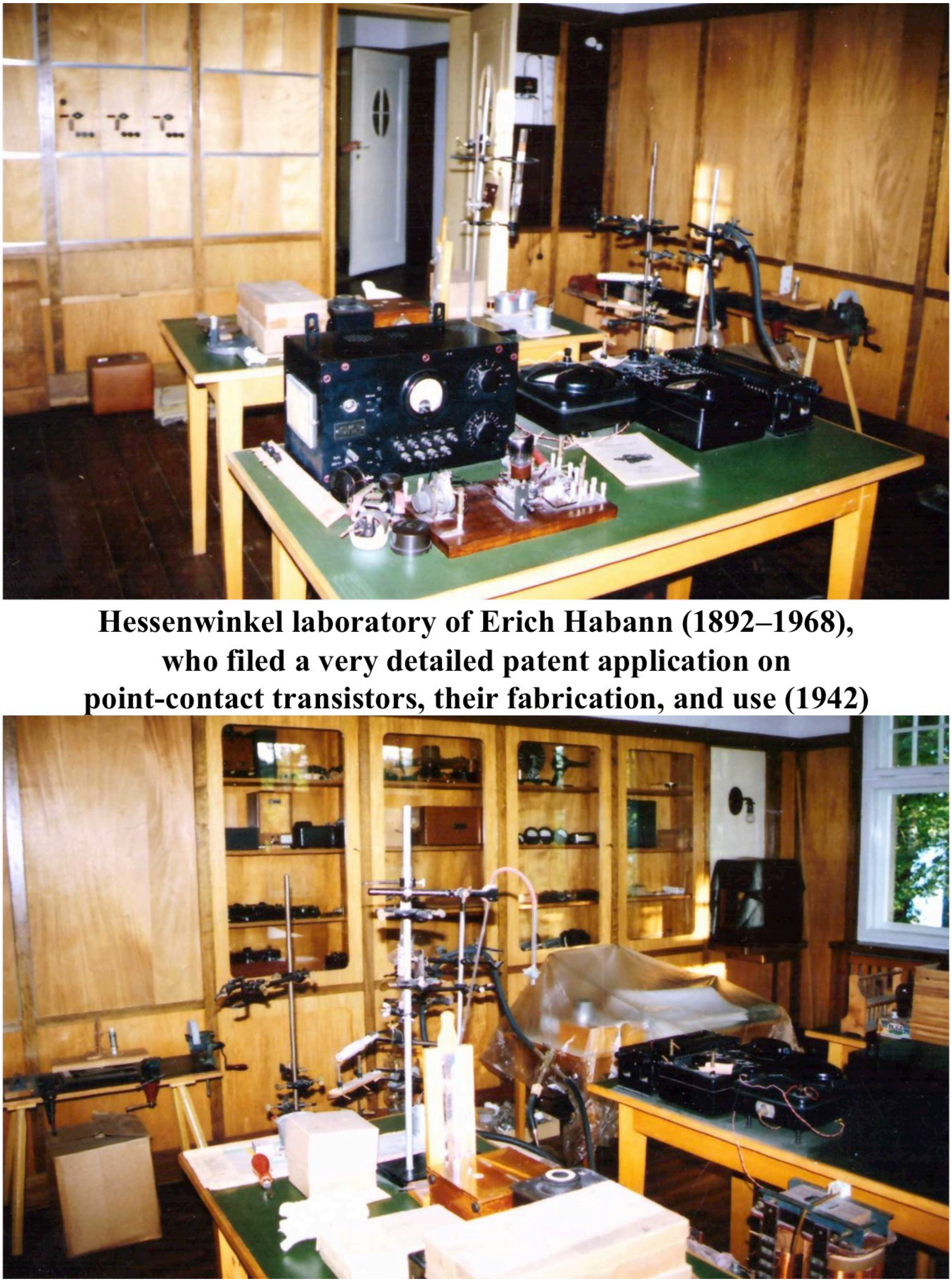


Figure B.40: The Hessenwinkel laboratory of Erich Habann, who filed a very detailed patent application on point-contact transistors, their fabrication, and use in 1942 [courtesy of Günter Nagel].

[**6. Walter Schottky (Swiss/German, 1886–1976)** conducted detailed analyses of semiconductor properties necessary for transistors during World War II [Handel 1999]. See for example:

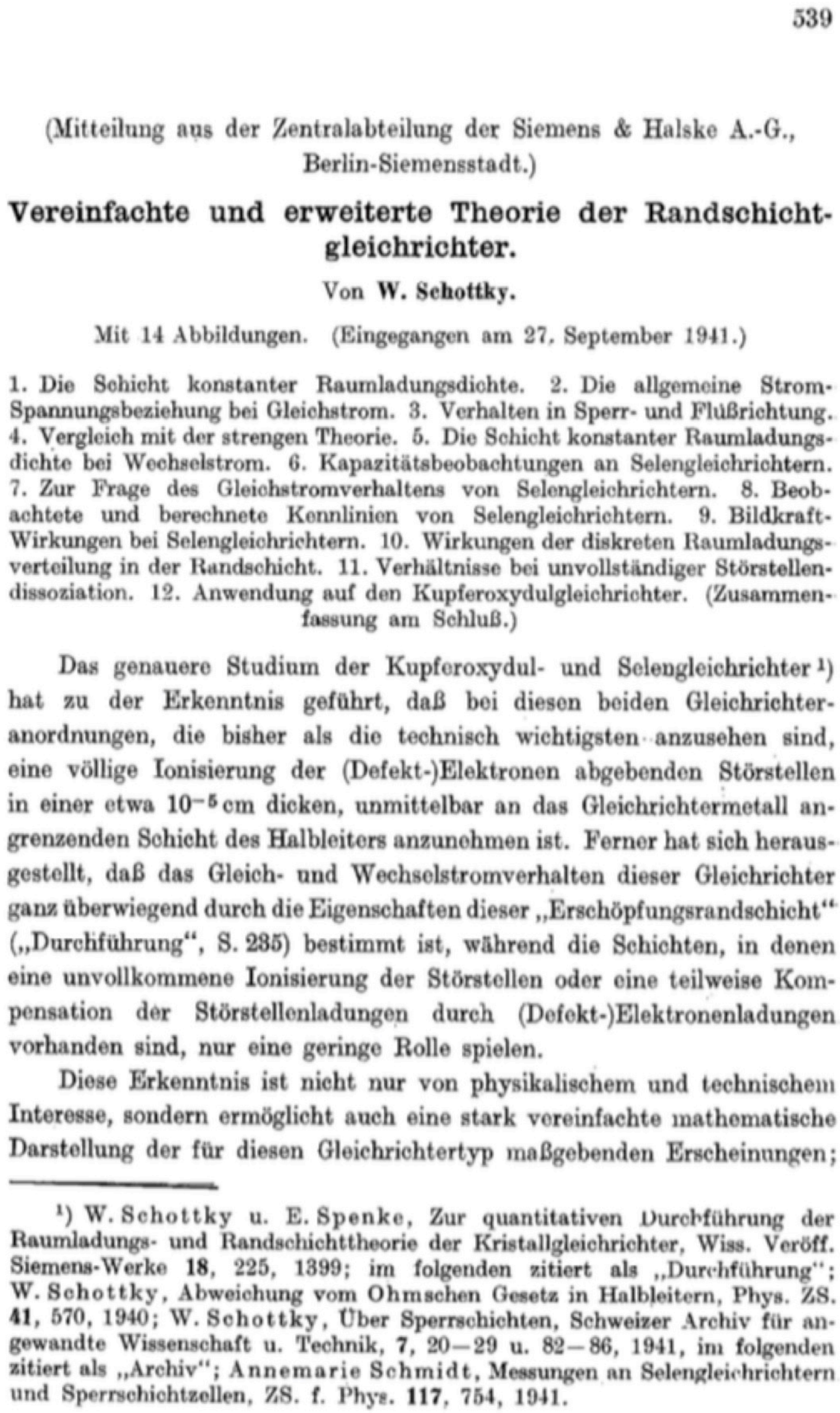
> Walter Schottky. 1942. Vereinfachte und erweiterte Theorie der Randschichtgleichrichter. [Simplified and Extended Theory of Boundary Layer Rectifiers.] *Zeitschrift für Physik* 118:539–592. (p. 2701)

> Walter Schottky. Filed in 1948 but based on wartime work. German patent DE 841,174. Halbleiteranordnung. [Semiconductor Device.] (pp. 2702–2707)

All of Schottky's research papers were seized by the United States in 1945 and never returned to him or publicly disclosed:

> NARA RG 40, Entry UD-75, Box 24, Folder Selenium Rectifier Machinery. (pp. 2708–2709)

Did Schottky's work lead to functional transistors in wartime Germany and/or the postwar United States? Historians should carry out much more research on this topic.]



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(Mitteilung aus der Zentralabteilung der Siemens & Halske A.-G., Berlin-Siemensstadt.)

Vereinfachte und erweiterte Theorie der Randschicht-gleichrichter.

Von **W. Schottky.**

Mit 14 Abbildungen. (Eingegangen am 27. September 1941.)

1. Die Schicht konstanter Raumladungsdichte. 2. Die allgemeine Strom-Spannungsbeziehung bei Gleichstrom. 3. Verhalten in Sperr- und Flußrichtung. 4. Vergleich mit der strengen Theorie. 5. Die Schicht konstanter Raumladungsdichte bei Wechselstrom. 6. Kapazitätsbeobachtungen an Selengleichrichtern. 7. Zur Frage des Gleichstromverhaltens von Selengleichrichtern. 8. Beobachtete und berechnete Kennlinien von Selengleichrichtern. 9. Bildkraft-Wirkungen bei Selengleichrichtern. 10. Wirkungen der diskreten Raumladungsverteilung in der Randschicht. 11. Verhältnisse bei unvollständiger Störstellendissoziation. 12. Anwendung auf den Kupferoxydulgleichrichter. (Zusammenfassung am Schluß.)

Das genauere Studium der Kupferoxydul- und Selengleichrichter [1]) hat zu der Erkenntnis geführt, daß bei diesen beiden Gleichrichteranordnungen, die bisher als die technisch wichtigsten anzusehen sind, eine völlige Ionisierung der (Defekt-)Elektronen abgebenden Störstellen in einer etwa 10^{-5} cm dicken, unmittelbar an das Gleichrichtermetall angrenzenden Schicht des Halbleiters anzunehmen ist. Ferner hat sich herausgestellt, daß das Gleich- und Wechselstromverhalten dieser Gleichrichter ganz überwiegend durch die Eigenschaften dieser „Erschöpfungsrandschicht" („Durchführung", S. 235) bestimmt ist, während die Schichten, in denen eine unvollkommene Ionisierung der Störstellen oder eine teilweise Kompensation der Störstellenladungen durch (Defekt-)Elektronenladungen vorhanden sind, nur eine geringe Rolle spielen.

Diese Erkenntnis ist nicht nur von physikalischem und technischem Interesse, sondern ermöglicht auch eine stark vereinfachte mathematische Darstellung der für diesen Gleichrichtertyp maßgebenden Erscheinungen;

[1]) W. Schottky u. E. Spenke, Zur quantitativen Durchführung der Raumladungs- und Randschichttheorie der Kristallgleichrichter, Wiss. Veröff. Siemens-Werke **18**, 225, 1399; im folgenden zitiert als „Durchführung"; W. Schottky, Abweichung vom Ohmschen Gesetz in Halbleitern, Phys. ZS. **41**, 570, 1940; W. Schottky, Über Sperrschichten, Schweizer Archiv für angewandte Wissenschaft u. Technik, **7**, 20—29 u. 82—86, 1941, im folgenden zitiert als „Archiv"; Annemarie Schmidt, Messungen an Selengleichrichtern und Sperrschichtzellen, ZS. f. Phys. **117**, 754, 1941.

Figure B.41: Walter Schottky published detailed analyses of semiconductor properties necessary for transistors in 1942 [*Zeitschrift für Physik* (1942) 118:539–592].

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Dr. Walter Schottky, Pretzfeld (OFr.)
ist als Erfinder genannt worden

Siemens & Halske Aktiengesellschaft, Berlin und München

Halbleiteranordnung

Patentiert im Gebiet der Bundesrepublik Deutschland vom 2. Oktober 1948 an
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Es sind Anordnungen bekanntgeworden, bei denen ein Störstellenhalbleiter (Germanium) von beispielsweise flachzylindrischer Form so mit Elektroden versehen wird, daß die Grundfläche mit einer großen, im folgenden als *O*-Elektrode bezeichneten Metallelektrode im Kontakt ist, während auf der oberen Fläche eine Metallspitze mit positivem Potential von etwa 1 V gegen die *O*-Elektrode als Steuerelektrode, im folgenden als *G* bezeichnet, dient und eine etwa $^1/_{10}$ mm davon entfernt aufgesetzte Spitze, im folgenden mit *B* bezeichnet, den zu beeinflussenden Strom nach der *O*-Elektrode abführt; die *B*-Elektrode hat hierbei ein negatives Potential von etwa 10 V gegen die *O*-Elektrode.

Die Steuerwirkung derartiger Anordnungen beruht darauf, daß die *G*-Elektrode bei den gewählten Betriebsspannungen einen durch kleine Änderungen von U_g stark variierenden Strom von Defektelektronen in den Halbleiter entsendet, wobei dieser Halbleiter infolge eines gewissen Zusatzes von Elektronen abgebenden Störstellen als Überschußhalbleiter wirkt. Die *B*-Elektrode, die als Kathode gegenüber der *O*-Elektrode geschaltet ist, stößt die Überschußelektroden des Halbleiters ab und vermag, solange kein *G*-Strom fließt, nur dadurch einen Strom zu führen, daß Elektronen aus *B* in den Halbleiter entsendet werden, was bei dem gewählten Halbleiter bedeutend höhere Spannungen erfordert als in umgekehrter Richtung zur Emission von Defektelektronen notwendig sind. Da unter diesen Bedingungen die Elektronenemission von der an der *B*-Elektrode herrschenden Feldstärke ab-

Figure B.42: Walter Schottky published detailed analyses of semiconductor properties necessary for transistors in 1942.

hängt, ist es möglich, diesen Elektronenstrom dadurch zu beeinflussen, daß die von *G* kommenden Defektelektronen teilweise zur Elektrode *B* abfließen; bei den großen Absolutstromdichten, von der Größenordnung 100 A/cm², um die es sich dabei handelt, bilden die nach *B* abfließenden Defektelektronen in den unmittelbar an *B* angrenzenden Schichten des Halbleiters eine positive Raumladung aus, die in der bekanntgewordenen Anordnung anscheinend noch dadurch verstärkt wird, daß in einer dünnen die obere Fläche des Halbleiters bedeckenden Schicht Defektelektronen abgebende Störstellen eingebaut sind, die im Betriebszustand weitgehend ihrer Defektelektronen beraubt sind (Erschöpfungsrandschicht) und infolgedessen die von *G* durch den Halbleiter nach *B* gelangenden Defektelektronen zu binden vermögen, so daß im Effekt die Defektelektronen zu längerem Aufenthalt im Randgebiet vor *B* gezwungen und somit in ihrer felderhöhenden Raumladungswirkung unterstützt werden.

In Erkenntnis dieser in der Literatur bisher nicht beschriebenen Wirkungsweise der an sich bekannten Anordnungen, in denen übrigens die Rolle der Überschuß- und Defektelektronen bei geeigneter anderer Wahl der Störstellen und evtl. des Grundmaterials sowie der Spannungen vertauscht werden kann, erscheint es als Idealziel, das Eindringen der Defektelektronen in die *B*-Elektrode, das deren Raumladungswirksamkeit gewissermaßen vorzeitig beendet, ganz zu vermeiden und die Defektelektronen so lange in der vor *B* wirksamen Raumladungskathodenschicht des Halbleiters verweilen zu lassen, bis sie durch Wiedervereinigung mit den diese Schicht passierenden Elektronen, ihr unvermeidliches und natürliches Ende finden. In dieser Richtung bieten sich im Rahmen der bekannten Anordnung gewisse Möglichkeiten, indem man die Defektelektronen abgebende Störstellenschicht vor der *B*-Elektrode genügend breit macht und die Ablösungsarbeit der Defektelektronen von ihren neutralen Störstellen genügend groß, so daß eine durch das starke Randfeld ihres Defektelektrons beraubte und dann durch ein aus dem Halbleiter kommendes Defektelektron wieder neutralisierte Störstelle ihre neutrale Ladung genügend lange behält, ehe sie durch thermische Anregung in Form eines abgespaltenen Defektelektrons wieder negativ aufgeladen wird.

Doch sind diesen Retardierungsmethoden der auf die *B*-Elektrode zuströmenden positiven Ladungsteilchen gewisse Schranken gesetzt. Erfindungsgemäß wird nun, alternativ oder in Kombination mit der Störstellenretardierung ein anderes Mittel angewandt, um die aus *G* kommenden Defektelektronen am Eindringen in die *B*-Elektrode zu verhindern und sie so lange in der vor *B* ausgebildeten Raumladungsrandschicht zurückzuhalten, bis sie durch Wiedervereinigung mit den aus *B* kommenden Überschußelektronen ihr natürliches Ende gefunden haben. Dieses Mittel besteht darin, daß man die Elektrode *B* nicht in direkte Berührung mit dem benutzten Halbleiter, der im folgenden als Grundkristall *Gr* bezeichnet wird, bringt, sondern zwischen Grundkristall und *B*-Elektrode eine vorzugsweise 10^{-5} bis 10^{-4} cm dicke Schicht eines anderen kristallinen Stoffes mit besonderen Eigenschaften, im folgenden als Fremdschicht *F* bezeichnet, zwischenschaltet.

Um die erfindungsgemäß verlangten Eigenschaften und die Wirkungsweise dieser Fremdschicht zu erläutern, sind in Fig. 1 die Energieniveaus für Überschuß- und Defektelektronen für zwei störstellenfreie, einander unmittelbar berührende verschiedenartige Kristalle dargestellt, wie sie gemäß der Erfindung für die Fremdschicht und den Grundkristall vorgeschrieben werden.

E_- bedeutet das Energieniveau, das ein überschüssig in den Kristall eingebrachtes Elektron im Ruhezustand einnehmen würde, E_+ das Energieniveau, das ein von außen eingebrachtes Elektron vorfindet, wenn es sich an den Ort einer ruhenden im Grundgitter des betreffenden Kristalls vorhandenen Elektronenlücke einbaut. (Im Rahmen der wellenmechanischen Vorstellungen bedeutet E_- den unteren Rand des tiefsten elektronenfreien Energiebandes, E_+ den oberen Rand des höchsten noch mit Elektronen voll besetzten Energiebandes). Der Niveauunterschied zwischen E_- und E_+ innerhalb jedes Kristalls bedeutet den Energieaufwand, um im ungestörten Kristall ein Elektron aus seinem normalen gebundenen Zustand in den freien beweglichen Zustand zu bringen, wobei gleichzeitig eine Elektronenlücke (Defektelektron) und ein Überschußelektron entsteht. Dieser Energieunterschied wird deshalb im folgenden als Elektronenpaarbildungsarbeit oder kurz als Paarbildungsarbeit bezeichnet. Die relative Lage von E_- bzw. E_+ in den beiden aneinandergrenzenden Kristallen kann, außer von den verschiedenen chemisch und strukturell bedingten Kräften, mit denen die Elektronen im E_- bzw. E_+ Niveau der beiden Kristalle gebunden sind, noch von etwaigen molekularen elektrischen Doppelschichten an der Kristallgrenze abhängen, ist aber bei reinen Substanzen und reinen Oberflächen sowie gegebenenfalls festgelegter Kristallorientierung eine eindeutige Eigenschaft der beiden Kristalle.

Erfindungsgemäß wird nun für den Grundkristall eine Substanz mit kleiner Paarbildungsarbeit gewählt, wie z. B. *Ge*, während die Fremdschicht eine mindestens um mehrere Zehntel *eV* größere Paarbildungsarbeit aufweisen soll, z. B. *Si*. Ferner soll E_+ im Grundkristall mindestens einige Zehntel *eV* oberhalb des E_+-Niveaus in der Fremdschicht liegen, während E_- im Grundkristall entweder unterhalb oder nur knapp oberhalb des E_--Niveaus in der Fremdschicht liegen soll. Da, wie durch die Pfeile in Fig. 1 angedeutet, die mit − bezeichneten Überschußelektronen jeweils das niedrigere Energieniveau zu erreichen streben, besteht unter den Verhältnissen von Fig. 1 keine Hemmung für den Übergang der Überschußelektronen aus der Fremdschicht in den Grundkristall. Dagegen bedeutet der Übergang einer Elektronenlücke, d. h. eines Defektelektrons +, von unten nach oben den Übergang eines Elektrons von oben nach unten;

Figure B.43: Walter Schottky published detailed analyses of semiconductor properties necessary for transistors in 1942.

die Defektelektronen streben also im Energieschema der Fig. 1 nach oben, und es ist deshalb bei genügendem Niveauunterschied von E_+ im Grundkristall und in der Fremdschicht nicht möglich, daß in den Grundkristall einmal eingedrungene Defektelektronen durch die Grenze zwischen Grundkristall und Fremdschicht hindurch in die Fremdschicht gelangen.

Wie sich diese Schrankenwirkung der Fremdschicht bei der betriebsmäßigen, stark negativen Spannung der B-Elektrode in der Verstärkeranordnung der eingangs geschilderten Art auswirkt, wird durch Fig. 2 verdeutlicht, wo die Energieniveaus in Fremdschicht und Grundkristall unter der Einwirkung des starken in B auftretenden Randschichtfeldes dargestellt sind. Der kathodischen Aufladung der Elektrode B entspricht eine abstoßende Wirkung auf die Überschußelektronen −, also ein Anstieg des Energieniveaus E_- und E_+. Man erkennt, daß die Überschußelektronen, die aus der Elektrode B durch die Fremdschicht in den Grundkristall gezogen werden, an der Grenze F-Gr kein Hindernis vorfinden, daß dagegen die ursprünglich von der Elektrode G kommenden im Grundkristall vorhandenen Defektelektronen an der Grenze F-Gr aufgehalten werden und nicht weiter können. Sie bilden infolgedessen in der an F angrenzenden Schicht des Grundkristalls eine positive Raumladung aus, die die in Fig. 2 durch eine nach unten konvexe Krümmung der E-Niveaus angedeutete Störstellenraumladung mehr oder weniger stark kompensiert bzw. überkompensiert, oder, alternativ, eine durchweg bereits vorhandene positive Raumladung, wie sie durch Elektronen abgebende Störstellen hervorgerufen werden würde, E nach oben konvex gekrümmt, verstärkt. Dieser Einfluß ist in Fig. 3 angedeutet, wo neben der defektelektronenfreien E_--Verteilung die durch die Defektelektronenraumladung modifizierte E_--Kurve gestrichelt dargestellt ist. (Die entsprechend E_--abgeänderte E_+-Kurve konnte hier weggelassen werden). Man erkennt, daß die Steigung von E_- an der B-Elektrode, und damit die die Elektronen aus B herausziehende Feldstärke, durch die Raumladungswirkung der + erhöht ist, so daß dadurch ein Erhöhung des Elektronenstromes bewirkt wird, auf der die Steuerwirkung beruht.

Gelangen die Defektelektronen, wie es in der eingangs geschilderten bekannten drei Elektrodenanordnung der Fall ist, von der Seite in den Raum vor der Elektrode B, so bewegen sie sich dauernd durch überschußhaltige Gebiete hindurch, wo bereits eine Wiedervereinigung der + und — möglich ist, so daß der +-Strom, desto stärker geschwächt wird, je weiter man sich von der Elektrode G entfernt. Eine Abschätzung der Strecken, die die Defektelektronen ohne Wiedervereinigung zurückzulegen vermögen, ergibt, daß die Größenordnung der Abklingstrecke hier etwa 1/10 mm beträgt.

Es hat bei dieser Anordnung keinen Zweck, die Breite der B-Elektrode größer als die Abklingstrecke der Defektelektronen, in diesem Fall einige Zehntelmillimeter zu wählen, da die von G entfernten Teile der B-Elektrode der Raumladungssteuerung durch die + nicht mehr unterliegen.

Da ein Stoff mit tiefem Defektelektronenniveau E_+ den Austritt von Defektelektronen aus einer Metallelektrode, Übergang eines gebundenen Elektrons aus dem Halbleiter in das Metall, nur erschwert, ist es erfindungsgemäß zweckmäßig, die G-Elektrode nicht durch eine Fremdschicht der beschriebenen Art vom Grundkristall zu trennen, sondern mit dem Grundkristall in direkte Berührung zu bringen. Dies kann z. B. durch Aussparen der Fremdschichtbedeckung in der Berührungsfläche der G-Elektrode oder durch nachträgliches Entfernen der Fremdschicht an dieser Stelle bewirkt werden.

Eine weitere Ausbildung der Erfindung besteht darin, daß man mehrere Berührungsgrenzen verschiedener Halbleiter in der Raumladungsrandschicht vor der B-Elektrode hintereinander anordnet. Steht insbesondere eine dünne Zwischenschicht mit hohem E_+-Niveau beiderseits mit kristalliner Substanz mit tieferen E_+-Niveaus in Berührung, so können Defektelektronen, die aus einer vorzugsweise in direktem Kontakt mit der Zwischenschicht angeordneten Elektrode in die Zwischenschicht einströmen, diese Schicht weder nach der B-Elektrode noch nach der O-Elektrode hin verlassen. Das Potential dieser Schichten folgt dann, wenigstens auf Querabmessungen von der Größenordnung der Abklingstrecke der Defektelektronen hin, den Potentialschwankungen der betreffenden Elektrode, wobei nur die Defektelektronenmengen, die durch Wiedervereinigung verlorengehen, aus der betreffenden Elektrode nachzuliefern sind, während ein Verluststrom zur B- oder O-Elektrode nicht in Frage kommt.

Auf diese Weise ist, ähnlich wie in Vakuumröhren, eine ziemlich stromlose Steuerung von Elektronenströmen durch quer zu dem Elektronenstrom angeordnete Flächen annähernd konstanten Potentials möglich, wobei neben der steuernden Zwischenschicht auch noch weitere Zwischenschichten mit festem Potential zur Beeinflussung des Ruhefeldes sowie zur Abschirmung der Potentialschwankungen der B-Elektrode verwendet werden können. Weitere Anwendungen von Halbleitergrenzen der durch Fig. 1 gezeichneten Art ergeben sich daraus, daß bei nicht allzu großem Niveauunterschied von E_+ im Grundkristall und der Fremdschicht von gewissen Feldstärken an mit einem zunehmenden Übergang von Defektelektronen aus dem Grundkristall in die Fremdschicht als Folge des wellenmechanischen Tunneleffekts zu rechnen ist. Erhält hierbei der Grundkristall einen hinreichend großen Gehalt an Defektelektronen abgebenden Störstellen, so wirkt er gegenüber der Fremdschicht wie eine durch Feldeinwirkung Defektelektronen abgebende Elektrode, der in einiger Entfernung die Elektrode B als durch Feldeinwirkung Elektronen abgebende Elektrode gegenübersteht. Gelingt es nun, die Defektelektronen unmittelbar vor der Elektrode B und die Elektronen unmittelbar vor der Grenzfläche Fremdschicht — Grundkristall zu retardieren, so

Figure B.44: Walter Schottky published detailed analyses of semiconductor properties necessary for transistors in 1942.

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entsteht als Folge des gleichzeitigen Durchgangs beider Elektronenarten je ein besonderer Kathoden- und Anodenfall, während in der Mitte der Fremdschicht kleinere Feldstärken herrschen. Diese Ladungsverteilung begünstigt ihrerseits die Feldmission sowohl der Elektronen aus der Elektrode *B* wie der Defektelektronen aus der Grenzfläche Grundkristall — Fremdschicht. Derartige Anordnungen können nicht nur als extrem spannungsabhängige Widerstände, und damit als Spannungsregler, benutzt werden, sondern zeigen von gewissen Feldstärken an sogar eine fallende Charakteristik, so daß sie zur Verstärkung und Schwingungserzeugung dienen können. Es handelt sich dabei um eine 2-Elektroden-Anordnung, bei der die *O*-Elektrode in breiter Fläche Kontakt macht und aus einem Metall gewählt wird, das leicht Defektelektronen abgibt, während die Querabmessungen der *B*-Elektrode vorzugsweise in der Größenordnung der Fremdschichtdicke (Spitzenberührung) gewählt werden, um die zur Vermeidung von lokalen Durchschlägen notwendige Kohärenz solcher Anordnungen zu gewährleisten. Die Fremdschichtdicke wird zweckmäßig in der Größenordnung der Wiedervereinigungsstrecke (Abklingstrecke) der Defektelektronen gewählt.

Als Mittel für die in diesem Teil der Erfindung verlangte Retardierung der Elektronen bzw. Defektelektronen wird erfindungsgemäß eine Anreicherung der Fremdschicht mit Elektronen abgebenden Störstellen auf der Grundkristallseite, mit Defektelektronen abgebenden Störstellen auf der *B*-Seite vorgeschlagen, wobei die Wirkungsweise dieser Störstellen, die sich in dem betriebsmäßigen Feld bei schwachem Stromdurchgang überwiegend im ionisierten Zustand befinden sollen, in der früher beschriebenen Weise zu verstehen ist. Ein anderes Mittel, um die Defektelektronen vor der *B*-Elektrode und/oder die Überschußelektronen vor der Grundkristallgrenze zu retardieren, besteht gemäß der Haupterfindung darin, daß weitere Zwischenschichten mit solchem E_+- bzw. E_--Niveau eingeschaltet werden, das nur für die zu retardierende Elektronenart, dagegen nicht für die andere Elektronenart, eine Energieschranke entsteht.

Selbstverständlich kann in der zuletzt beschriebenen 2-Elektroden-Anordnung auch der Grundkristall durch eine direkt die Defektelektronen abgebende metallische Elektrode ersetzt werden. Doch scheint eine Halbleiterelektrode infolge ihres nicht ganz zu vernachlässigenden spezifischen Widerstandes gewisse Stabilisierungsvorteile in bezug auf die lokale Durchschlagsgefahr zu besitzen. Auch ist hervorzuheben, daß in allen durch die Erfindung erfaßten Anordnungen die Rolle der Überschuß- und Defektelektronen, der Überschuß- und Defektstörstellen, und der positiven und negativen Potentiale gleichzeitig vertauscht werden kann.

Der Hauptgedanke der Erfindung, den Aufenthalt einer raumladungsmäßig beeinflussenden Elektronenart relativ zu dem der beeinflußten Elektronenart im Beeinflussungsgebiet möglichst zu verlängern, kann endlich auch dadurch verwirklicht werden, daß die beeinflußte Elektronenart infolge eines in kurzer Strecke durchlaufenen starken Potentialabfalls überthermische Geschwindigkeiten erhält und dadurch ein durch passende Verteilung von positiven und negativen Störstellen erzeugbares schwaches Gegenfeld zu überwinden vermag, welches die andere, nicht in derselben Weise beschleunigte Elektronenart vollkommen zurückhält.

PATENTANSPRÜCHE:

1. Halbleiteranordnung mit Strömungsgebieten, in denen im Betriebszustand sowohl Überschuß- wie Defektelektronen vorhanden sind, dadurch gekennzeichnet, daß in diesen Gebieten zwei Halbleiterkristalle aneinandergrenzen, deren Energieniveau E_- für Überschuß- bzw. E_+ für Defektelektronen an der Berührungsfläche so gegeneinander verlagert sind, daß in Richtung des vorgeschriebenen Stromflusses nur für die eine Elektronenart eine erhebliche Energieschranke vorhanden ist.

2. Anordnung nach Anspruch 1, dadurch gekennzeichnet, daß die Paarbildungsarbeiten beider Kristalle erheblich verschieden sind, die absolute Lage des E_-- bzw. E_+-Niveaus jedoch nahezu gleich ist.

3. Anordnung nach Anspruch 1, dadurch gekennzeichnet, daß mehrere, vorzugsweise parallele Grenzflächen der beanspruchten Art verwendet werden.

4. Anordnung nach Anspruch 1 und 2, dadurch gekennzeichnet, daß die Halbleitergrenze der beanspruchten Art in einer an sich bekannten strombeeinflussenden 3-Elektroden-Anordnung zur Anwendung gelangt, in der eine vorzugsweise als Spitze ausgebildete beeinflussende Elektrode *G* Defektelektronen, eine ihr benachbarte, vorzugsweise ebenfalls als Spitze ausgebildete Beeinflussungselektrode *B* Überschußelektronen in den Halbleiter entsendet, der seinerseits mit einer Grundelektrode *O* in Berührung ist, wobei die Grenze vorzugsweise nur vor der Elektrode *B* angeordnet ist und dadurch entsteht, daß zwischen Grundkristall und *B*-Elektrode eine vorzugsweise 10^{-5} bis 10^{-4} cm dicke Fremdschicht eingefügt ist, die für den Durchtritt der Elektronen aus *B* in den Grundkristall kein Hindernis bildet, dagegen die Defektelektronen am Abfließen nach der Elektrode *B* verhindert.

5. Anordnung nach Anspruch 3 und 4, dadurch gekennzeichnet, daß die Defektelektronen von *G* aus in eine Schicht gelangen, die beiderseits von Energieschranken für die Defektelektronen eingeschlossen ist.

6. Anordnung nach Anspruch 3 bis 5, dadurch gekennzeichnet, daß weitere Schichten der in 5 beschriebenen Art verwendet werden, die jeweils mit weiteren vorzugsweise auf konstanter Spannung gehaltenen Defektelektronen abgebenden Hilfselektroden in Berührung stehen.

Figure B.45: Walter Schottky published detailed analyses of semiconductor properties necessary for transistors in 1942.

7. Anordnung nach Anspruch 4 bis 6 mit Vertauschung der Rolle der Überschuß- und Defektelektronen.

8. Anordnung nach Anspruch 1 und 2, dadurch gekennzeichnet, daß ein gut defekthalbleitender Grundkristall als Defektelektronen-Emissionselektrode für eine Fremdschicht verwendet wird, die gegenüber dem Grundkristall für die Defektelektronen eine Energieschranke bildet.

9. Kombination der Anordnung nach Anspruch 8 mit einer Elektronen emittierenden B-Elektrode auf der anderen Seite der Fremdschicht, wobei die Dicke der Fremdschicht vorzugsweise von derselben Größenordnung wie die Fremdschichtdicke ist.

10. Anordnung nach Anspruch 9, wobei, vorzugsweise durch geeignete Verteilung verschiedener Störstellenarten oder auch durch Benutzung weiterer Grenzflächen nach Anspruch 1, für eine Retardierung der Defektelektronen vor der B-Elektrode und/oder für eine Retardierung der Überschußelektronen vor der Grundkristallgrenze gesorgt wird, zu dem Zwecke, einen die Emission auf beiden Seiten steigernden und mit wachsender Stromstärke zunehmenden Anoden- bzw. Kathodenfall hervorzurufen, der von gewissen Stromstärken ab der Anordnung eine fallende Charakteristik verleiht.

11. Anordnung nach Anspruch 10, wobei jedoch der Grundkristall durch eine Defektelektronen abgebende Metallelektrode ersetzt ist.

12. Anordnung nach Anspruch 8 bis 11, dadurch gekennzeichnet, daß die Rolle der Überschuß- und Defektelektronen vertauscht ist.

13. Anordnung nach Anspruch 1 und folgenden, wobei jedoch die gleichzeitige Durchlässigkeit für die eine Elektronenart und Undurchlässigkeit für die in entgegengesetzter Richtung strömende andere Elektronenart durch ein mittels geeigneter Störstellenraumladungen verwirklichtes rein elektrisches Feld erreicht ist, wobei die Durchlässigkeit dieses Feldgebietes für die eine Elektronenart durch vorausgehende überthermische Beschleunigung dieser Elektronenart erreicht wird.

Angezogene Druckschriften:
Österreichische Patentschrift Nr. 153 123;
schweizerische Patentschrift Nr. 203 236.

Hierzu 1 Blatt Zeichnungen

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Figure B.46: Walter Schottky published detailed analyses of semiconductor properties necessary for transistors in 1942.

Zu der Patentschrift 841 174
Kl. 21 g Gr. 11 02

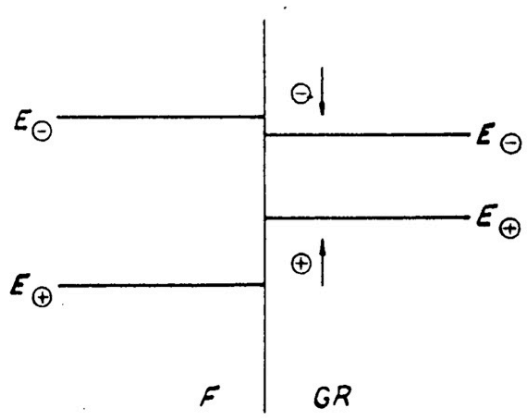


Fig. 1

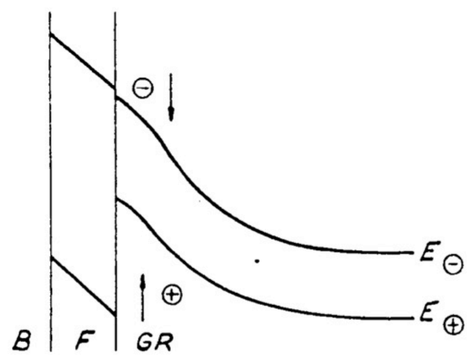


Fig. 2

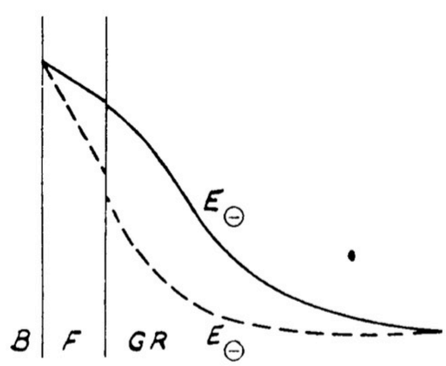
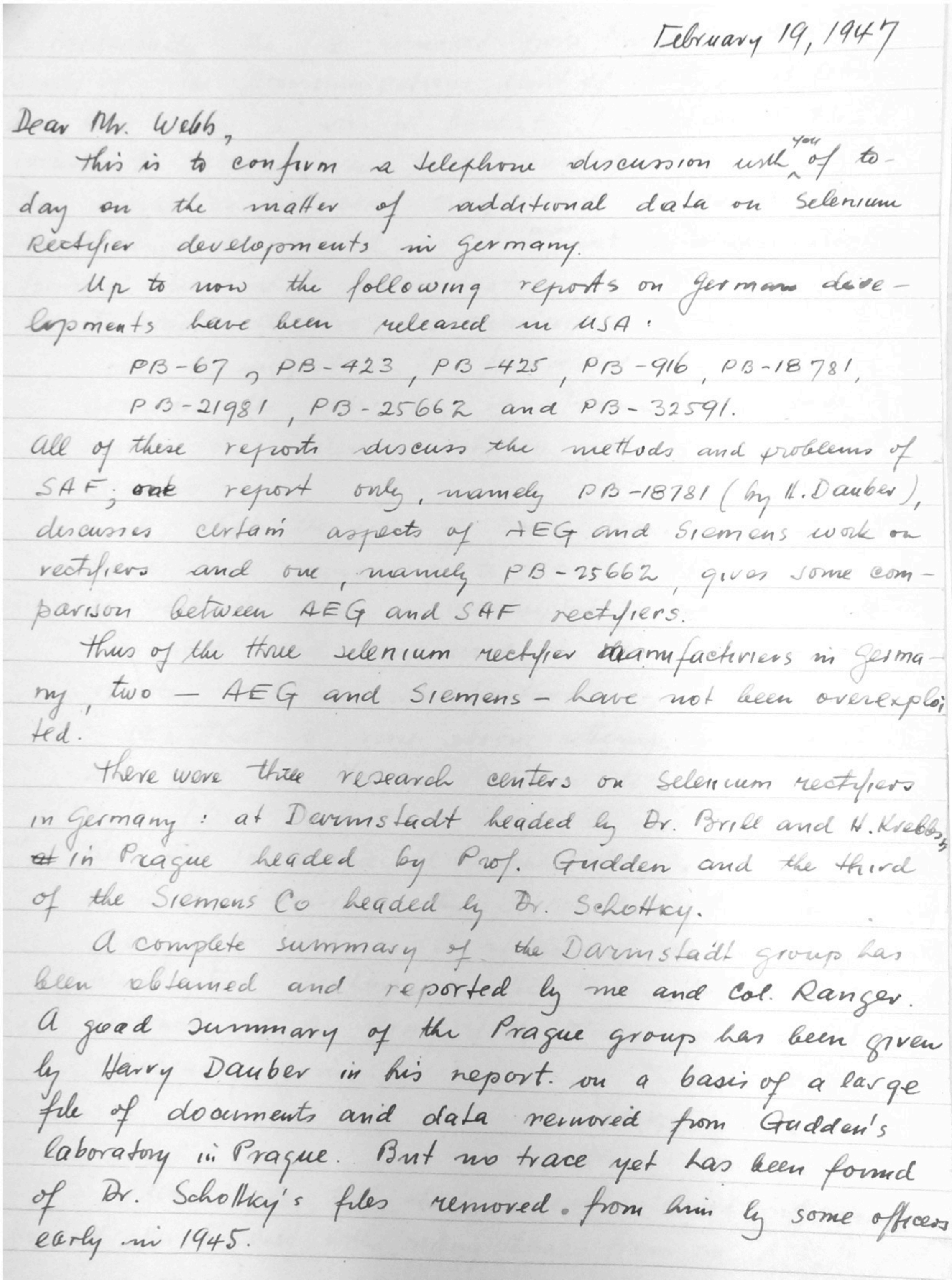


Fig. 3

Figure B.47: Walter Schottky published detailed analyses of semiconductor properties necessary for transistors in 1942.

DECLASSIFIED
Authority NND968018

NARA RG 40, Entry UD-75, Box 24, Folder Selenium Rectifier Machinery



February 19, 1947

Dear Mr. Webb,

this is to confirm a telephone discussion with you of today on the matter of additional data on Selenium Rectifier developments in Germany.

Up to now the following reports on German developments have been released in USA:

PB-67, PB-423, PB-425, PB-916, PB-18781,
PB-21981, PB-25662 and PB-32591.

All of these reports discuss the methods and problems of SAF; one report only, namely PB-18781 (by H. Dauber), discusses certain aspects of AEG and Siemens work on rectifiers and one, namely PB-25662, gives some comparison between AEG and SAF rectifiers.

Thus of the three selenium rectifier manufacturers in Germany, two – AEG and Siemens – have not been overexploited.

There were three research centers on Selenium rectifiers in Germany: at Darmstadt headed by Dr. Brill and H. Krebbs, in Prague headed by Prof. Gudden and the third of the Siemens Co headed by Dr. Schottky.

A complete summary of the Darmstadt group has been obtained and reported by me and Col. Ranger. A good summary of the Prague group has been given by Harry Dauber in his report on a basis of a large file of documents and data removed from Gudden's laboratory in Prague. But no trace yet has been found of Dr. Schottky's files removed from him by some officers early in 1945.

Figure B.48: Walter Schottky published detailed analyses of semiconductor properties necessary for transistors in 1942. All of his papers were seized by the United States in 1945 and never returned [NARA RG 40, Entry UD-75, Box 24, Folder Selenium Rectifier Machinery].

NARA RG 40, Entry UD-75, Box 24, Folder Selenium Rectifier Machinery

Incidentally the file removed from Prague is still in the hands of the Communications Unit of Fiat, or at least was there when I was in Höchst. I suggested to Mr. Weaver to turn it over to the microfilming group but am afraid, on the second though, that the value of the material might be ruined as it was, not in a very neat form at the time I saw it last.

I would therefore recommend:

(a) a suggestion be forwarded to Mr. Weaver to consider the possibility of obtaining additional information on selenium rectifiers work of AEG and Siemens

(b) that the files of Harry Dauber left in his hands and amounting to some 6"–10" of material be sent to you in Washington where it might be rearanged and appraised by an expert from one of the rectifier manufacturers.

(c) That a very strong attemp be made both here and in Great Britain to locate Dr. Schottky's files. In USA it might be in the hands of the Air Intelligence at Wright Field, or in Pentagon, or in the hands of the Signal Corps Labs in New-Jersey, or else in the hands of the US Navy in Washington. Perhaps a letter to the Intelligence Branches of the Army & the Navy might start the machinery going.

Yours JML.

P.S. Please give this check to our esteemed and mutual friend Mr Powell with many thanks from me.

Figure B.49: Walter Schottky published detailed analyses of semiconductor properties necessary for transistors in 1942. All of his papers were seized by the United States in 1945 and never returned [NARA RG 40, Entry UD-75, Box 24, Folder Selenium Rectifier Machinery].

[**7. Heinrich Welker (German, 1912–1981) and Herbert Mataré (German, 1912–2011)** began developing a point-contact transistor in Germany during the war. Welker filed a detailed patent application based on that wartime work on 6 April 1945.

After the war, Welker and Mataré continued their work in France. In 1948, they publicly announced their transistor (p. 2711) and filed further patent applications.[3]

For more information, see:

> Heinrich Welker. Filed in 1945. German patent DE 980,084. Halbleiteranordnung zur kapazitiven Steuerung von Strömen in einem Halbleiterkristall. [Semiconductor Device for Capacitively Controlling Currents in a Semiconductor Crystal.] (pp. 2712–2716)
>
> Herbert Mataré and Heinrich Welker. Filed in 1948 but based on wartime work. U.S. patent 2,673,948. Crystal Device for Controlling Electric Currents by Means of a Solid Semiconductor. (pp. 2717–2720)

The postwar work by Welker and Mataré in France is relatively well known, but much more archival research needs to be conducted to investigate the history and accomplishments of their German projects during the war. Among many other questions, was their postwar French work an improvement upon their wartime German work, or was it rather a reconstruction of their wartime German work?]

[3] Handel 1999; Ringer and Welker 1948; Riordan 2005; Van Dormael 2004, 2009, 2012.

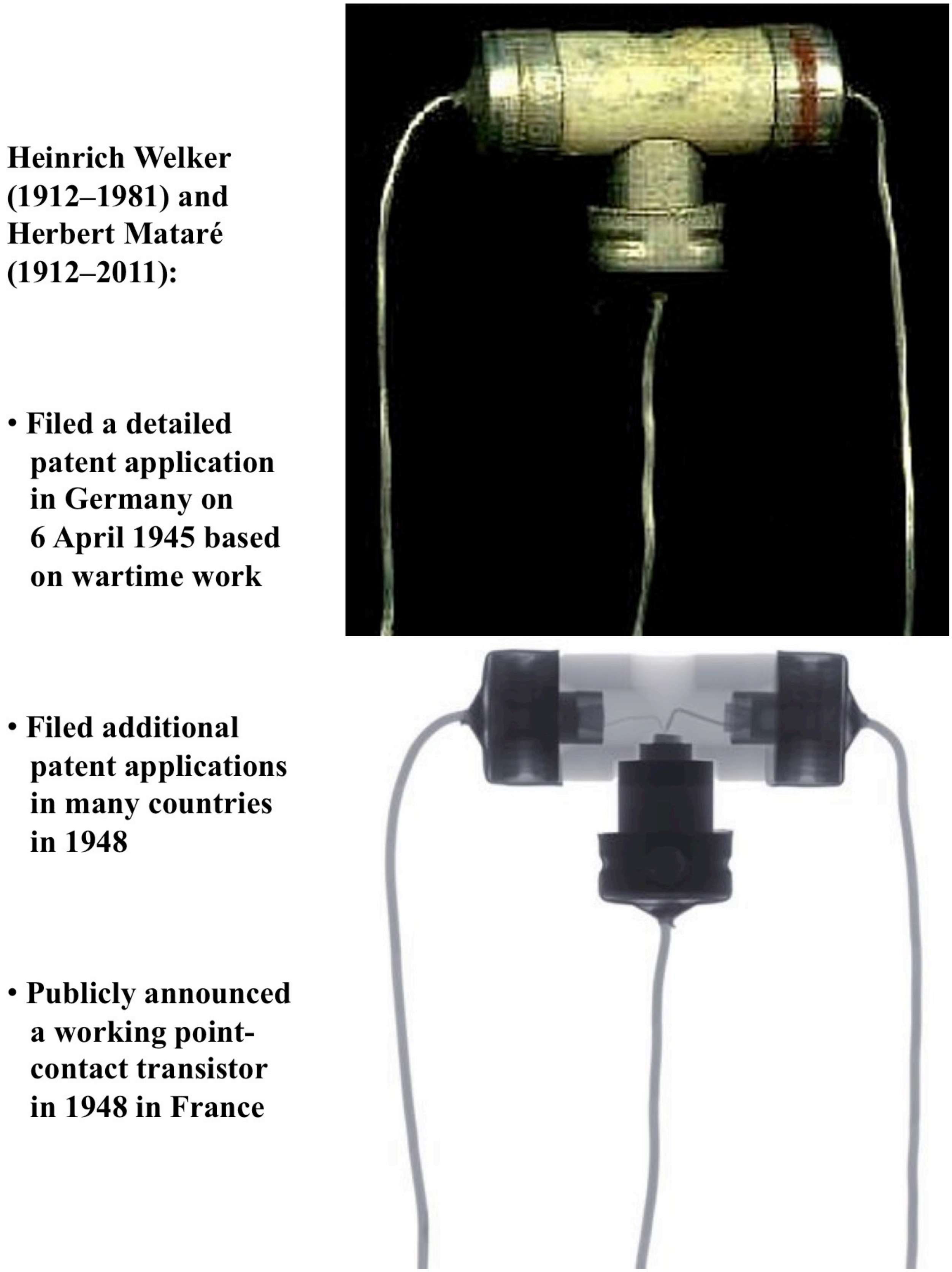


Figure B.50: Heinrich Welker and Herbert Mataré began developing a point-contact transistor in Germany during the war, filed a detailed patent application based on that wartime work on 6 April 1945, and publicly announced their transistor in 1948 in France.

(51) Int. Cl.: H 01 l, 11/14

BUNDESREPUBLIK DEUTSCHLAND

DEUTSCHES PATENTAMT

(52) Deutsche Kl.: 21 g, 11/02

(10)
(11)
Patentschrift 980 084

(21) Aktenzeichen: P 98 00 84.4-33 (F 7622)
(22) Anmeldetag: ~~11. August 1955~~ 6. 4. 1945
(43) Offenlegungstag: —
(44) Auslegetag: —
(45) Ausgabetag: 2. August 1973
Beginn des Patents: 7. April 1945

Der Zeitraum vom 8. Mai 1945 bis einschließlich 7. Mai 1950 wird auf die Patentdauer nicht angerechnet (Ges. v. 15. 7. 1951)

Ausstellungspriorität: —
(30) Unionspriorität
(32) Datum: —
(33) Land: —
(31) Aktenzeichen: —

(54) Bezeichnung: Halbleiteranordnung zur kapazitiven Steuerung von Strömen in einem Halbleiterkristall

(61) Zusatz zu: —

(62) Ausscheidung aus: —

(73) Patentiert für: Siemens AG, 1000 Berlin und 8000 München;
Telefunken GmbH, 1000 Berlin;
Standard Elektrik Lorenz AG, 7000 Stuttgart

Vertreter gem. § 16 PatG: —

(72) Als Erfinder benannt: Welker, Heinrich, Prof. Dr. habil., 8520 Erlangen

(56) Für die Beurteilung der Patentfähigkeit in Betracht gezogene Druckschriften:
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Figure B.51: Heinrich Welker and Herbert Mataré began developing a point-contact transistor in Germany during the war, filed a detailed patent application based on that wartime work on 6 April 1945, and publicly announced their transistor in 1948 in France.

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Patentansprüche:

1. Halbleiteranordnung mit einem Halbleiterkristall, der mit zwei stromführenden Elektroden kontaktiert und außerdem mit einer Steuerelektrode versehen ist, welche den zwischen den beiden stromführenden Elektroden im Halbleiterkristall im wesentlichen parallel zur Fläche der Steuerelektrode fließenden elektrischen Strom kapazitiv steuert, **dadurch gekennzeichnet,** daß zwischen dem stromführenden Halbleiterkristall und der ebenfalls als Halbleiterkristall ausgebildeten Steuerelektrode eine elektronische Sperrschicht (Verarmungsrandschicht) erzeugt ist.

2. Halbleiteranordnung nach Anspruch 1, dadurch gekennzeichnet, daß die Kristallite der Halbleiterkörper so groß sind, daß eine etwaige weitere Auskristallisation den Widerstand des gesamten Halbleiters nicht mehr verändert.

3. Halbleiteranordnung nach Anspruch 1 oder 2, dadurch gekennzeichnet, daß ein elektronenleitender Halbleiterkristall durch einen defektelektronenleitenden Halbleiterkristall gesteuert ist.

4. Halbleiteranordnung nach Anspruch 1 oder 2, dadurch gekennzeichnet, daß ein defektelektronenleitender Halbleiterkristall durch einen elektronenleitenden Halbleiterkristall gesteuert ist.

5. Halbleiteranordnung nach einem der Ansprüche 1 bis 4, dadurch gekennzeichnet, daß zusätzlich zu dem äußeren Feld der Steuerelektrode noch innere Felder vorgesehen sind, die von geordneten atomaren oder molekularen Schichten ausgehen.

6. Halbleiteranordnung nach einem der Ansprüche 1 bis 5, dadurch gekennzeichnet, daß die Halbleiter aus Silicium oder Germanium bestehen.

7. Halbleiteranordnung nach einem der Ansprüche 1 bis 6, dadurch gekennzeichnet, daß die Halbleiter aus CU_2O, Se, PbS oder ZnS bestehen.

8. Halbleiteranordnung nach einem der Ansprüche 1 bis 7, dadurch gekennzeichnet, daß an der Steuerelektrode ein Spannungsabfall aufrechterhalten ist.

9. Halbleiteranordnung nach einem der Ansprüche 1 bis 8, dadurch gekennzeichnet, daß die Stromelektroden auf die Halbleiterkristalle sperrschichtfrei aufgebracht sind.

10. Halbleiteranordnung nach einem der Ansprüche 1 bis 9, dadurch gekennzeichnet, daß der stromführende Halbleiterkristall auf eine elektrisch isolierende Trägerplatte möglichst hoher Wärmeleitfähigkeit aufgebracht ist.

Bei Untersuchungen über die Wanderung von Farbzentren in einem Alkalihalogenidkristall, die von R. W. Pohl in den Nachr. von der Ges. d. Wiss. zu Göttingen, Jahresber. 1933/34, S. 55, beschrieben sind, ist der Gedanke geäußert worden, die Elektronenröhren in den Rundfunkgeräten durch kleine Kristalle zu ersetzen. Zu einem mo-

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dellmäßigen Versuch über die Steuerung von Elektronen in Kristallen kam es jedoch erst mehrere Jahre später, als man die Bedeutung der Sperrschichten für die Gleichrichtung erkannt hatte. Es ist damals vorgeschlagen worden, in die Sperrschicht eines Alkalihalogenidkristalls ein Steuergitter einzubauen; vgl. hierzu R. Hilsch und R. W. Pohl, Z. S. Phys., 111, 399, 1938. Die Sperrschicht ist hier der glasklare, an eine Elektrode grenzende Teil des sonst mit Farbzentren erfüllten Kristalls. Sie ist bei diesen Versuchen von makroskopischen Abmessungen, und der zu steuernde Strom durchfließt dabei die Sperrschicht senkrecht, oder genauer gesagt, er fließt im wesentlichen parallel zur Dickenausdehnung der Sperrschicht. Im allgemeinen ist die Trägheit der mit Alkalihalogenidkristallen arbeitenden Anordnung ungeheuer groß, und ein stationärer Zustand stellt sich überhaupt nicht ein. Aus diesen Gründen haben die genannten Versuche nicht zu einem technisch brauchbaren Gleichrichter oder gar Verstärker geführt.

Ganz anders liegen die Verhältnisse bei den technischen Gleichrichtern (Selen- u. Kupferoxydulgleichrichter, Spitzendetektor). Die hier auftretenden Sperrschichten sind nicht wie die glasklaren Sperrschichten bei den Alkalihalogenidkristallen elektrisch neutral, sondern besitzen eine merkliche, mit der äußeren elektrischen Spannung veränderliche elektrische Raumladung. Zur Erläuterung des Sachverhaltes wird festgestellt, daß bei obigen Versuchen außer den beweglichen Elektronen (gewöhnliche Elektronen oder die neuerdings viel diskutierten Defektelektronen) gleichzeitig auch bewegliche Ionen vorhanden sind. Eine Sperrschicht entsteht in diesem Falle dadurch, daß sowohl die Elektronen als auch die Ionen aus dem fraglichen Gebiet herauswandern. Die Bewegung erfolgt so, daß nirgends ein Überschuß an Ladung auftritt; es treten daher auch keine rücktreibenden Kräfte auf; die Dicke der Sperrschicht kann daher unbegrenzt wachsen. Bei den technischen Gleichrichtern hingegen ist die Ionenbeweglichkeit vernachlässigbar klein. Das Herauswandern der Elektronen aus einem Randgebiet führt notwendig zur elektrischen Aufladung dieses Gebietes. Die dabei auftretenden rücktreibenden Kräfte verhindern, daß die Sperrschichten beliebig dick werden. Neuerdings, vergleiche hierzu W. Schottky: Über Sperrschichten, Schweizer Archiv, 1941, Heft 1 und 3, insbesondere S. 29 oben rechts und Anmerkung 13, hat man die Dicke dieser Sperrschichten, die wir zur Unterscheidung von den Sperrschichten bei Alkalihalogenidkristallen elektronische Sperrschichten nennen wollen, zu 10^{-5} cm abgeschätzt und auch aufgeklärt, weshalb gerade bei den technisch brauchbaren Kristallgleichrichtern der Einbau eines Steuergitters in die Sperrschicht und damit der Bau eines Kristallverstärkers auf rein elektronischer Grundlage unmöglich ist.

Heil beschreibt in der britischen Patentschrift 439 457 eine Anordnung, bei der die nach dem geschilderten Stand der Technik sich darbietenden Schwierigkeiten teilweise vermieden werden. Bei dieser bekannten Anordnung werden in Kristallen unter der Wirkung eines elektrischen Steuerfeldes elektronische Randschichten erzeugt und verändert, und der zu steuernde Strom wird senkrecht zur

Figure B.52: Heinrich Welker and Herbert Mataré began developing a point-contact transistor in Germany during the war, filed a detailed patent application based on that wartime work on 6 April 1945, and publicly announced their transistor in 1948 in France.

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Dickenausdehnung dieser Randschichten — also im wesentlichen parallel zur Fläche der Steuerelektrode — geführt und kapazitiv gesteuert.

Unter einer elektronischen Randschicht wird eine Oberflächenschicht im Kristall verstanden, die gegenüber dem Kristallinnern dadurch ausgezeichnet ist, daß in ihr entweder die Konzentration der Leitungselektronen kleiner (Verarmungsrandschicht, Sperrschicht) oder größer ist (Anreicherungsrandschicht, Leitschicht) als im Innern des Kristalls. Physikalisch wird eine elektronische Randschicht dadurch erzeugt, daß z. B. ein elektrisches Feld mit einer Komponente senkrecht zur Kristalloberfläche auf den Kristall auftrifft.

Nach den bekannten Gesetzen der Elektrostatik bildet sich eine Oberflächenladung, wobei die Elektronen, je nach dem Vorzeichen des Feldes, von der Oberfläche zurückgedrängt (Verarmungsrandschicht) oder an die Oberfläche hingezogen werden (Anreicherungsrandschicht). Unter dem Einfluß einer veränderlichen Steuerfeldstärke verändern sich die Eigenschaften der Randschicht, z. B. ihr elektrisches Leitvermögen und ihre Dicke. Wird daher ein Strom durch den Kristall geschickt, so wird dieser einen mit der Steuerfeldstärke variierenden Widerstand vorfinden, und er wird seine Größe in demselben Maße verändern.

Die Wirkungsweise dieser bekannten Anordnung soll nun mit Hilfe der Figur näher erläutert werden. In dieser Abbildung ist der Kristall H quaderförmig angenommen. Die Randschicht ist schraffiert eingezeichnet. Der Strom wird durch Anlegen einer Spannung an die Elektroden E_1 und E_2 erzeugt und fließt ersichtlich parallel zur Randschicht. D bedeutet ein isolierendes Dielektrikum; E_3 ist die Steuerelektrode. Beim Eintritt in den Kristall teilt sich der Strom auf. Ein Teil fließt durch das Innere des Kristalls, der andere Teil fließt longitudinal durch die Randschicht. Beispielsweise im Fall der Anreicherungsrandschicht — eine analoge Überlegung für Verarmungsrandschichten führt zu demselben Schlußergebnis — wird nur der letztere Teil des Stroms durch die Steuerfeldstärke beeinflußt, welche durch Anlegen einer Spannung an die Steuerelektrode E_3 erzeugt wird.

Jene bekannte Anordnung zeigte jedoch nur geringe Effekte, da infolge der vorhandenen dielektrischen Isolierschicht die Abmessungen größer waren als sie gemäß den in der Einleitung gemachten Ausführungen für eine wirksame Aufladung der die Steuerung bedingenden Gebiete sein dürften. Aus dem gleichen Grunde konnte daher auch ein Kontaktgleichrichter mit zwei durch eine Sperrschicht getrennten Metallelektroden und einem in diese eingebauten Steuergitter gemäß der österreichischen Patentschrift 130 102 zu keinem technischen Erfolg führen.

In diesem Zusammenhang wird darauf aufmerksam gemacht, daß in der USA.-Patentschrift 1 900 018 eine Halbleiteranordnung zum Steuern elektrischer Ströme beschrieben ist, bei der auf einer plattenförmigen Aluminiumelektrode zunächst eine isolierende Oxidschicht und auf dieser eine sehr dünne halbleitende Schicht aus Kupfersulfid angebracht ist. Diese ist mit zwei mit Abstand voneinander angeordneten Elektroden kontaktiert. Durch die Trägerelektrode wird bei jener Anordnung der in der Kupfersulfidschicht fließende Strom

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gesteuert. Eine ähnliche Anordnung ist in der USA.-Patentschrift 1 745 175 beschrieben.

Die Erfindung betrifft eine Halbleiteranordnung mit einem Halbleiterkristall, der mit zwei stromführenden Elektroden kontaktiert und außerdem mit einer Steuerelektrode versehen ist, welche den zwischen den beiden stromführenden Elektroden im Halbleiterkristall im wesentlichen parallel zur Fläche der Steuerelektrode fließenden elektrischen Strom kapazitiv steuert.

Der Erfindung liegt die Aufgabe zugrunde, den Wirkungsgrad gegenüber dem der bekannten Anordnungen vorgenannter Art, also vor allem die Steuerbarkeit des Stromes, zu verbessern.

Diese Aufgabe ist dadurch gelöst, daß zwischen dem stromführenden Halbleiterkristall und der ebenfalls als Halbleiterkristall ausgebildeten Steuerelektrode eine elektronische Sperrschicht (Verarmungsrandschicht) erzeugt ist.

In diesem Zusammenhang ist noch auf eine bekannte Vorrichtung nach der britischen Patentschrift 264 270 hinzuweisen, bei der sich ein stromdurchflossener Alaunkristall und ein ebenfalls stromdurchflossener Salpeterkristall spitzenartig berühren.

Die bei jener bekannten Anordnung verwendeten Kristalle sind jedoch Ionenleiter und keine Halbleiter; demzufolge wird die in ihnen erzeugte Leitfähigkeit von Ionen und nicht von Elektronen getragen. Nachdem die Wahrscheinlichkeit einer Fehlstelle im Gitter eines Ionenkristalls wesentlich geringer als im Innern eines elektronischen Halbleiters, wie z. B. Germanium oder Silicium, ist und außerdem die Beweglichkeit der Ionen bzw. der Ionenlücken im Kristall um viele Größenordnungen geringer als diejenige der Ladungsträger im elektronischen Halbleiterkristall ist, ist der mit einer solchen Anordnung erzielbare Steuer- und Verstärkungseffekt um ein Vielfaches kleiner als der einer Halbleiteranordnung gemäß der Erfindung.

Deshalb fehlt auch der bekannten Anordnung vor allem die hohe Belastbarkeit der erfindungsgemäßen Anordnung, die teils auf einer gleichmäßigeren Ausbildung der sich auf Grund eingeprägter Spannungen aufbauenden Felder beruht. Deshalb lassen sich erfindungsgemäße Anordnungen für den Betrieb mit beträchtlichen Leistungen herstellen, was mit den bekannten Anordnungen dieser Art nicht erzielbar ist.

Zweckmäßig sind bei der Halbleiteranordnung nach der Erfindung die Kristallite der Halbleiterkörper so groß, daß eine etwaige weitere Auskristallisation den Widerstand des gesamten Halbleiters nicht mehr verändert. Eine andere Ausführung besteht darin, daß abwechselungsweise ein Kristall ein Elektronenleiter und ein Kristall ein Defektelektronenleiter ist. Dann befinden sich gleichzeitig die Kristalle in jedem Augenblick der Steuerung in einem äquivalenten Zustand der Leitfähigkeit z. B. im Zustand der größten Leitfähigkeit. Dann können sich Halbleiter und Steuerelektrode gegenseitig vertreten, was für gewisse technische Schaltmöglichkeiten von Vorteil ist. Diese Anordnung stellt gewissermaßen einen »Vierelektrodenkristall« dar.

Der longitudinale Widerstand des Kristalls verändert sich im gleichen Sinn wie die Sperrschichtdicke. Damit bei einer derartigen Anordnung der

Figure B.53: Heinrich Welker and Herbert Mataré began developing a point-contact transistor in Germany during the war, filed a detailed patent application based on that wartime work on 6 April 1945, and publicly announced their transistor in 1948 in France.

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zu steuernde Strom nicht durch die Steuerelektrode kurzgeschlossen wird und auch die aufgewendete Steuerleistung vernachlässigt werden kann, muß allerdings die Ausdehnung des Kristalls in Richtung des zu steuernden Stromes, das ist der Abstand zwischen E_1 und E_2, beschränkt werden. Bei dieser Anordnung übernimmt die Sperrschicht zwei Funktionen: die Steuerung des Stromes und die Rolle der Isolierschicht *D*.

Da Halbleiter meist sehr brüchige Stoffe sind, ist es vorteilhaft, sie auf eine Trägerplatte aufzubringen und sie dadurch vor mechanischer Zerstörung zu schützen. Die Trägerplatte muß natürlich elektrisch isolieren. Ist ihre Wärmeleitung gut, so vergrößert sie in erwünschter Weise die Strombelastbarkeit der Anordnung.

Der Kristallaufbau braucht durchaus nicht eben zu sein. So kann auch ein zylindrischer Aufbau gewählt werden, wobei die Steuerelektrode die Achse ist, welche von der Sperrschicht und dem Halbleiter konzentrisch umgeben wird. Die beiden Stromzuführungselektroden können dabei noch auf zwei verschiedene Arten angebracht werden, nämlich auf zwei diametral gegenüberliegenden Mantellinien des halbleitenden Zylinders oder ringförmig an den beiden Enden des Zylinders.

Damit der gesteuerte Anteil des Stromes möglichst groß ist, muß grundsätzlich der durch das Kristallinnere fließende Strom klein gehalten werden. Um die dazu erforderlichen Maßnahmen zu erkennen, wird festgestellt, daß die Anzahl der je Flächeneinheit in der Randschicht angereicherten Elektronen lediglich von der Steuerfeldstärke und der Dielektrizitätskonstante außerhalb des Kristalls abhängt. Die Zahl der im Inneren des Kristalls vorhandenen Elektronen ist eine Materialgröße und variiert bei den verschiedenen Stoffen vom Wert Null bei vollkommenen Isolatoren bis zum Wert 10^{23} pro cm^3 bei Metallen. Damit überhaupt ein Strom fließt, muß der Kristall natürlich ein Leiter sein. Es ist jedoch unbedingt erforderlich, die Größe der Elektronenkonzentration im Leiter zu begrenzen, da sonst die Elektronen der Randschicht gegenüber den Elektronen im Inneren des Kristalls vollständig in den Hintergrund treten. Deshalb beschränken wir uns bei der Wahl des geeigneten Stoffes auf die unter dem Namen Halbleiter zusammengefaßten Elektrizitätsleiter. Es sei hierzu bemerkt, daß auch Stoffe wie Silicium und Germanium usw., die vielfach zu den Metallen gerechnet werden, im Sinne des Erfindungsgedankens zu den Halbleitern zählen.

Eine genauere Berechnung der mit technisch herstellbaren Steuerfeldern erzeugten Oberflächenladung zeigt, daß es sogar zweckmäßig ist, Halbleiter zu verwenden, die im Innern (nicht in den Randschichten) eine geringere Elektronenkonzentration besitzen als die bei den optimal gebauten technischen Gleichrichtern übliche.

Weiterhin ist es zweckmäßig, die Kristallitgröße für den Halbleiter mindestens so groß zu wählen, daß die Übergangswiderstände zwischen den Kristalliten kleiner sind als die Widerstände der kristallisierten Substanz selbst, da nur die letzteren durch das Steuerfeld beeinflußt werden. Durch diese Maßnahme wird verhindert, daß sich bei einer etwaigen weiteren Auskristallisation der Widerstand des Halbleiters noch wesentlich ändert.

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Um bei gegebener Steuerspannung und sonstigen festbleibenden Abmessungen der Anordnung eine möglichst große Steuerwirkung zu erzielen, wenn außer der Sperrschicht eine weitere Isolierschicht vorgesehen ist, wird für die kapazitive Steuerung des Stromes ein Stoff mit möglichst großer Dielektrizitätskonstante als Kondensatordielektrikum gewählt. (Diese Bedingung steht nicht der Verwendung im cm-Wellengebiet entgegen.) Die Durchschlagsfestigkeit kann auch dadurch gesteigert werden, daß das Kondensatordielektrikum eine veränderliche Dicke besitzt, z. B. keilförmig gestaltet ist, so daß die dicken Teile in dem Gebiet hoher Feldstärke liegen.

Die Herstellung (Bildung) der Randschichten kann in mancher Weise noch verbessert werden. Wenn gewünscht wird, daß bereits ohne äußere Steuerspannung eine Randschicht vorhanden ist, so empfiehlt es sich, die elektrischen Kraftfelder von Atomen und Molekülen auszunutzen. Dies geschieht dadurch, daß z. B. geordnete Dipolschichten zwischen dem Kristall und dem Dielektrikum eingelagert sind.

Die Belastbarkeit der Anordnung kann erhöht werden, indem man denjenigen Teil des Kondensatorfeldes teilweise oder ganz kompensiert, der von dem unvermeidlichen Spannungsabfall längs des Halbleiters herrührt. Dies kann dadurch geschehen, daß die Steuerelektrode als Widerstand ausgebildet wird und daß in ihr ein gleichsinniger Spannungsabfall aufrechterhalten wird wie im Kristall. Beim praktischen Aufbau des Kristallverstärkers ist darauf zu achten, daß durch eine geeignete Formgebung der Elektroden Kurzschlüsse vermieden werden. Bei der Ausführung ist sehr darauf zu achten, daß die Elektroden möglichst ohne Übergangswiderstände (sperrfrei) auf den Kristall aufgebracht sind. Der Innenwiderstand des Kristallverstärkers kann beliebig verändert werden, indem die Abmessungen des Kristalls senkrecht zur Dicke der Randschicht verändert werden. Um besonders kleine Innenwiderstände herzustellen, können auch mehrere Kristalle aufeinandergelegt werden. So kann bei einer derartigen Anordnung eine Steuerelektrode zwei Kristalle steuern, und ein Kristall kann von zwei Steuerelektroden aus gesteuert werden.

Die Halbleiteranordnung nach der Erfindung kann insbesondere zur elektrischen Spannungs- bzw. Leistungsverstärkung, ferner ebenso auch zur Erzeugung (Anfachung) elektromagnetischer Schwingungen verwendet werden. Einer der Vorteile der Steuerung von elektrischen Strömen mit der Halbleiteranordnung nach der Erfindung gegenüber der Verwendung von Elektronenröhren besteht darin, daß keine geheizte Kathode notwendig ist. Dies bedeutet zunächst eine Ersparnis im Leistungsbedarf. Ferner kann der Kristallverstärker bei jeder beliebigen Temperatur betrieben werden. Bei tiefen Temperaturen wird das Eigenrauschen geringer. Wegen des Fehlens einer Glühkathode mit begrenzter Emission kennt der Kristallverstärker keine Sättigungserscheinungen. Bezüglich des Frequenzverhaltens gilt für den Kristallverstärker etwa dasselbe wie für die entsprechenden Kristallgleichrichter. Insbesondere ist es möglich, bei Verwendung von Halbleitern mit extrem großer Elektronenbeweglichkeit kürzeste Wellen zu verstärken.

Hierzu 1 Blatt Zeichnungen

Figure B.54: Heinrich Welker and Herbert Mataré began developing a point-contact transistor in Germany during the war, filed a detailed patent application based on that wartime work on 6 April 1945, and publicly announced their transistor in 1948 in France.

ZEICHNUNGEN BLATT 1

Nummer:	**980 084**
Int. Cl.:	**H 01 l, 11/14**
Deutsche Kl.:	**21 g, 11/02**
Auslegetag:	2. August 1973

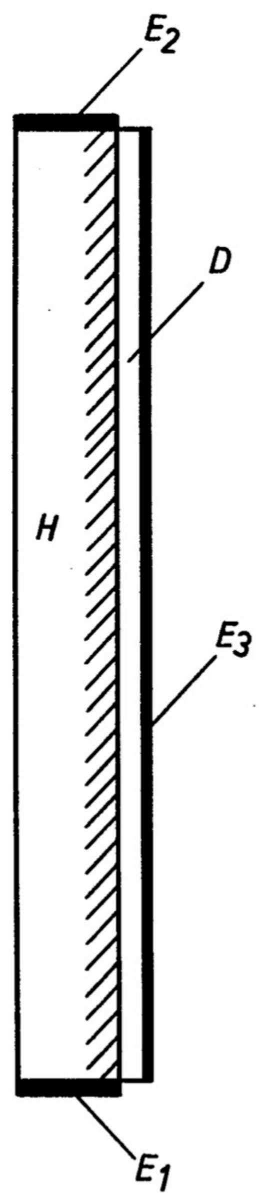

Figure B.55: Heinrich Welker and Herbert Mataré began developing a point-contact transistor in Germany during the war, filed a detailed patent application based on that wartime work on 6 April 1945, and publicly announced their transistor in 1948 in France.

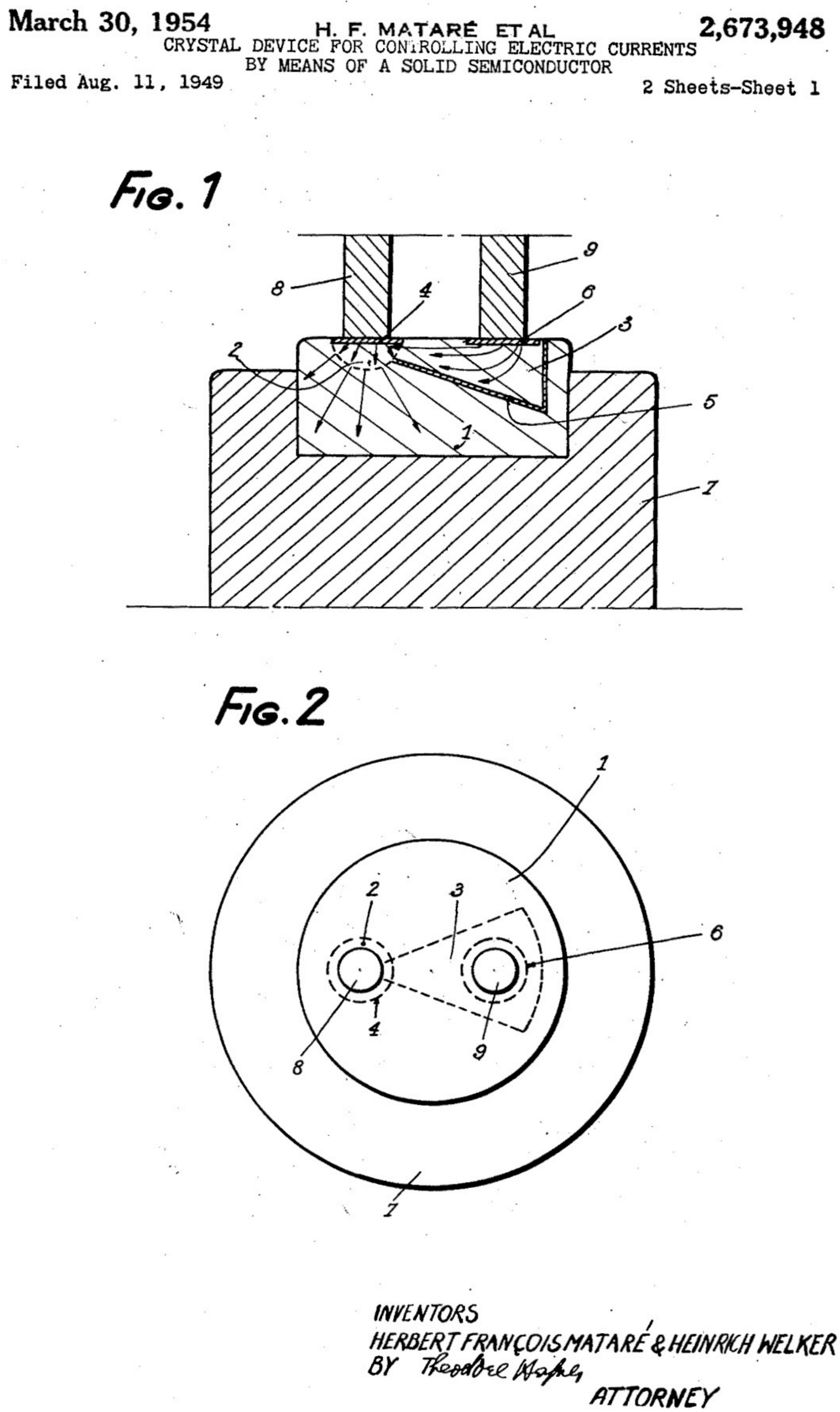

Figure B.56: Heinrich Welker and Herbert Mataré began developing a point-contact transistor in Germany during the war, filed a detailed patent application based on that wartime work on 6 April 1945, and publicly announced their transistor in 1948 in France.

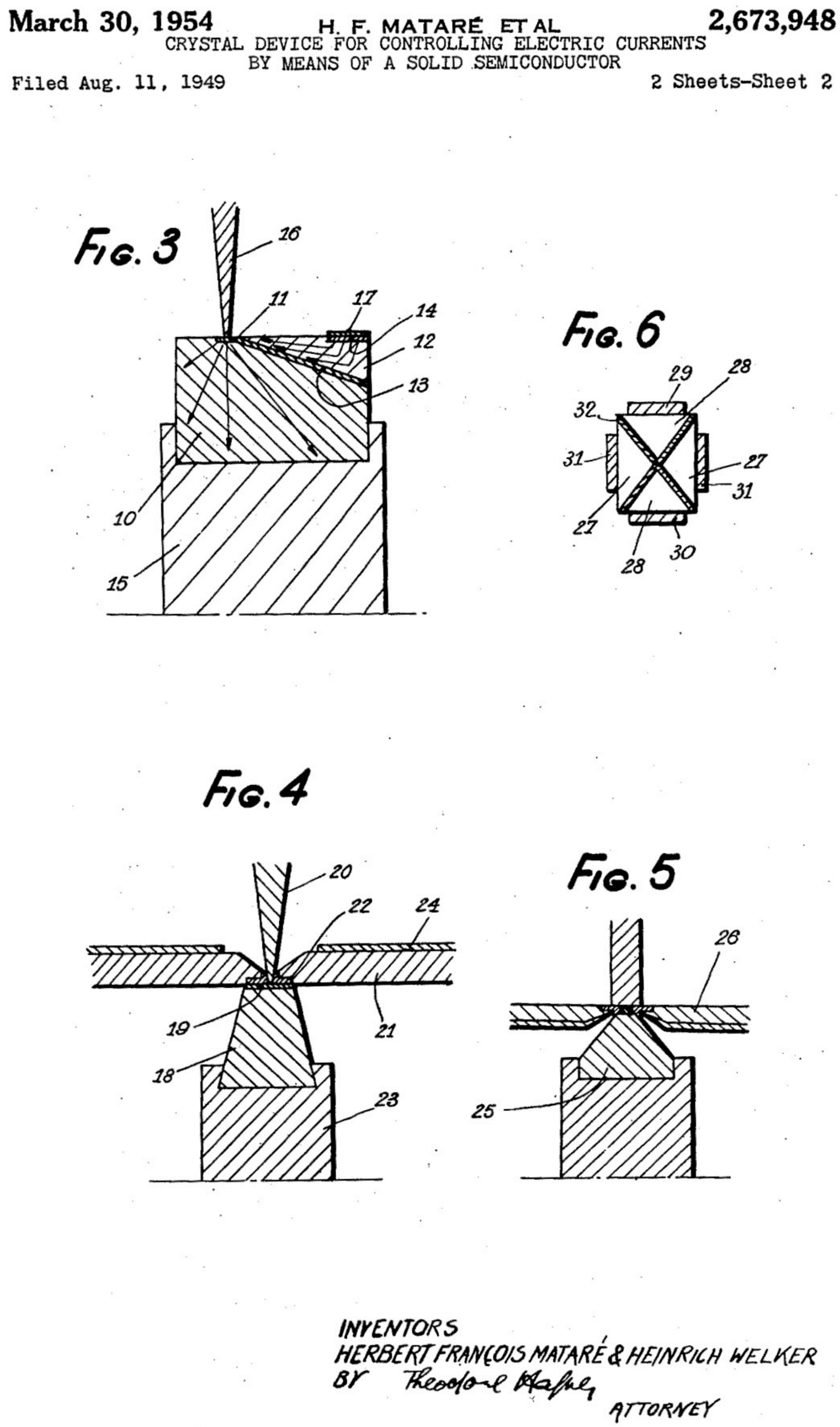

Figure B.57: Heinrich Welker and Herbert Mataré began developing a point-contact transistor in Germany during the war, filed a detailed patent application based on that wartime work on 6 April 1945, and publicly announced their transistor in 1948 in France.

Patented Mar. 30, 1954 **2,673,948**

UNITED STATES PATENT OFFICE

2,673,948

CRYSTAL DEVICE FOR CONTROLLING ELECTRIC CURRENTS BY MEANS OF A SOLID SEMICONDUCTOR

Herbert François Mataré and Heinrich Welker, Vaucresson, France, assignors to Societe Anonyme dite: Compagnie des Freins et Signaux Westinghouse, Paris, France

Application August 11, 1949, Serial No. 109,752

Claims priority, application France August 13, 1948

3 Claims. (Cl. 317—235)

1

This invention relates to crystal devices for controlling electric currents by means of a solid semiconductor with the use of one or more control electrodes, either in a barrier layer of the semiconductor (see for example patent of addition No. 38,744 of July 5, 1930, to French Patent No. 649,432 of January 28, 1928, and French Patent No. 866,372 of October 5, 1942), or closely adjacent to semiconductive layers with a suitable insulator interposed therebetween (see French Patent No. 786,454 of March 1, 1935).

However, such systems were so difficult to apply on a commercial scale that they had to be abandoned or development had to be restricted to simple experimental models or laboratory samples. This experience is supported by publications such as: Nachrichten der Gesellschaft der Wissenschaften zu Göttingen, Yearly Report, by R. W. Pohl, 1933/34, page 55; Schweizer Archive, 1941, volumes 1 and 3: Ueber Sperrschichten, by W. Schottky; Zeitschrift fur Physik, vol. 111, volumes 5 and 6, 1938 (R. Hilsch and R. W. Pohl); Modern Theory of Solids, 1940 (F. Seitz); Crystal Rectifiers, 1948 (H. C. Torrey and C. A. Whitmer).

In order practically to carry into effect systems comprising solid semiconductors arranged to produce electronic relay effects similar to those occurring in electronic tubes, two essential difficulties must be overcome. Firstly, the diameter of the contact area between metal needle and crystal should be of an order proportional to the thickness of the crystal barrier layer. Secondly, the gap between the conductive electrodes where engagement occurs with the semiconductor should be so selected that one of the conductive electrode point members will be positioned inside the barrier layer area of the other point member.

With the thickest barrier layer made hitherto, it would have been necessary to use values lower than 5 μ both for the diameters of the contact areas, on the one hand, and for the gap between the pair of point members, on the other hand. Now if the first requirement could be met, provided that a needle is applied to a crystal with a pressure lower than 0.33 oz., for example, the second requirement causes considerable mechanical difficulties.

Various attempts have been made to find workable arrangements comprising three-electrode semiconductors of microscopic dimensions. However, in order to obtain an appreciable control action, it is necessary to select a crystal of such a low electronic or non-electronic concentration,

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or n-type excess and p-type deficiency concentration, respectively, that the inner resistivity of the device becomes very high. Arrangements of this type cannot be used practically for technical purposes.

The present invention permits to eliminate the above-mentioned difficulties and to realize on a commercial scale multi-electrode crystal devices of this kind for producing electronic relay action.

A more specific object of this invention is a multi-electrode device with at least two semiconductors of different conductivity characteristics; one of the semiconductors forms a control electrode and includes a surface barrier layer.

According to another feature of the invention, one of the semiconductors preferably the control electrode has a p-type (deficiency) or non-electronic conductivity and the other semiconductor an n-type (excess) or electronic conductivity.

According to a further feature of the invention, a semiconductor, preferably the other semiconductor mentioned above also includes a surface or internal barrier layer.

In one embodiment of the invention, the semiconductors or electrodes of the crystal are formed simultaneously from a single semiconductive element (such as germanium). In this element, by any suitable known method, zones of different conductivity characteristics are created.

Still in accordance with the invention, in at least one of said semiconductors or in one of the zones thereof such geometrical configuration is provided as to assure substantial radial distribution of the lines of force of the electric fields.

Furthermore, the invention relates to novel commercial products comprising multi-electrode crystal devices wherein external conductive electrodes are in direct contact with each semiconductive electrode, and wherein there is a gap between the contact points which is greater than 50 μ.

Other features and advantages of this invention will appear from the specification in connection with the accompanying drawings, which illustrate preferred embodiments of the invention in a diagrammatical fashion and by way of example only.

In the drawings:

Fig. 1 represents a cross section of a one embodiment,

Fig. 2 is a corresponding plan view, and

Figs. 3 to 6 represent cross-sections of other embodiments of the invention.

Figure B.58: Heinrich Welker and Herbert Mataré began developing a point-contact transistor in Germany during the war, filed a detailed patent application based on that wartime work on 6 April 1945, and publicly announced their transistor in 1948 in France.

2,673,948

3

Referring to the drawings and more specifically to Figs. 1 and 2, the device illustrated is a multi-electrode crystal device constructed according to the invention. It comprises a semiconductive crystal 1 (for example of germanium) in which two zones 2 and 3 of different conductivity characteristics have been formed. For example, zone 2 has an n-type (excess) electronic conductivity and zone 3 a p-type (deficiency) electronic conductivity or vice-versa. Zone 2 has a surface barrier layer 4 and zone 3 an internal barrier layer 5, and also if desired a surface barrier layer 6. Furthermore, zone 2 is so formed that its geometrical structure will direct the lines of force of the electric fields radially.

The formation in crystal 1 of the zones of different conductivity characteristics and barrier layers is carried out for each specific zone by means of conventional and well-known methods such as melting, casting or crystallizing.

The semi-conductive crystal 1 is mounted in a metal support 7. Two needles 8 and 9 are applied respectively to zones 2 and 3; zone 3 operates as a control semiconductor and needle 9 as an external control electrode.

It is well understood that metal support 7 and needles 8 and 9 may be connected in any desired utilization circuit.

In the embodiment of Fig. 3, the multi-electrode crystal device includes a crystal 10, for example of germanium, provided in conventional manner with a surface barrier layer 11. Crystal 10 is also associated with a portion 12, for example of selenium. A barrier layer 13 is formed in the zone separating germanium 10 and selenium 12. A surface barrier layer 14 may, but need not, be provided on the selenium portion 12.

The combined germanium-selenium crystal 10, 12 is mounted on metal support 15 which forms an external electrode. Needle 16 is another external electrode and applied to the surface barrier layer 11 of germanium. An external control electrode 17 is applied to the selenium portion 17.

In the embodiment of Fig. 4, the multi-electrode crystal device according to the invention comprises a semi-conductive crystal 18, for example, of germanium, having a surface barrier layer 19 engaged by needle 20 which forms an external electrode. An element 21, for example of selenium, forms a semi-conductive control electrode. Selenium element 21 has formed thereon a barrier layer 22 arranged to surround completely the point of needle 20. Crystal 18 is mounted in metal support 23 forming an external electrode. There is a metal layer 24 on selenium element 21. Metal layer 24 forms an external control electrode and is applied by any suitable means such as spraying, melting, etc.

The embodiment of Fig. 5 resembles that of Fig. 4 except that semiconductive crystal 25 which is for example of germanium, has a cone-shaped point with an opening angle sufficiently obtuse to pass through control semiconductor 26, which is for example of selenium.

This arrangement has the advantage that the

4

control field will act more directly upon crystal 25.

In the embodiment of Fig. 6, semi-conductive crystal 27, for example of selenium, encloses concentrically the needles or point crystals 28, for example, of germanium. The device is completed by external electrodes 29 and 30 contacting the germanium 28 and a ring-shaped external control electrode 31 surrounding selenium element 27, while barrier layers 32 are formed in the zone separating germanium 28 from selenium 27.

This arrangement has the advantage that the control field will act in all directions upon the germanium crystal.

It will be noted that in all the embodiments of Figs. 3 to 6 the germanium element may be replaced by any semiconductor of electronic type conductivity (such as silicon) and the selenium by any non-electronic type conductivity semiconductor (such as copper oxid).

In all these cases the control semiconductor should carry a barrier layer on its surface between the crystal semiconductor forming the other electrode and the needle or external electrode. In order to minimize the control losses it is preferable to select a semiconductor having a barrier layer the squared resistance value of which is very high in relation to the resistance of the crystal barrier layer.

What we claim is:

1. Multi-electrode crystal device for producing electronic relay action comprising a semi-conductor element having at least two zones of different conductivity characteristics, one of said zones being substantially of ring shape and the other zone comprising two substantially conically shaped portions extending axially from opposite directions along the axis and toward the center of the ring zone; said conical portions joining the ring zone in conical surfaces, said joining surfaces comprising at least one barrier layer, and said conical and ring shaped zones comprising individual metallic electrodes.

2. Device according to claim 1 wherein each of said conical portions has a separate electrode.

3. Device according to claim 1 wherein said conical portions meet with their tips at the center of the ring zone.

HERBERT FRANÇOIS MATARÉ.
HEINRICH WELKER.

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Number	Name	Date
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2,328,440	Esseling et al	Aug. 31, 1943
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2,552,052	Matare	May 8, 1951
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Figure B.59: Heinrich Welker and Herbert Mataré began developing a point-contact transistor in Germany during the war, filed a detailed patent application based on that wartime work on 6 April 1945, and publicly announced their transistor in 1948 in France.

[**8. Erwin Weise (German?, 19??–19??)** admitted to Allied investigators that he "had demonstrated the possibility of using thin films or control electrodes in semi-conducting materials to provide control of current flow similar to the control of current flow in high vacuum tubes" to create "electronic amplifiers without vacuum" (p. 2724).

For more information, see:

> CIOS XXXI-2. *Research Work Undertaken by the German Universities and Technical High Schools for the Bevollmaechtigter fuer Hochfrequenztechnik; Independent Research on Associated Subjects.* (pp. 2722–2724)
>
> BIOS 1658. *Interrogation of Erwin Weise. Research and Development of Semi-Conducting Materials. Practical Applications for Ultra-Sensitive Temperature Measuring Equipment and Automatic Control and Stabilizing Problems.*(pp. 2725–2729)
>
> Erwin Weise. Filed 1940. German patent DE 721,677. Einrichtung zur Entnahme gleichbleibender Gleich- oder Wechselspannung aus Netzen mit schwankender Spannung. [Device for Drawing Constant Direct or Alternating Voltage from Networks with Fluctuating Voltage.] (pp. 2730–2733)]

ITEM No. 1 & 7
FILE No. XXXI-2

COPY No. 30

[redacted]

DECLASSIFIED
SecDef Memo 16 May 61

RESEARCH WORK UNDERTAKEN

BY THE

GERMAN UNIVERSITIES AND TECHNICAL HIGH SCHOOLS

FOR THE

BEVOLLMAECHTIGTER FUER HOCHFREQUENZTECHNIK; INDEPENDENT RESEARCH ON ASSOCIATED SUBJECTS

[redacted]

COMBINED INTELLIGENCE OBJECTIVES SUB-COMMITTEE

Figure B.60: Erwin Weise told Allied investigators that he “had demonstrated the possibility of using thin films or control electrodes in semi-conducting materials to provide control of current flow similar to the control of current flow in high vacuum tubes” to create “electronic amplifiers without vacuum.”

CONFIDENTIAL

CIOS CONSOLIDATED ADVANCE FIELD TEAM
INVESTIGATION REPORT

TO: CIOS Secretariat.

1. Target No.

2.3. Laboratory of the Technical High School, Berlin, evacuated to Bad Liebenstein. Person interrogated: Dipl.Ing. Erwin Weise, formerly of Osram, now attached to this laboratory.

4. Interview only. Ovens and vacuum equipment for experimental work are in workable condition.

5. (1) Semi-conducting materials such as titanium-titanium dioxide resistors.
(11) Investigation of very thin films of titanium dioxide (TiO_2)
(111) Practical applications involving the use of these thin films:-
a. Pyrometers.
b. Gas pressure and flow devices.
c. Rapid acting simulated pendulum.
(1V) Electrically controlled friction devices for control and amplification of mechanical forces.

6. Laboratory subject to guard regulations of 8th Corps Area. A book was just being written on the subject of semi-conductors by Mr. Weise, and it is desirable to obtain a copy when available.

7. Priority.

8. Mr. Weise spoke disparagingly of Dr. Pearson's published works on semi-conductors (Bell Laboratories). He was scheduled to lecture in America on this subject prior to the war at the request of Western Electrical Instrument Co., Irvington, NY. Claims to be a friend of Henry Behring of this company.

9. 5th June 1945.

10. Investigators: Mr. C.W. Hansell
Lt. Col. J.J. Slattery
Maj. J.M. Sanabria
Pfc. F. Koppl

11. Documents removed: "Uber ein Messgerat fur hohe und niedrige Gasdrucke mit Halbleiterwiderstanden" by Erwin Weise. Zeitschr.f. techn. Physik, No.4 1943, pages 66 to 69.
No reports were available at the time but Mr. Weise stated that a manuscript of his should be produced within thirty days, and it is suggested that this matter be further investigated.

-55-

Figure B.61: Erwin Weise told Allied investigators that he "had demonstrated the possibility of using thin films or control electrodes in semi-conducting materials to provide control of current flow similar to the control of current flow in high vacuum tubes" to create "electronic amplifiers without vacuum."

CONFIDENTIAL

clutches and the clutches did find some use in telegraph signal recorders. The development was abandoned because of the poor quality of semi-conductors then available.

With the development of the new titanium dioxide semi-conductors this old abandoned development has been revived with much more promising results, because of the relative perfection, uniformity and hardness of the new materials. It has been suggested by Mr. Weise and others that electrically controlled friction clutches may very well assume considerable importance in the future.

In general the clutches provide control of mechanical power by electrical power in a manner to give very great amplification and rapid response. For many applications they might replace the Amplidyne or Metadyne control devices which are now in use on a large scale in military equipment and in industry.

THERMAL ELECTROMOTIVE FORCE OF TiO_2 SEMI-CONDUCTORS

Mr. Weise said that titanium dioxide types of semi-conductors had been found to provide thermal electromotive forces about ten times greater than that of metals and that this might lead to important applications.

ELECTRONIC AMPLIFIERS WITHOUT VACUUM.

According to Mr. Weise he had some ideas and had demonstrated the possibility of using thin films or control electrodes in semi-conducting materials to provide control of current flow similar to the control of current flow in high vacuum tubes. This work had not approached a stage where practical applications might be made.

-59-

Figure B.62: Erwin Weise told Allied investigators that he "had demonstrated the possibility of using thin films or control electrodes in semi-conducting materials to provide control of current flow similar to the control of current flow in high vacuum tubes" to create "electronic amplifiers without vacuum."

B.I.O.S. FINAL REPORT No. 1658 (Interrogation Report No. 600)

ITEM No. 9

INTERROGATION OF ERWIN WEISE

Research and Development of Semi-Conducting Materials

Practical Applications for Ultra-Sensitive Temperature Measuring Equipment and Automatic Control and Stabilizing Problems

This report is issued with the warning that, if the subject matter should be protected by British Patents or Patent applications, this publication cannot be held to give any protection against action for infringement.

BRITISH INTELLIGENCE OBJECTIVES

SUB-COMMITTEE

LONDON—H.M. STATIONERY OFFICE

One Shilling net

B/TK-383.

S.O. Code No. 51-6275-

Figure B.63: Erwin Weise told Allied investigators that he “had demonstrated the possibility of using thin films or control electrodes in semi-conducting materials to provide control of current flow similar to the control of current flow in high vacuum tubes” to create “electronic amplifiers without vacuum.”

Interrogation Report No. 600.
7th February, 1946.

British Intelligence Objectives Sub-Committee
Instrument Panel Group 2

Interrogation of:

Erwin Weise, Dipl. - Ing. (Director of the Semi-Conductivity (Laboratory at Osram 1939 - 1945. (Research work in the Rerhen Lab (Technical High School Berlin (evacuated to Bad Liebenstein (1943 to end of hostilities.

Target No. C9/627.

Interrogated by:- P. S. Brackenbury, Directorate of Instrument Production.

Main Interest: Research and Development of Semi-Conducting materials, practical applications for ultra-sensitive temperature measuring equipment and automatic control and stabilizing problems.

Semi-Conducting materials: The semi-conductors in which Weise had carried out research were in a material known as Magnesium Titanium Spinel ($MgO.TiO_2$) bearing the trade name of Urdox. This material is made in the form of sheet, rod and tube. The most common sizes being in rods-or tubes about one centimetre long with a diameter of from one to two millimetres. It was also possible to make them in the form of fine filaments of about seventy microns diameter formed on a thread of silk of about thirty microns diameter. Attempts to make a finer filament than this were unsuccessful as the material tended to form into globules and so became discontinuous. It should be noted that the filaments are in reality very fine tubes with a wall thickness of about twenty microns, as the silk core is burnt away during processing. In the case of sheet it was not possible to go below a thickness of about ten microns.

The material has a negative temperature coefficient ranging from 0 to 10% per degree Centigrade with a time constant of as low as half a second for 90% of the total change. The temperature coefficient can be varied at will during manufacture by varying the TiO_2 content, higher proportions of TiO_2 give the greatest negative temperature coefficient. A mixture containing less than 10% TiO_2 fails to give the desired spinel crystal structure. The specific resistance ranges from 10 ohms/centimetre to 10^8 ohms/centimetre and is a function of the temperature and baking time during manufacture.

Figure B.64: Erwin Weise told Allied investigators that he "had demonstrated the possibility of using thin films or control electrodes in semi-conducting materials to provide control of current flow similar to the control of current flow in high vacuum tubes" to create "electronic amplifiers without vacuum."

All the above publications were written by Weise either alone or in collaboration with another.

The following patents relate to inventions made by Weise:

DRP.607 444 Carrier with two records of oscillations in one trace
" 618 982 Control resistor to diminish the starting time of cathodes
" 632 820 Network for the quick starting of cathodes in discharge tubes
" 641 680 Pipe-shaped high frequency furnace.
" 696 463 Manufacture of very thin semi-conductors.
" 697 174 Resistors of semi-conducting materials.
" 701 478 Electrical measurement of low gas and steam pressures
" 716 052 Equipment for fitting very thin semi-conductors
" 721 677 Stabiliser for D.C. and A.C. voltages.
" 730 251 Equipment for fitting very thin semi-conductors.
" 743 780 Measurements of the velocity of gases, slight changes in air pressure, and altitudes of aircraft.
" 743 575 Network to raise the slope of the characteristics of electron tubes.
Secret 1 Use of resistance controller as an amplifier and generator of slow electrical oscillations.
Secret 2 Instrument for measuring the inclination of ships, incorporating semi-conductors of little inertia.

I questioned Weise as to details of some of these patents and obtained the following explanations:-

DRP 618 982. This patent relates to method of accelerating the warming up of indirectly heated cathodes. A voltage of some two or three times the working voltage of the heater is applied. The relay R at this stage is resting on its back contacts thereby short circuiting R_1. As soon as anode current commences R operates leaving R_1 in series thereby dropping the heater voltage to its normal value.

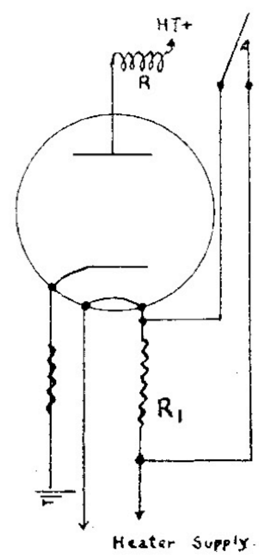
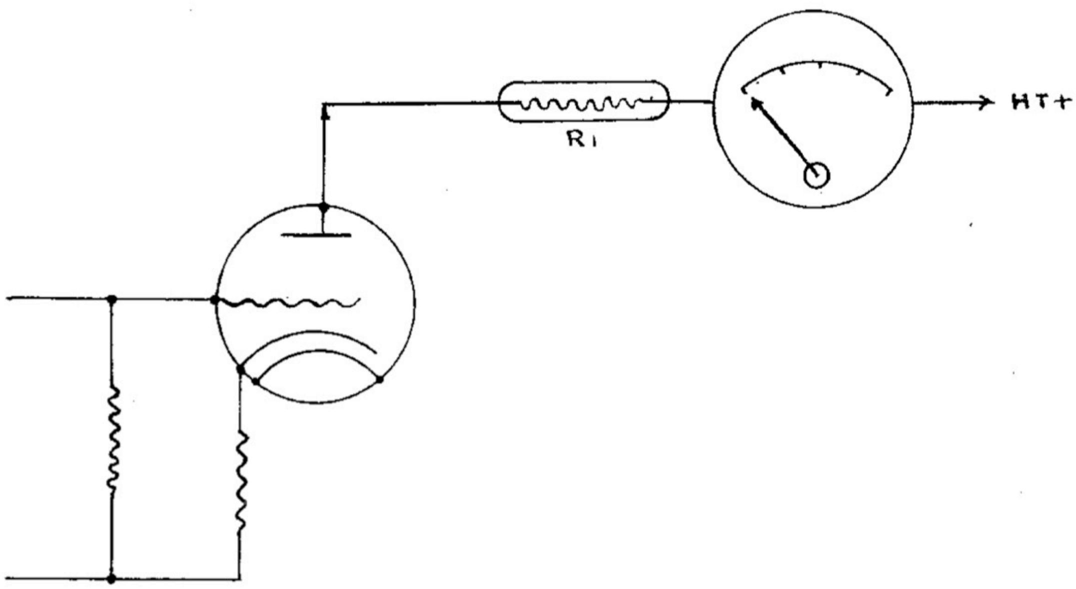


Figure B.65: Erwin Weise told Allied investigators that he "had demonstrated the possibility of using thin films or control electrodes in semi-conducting materials to provide control of current flow similar to the control of current flow in high vacuum tubes" to create "electronic amplifiers without vacuum."

Remarks. Exact details may not be quite as above, but will serve to illustrate the principle which no doubt is capable of considerable refinement. The system might be applied as a hot wire microphone in Sound Ranging if not already entirely superseded by the Moving Coil type.

DRP. 743 575. Where it is desired to raise the slope of a thermionic valve a resistor of high value made of semi-conductor material is placed in the anode lead as under:



Any increase in anode current brought about variation of grid volts will raise the temperature of R1 thereby lowering its resistance and bringing about a larger increase in anode current per unit change in grid volts than would have otherwise been the case.

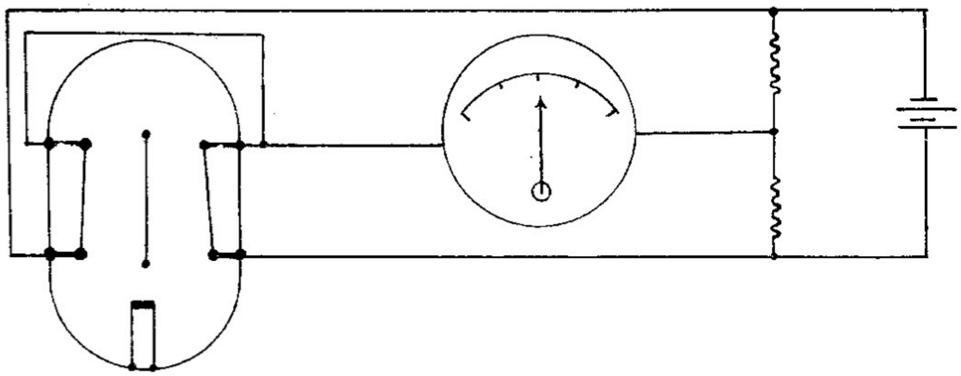
Remarks. Only applicable where grid voltage changes are fairly slow such as in a Valve Voltmeter. Correction for ambient temperature may be obtained if required by connecting a suitable metallic resistor in series with R1 although there is no material the exact counterpart of the semi-conducting material it is possible by careful selection of values to obtain almost exact compensation over a fairly useful range.

Secret 1. This application appears to be somewhat of an extension of the idea in the previous patent. By evolving a suitable valve/resistance/capacity network using semi-conductor resistors and their negative temperature/resistance characteristics it is possible to produce very slow and regular oscillations.

Remarks. Weise was unable to remember exact details of the circuit. It was not clear what the Germans proposed to use this for and as it was getting late the matter was not pursued further.

Figure B.66: Erwin Weise told Allied investigators that he "had demonstrated the possibility of using thin films or control electrodes in semi-conducting materials to provide control of current flow similar to the control of current flow in high vacuum tubes" to create "electronic amplifiers without vacuum."

Secret 2. This is a method of obtaining electrically an exact vertical reference. It is based on the fact that a hot gas in a perfectly still atmosphere will always rise vertically with almost negligible inertia. The tube consists of a small heater with four electrodes placed somewhat as the plates in a cathode ray tube.



The tubes are exhausted and filled with hydrogen. When the heater is excited warm gas will rise, and if the tube is exactly vertical will affect all four electrodes equally. These electrodes are made of fine filaments or strips of semi-conducting material. Tilting of the tube will give an unbalance of resistance which when coupled with a bridge network will give an indication of the degree of tilt in either plane, one of which is illustrated above. Alternatively a circuit could be evolved which coupled with a suitable servo system could control the flight of aircraft or projectiles. Weise stated that this had been tried with V1 and V2 with great success, but time had been too short for it to be adopted operationally. Almost any degree of sensitivity could be attained by amplification.

Remarks. It seems possible that very wide use could be made of this invention such as applying a correction factor for the errors introduced when a gun mounting or gun carriage settles during action or navigational problems requiring accurate control of elevation as the system is obviously proof against radio jamming or magnetic errors. When compared with gyroscopic methods the system would appear to have much to recommend it as regards simplicity.

Power measurements. Power measurements at centimetre wavelengths have been attempted using semi-conducting material. Stability is good for very long periods with temperatures up to 400° centigrade.

The firm named Funkstrahl near Bodensee had obtained very good results, although Weise's own experiments in this direction had not proved quite so successful.

Infra Red Image Converters. Weise had been carrying out experiments in this direction using semi-conducting material and had made two such tubes. Work on this however was cut short owing to Allied bombing and destruction of the laboratories. It seems that these image converters were sensitive to the longer waves in the infra-red range as compared with our own tubes which probably are only sensitive between fairly narrow limits.

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Figure B.67: Erwin Weise told Allied investigators that he "had demonstrated the possibility of using thin films or control electrodes in semi-conducting materials to provide control of current flow similar to the control of current flow in high vacuum tubes" to create "electronic amplifiers without vacuum."

DEUTSCHES REICH

AUSGEGEBEN AM
12. JUNI 1942

REICHSPATENTAMT

PATENTSCHRIFT

№ 721 677

KLASSE **21c** GRUPPE 67 70

P 81100 VIII d/21 c

Erwin Weise in Berlin-Charlottenburg

ist als Erfinder genannt worden.

Patent-Treuhand-Gesellschaft für elektrische Glühlampen m. b. H. in Berlin

Einrichtung zur Entnahme gleichbleibender Gleich- oder Wechselspannung aus Netzen mit schwankender Spannung

Patentiert im Deutschen Reich vom 3. August 1940 an

Patenterteilung bekanntgemacht am 7. Mai 1942

Um aus Netzen mit schwankender Spannung gleichbleibende Gleich- oder Wechselspannung entnehmen zu können, ist es bekannt, den Verbraucher, etwa eine Glühkathodenröhre, an die Enden eines mit einem Ohmschen Widerstand in Reihe geschalteten Halbleiterwiderstandes mit waagerecht bzw. parallel zur Stromachse verlaufender Stromspannungskennlinie anzuschließen, so daß der Verbraucher parallel zum Halbleiterwiderstand liegt. Diese Schalteinrichtung hat den Nachteil, daß beim Anlegen der Klemmenspannung der Halbleiterwiderstand noch kalt ist, also einen verhältnismäßig großen Widerstandwert aufweist. An ihm liegt daher für eine gewisse Zeit eine große Spannung, die damit ebenfalls am Verbraucher liegt. Diese führt zu Überlastungen, die z. B. für Glühkathoden schädlich sind. Würde man, um diesen Nachteil zu beheben, dem Verbraucher in an sich bekannter Weise einen den Einschaltüberstrom dämpfenden Halbleiterwiderstand vorschalten, so müßte die Wärmeträgheit des letzteren größer sein als die Wärmeträgheit des parallel zum Verbraucher liegenden Widerstandes, damit der vorgeschaltete Widerstand erst dann in seinem Ohmwert zusammenbricht, wenn der parallel liegende Widerstand bereits seine endgültige Temperatur weitgehend erreicht hat. Eine derartige Einrichtung hätte jedoch den großen Nachteil, daß beim Ausschalten und zu frühen Wiedereinschalten der dem Verbraucher vorgeschaltete Widerstand wegen seiner größeren Trägheit noch warm sein kann, wenn sich der andere parallel zum Verbraucher liegende Widerstand bereits abgekühlt hat. Es wird dann aber beim Wiedereinschalten eine große

Figure B.68: Erwin Weise told Allied investigators that he "had demonstrated the possibility of using thin films or control electrodes in semi-conducting materials to provide control of current flow similar to the control of current flow in high vacuum tubes" to create "electronic amplifiers without vacuum."

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Überspannung auftreten, die der dem Verbraucher vorgeschaltete Widerstand wegen seiner hohen Temperatur nicht unschädlich machen kann.

Eine zufriedenstellende Unterdrückung des Einschaltüberstromes läßt sich jedoch, ohne daß die Stromzufuhr zum Verbraucher nennenswert beeinträchtigt wird, bei jeglichem Einschalten erreichen, wenn erfindungsgemäß der bisher allein verwendete Halbleiterwiderstand mit waagerechter Stromspannungskennlinie zusammen mit einem dem Verbraucher vorgeschalteten Halbleiterwiderstand mit fallender Stromspannungskennlinie und geringerer Wärmeträgheit in einem Glasgefäß untergebracht wird. Während die Kuppe in der Stromspannungskennlinie des dem Verbraucher vorgeschalteten Halbleiterwiderstandes das Abfangen des Einschaltüberstromes sicherstellt, wird durch die Unterbringung der beiden verschiedenartigen Halbleiterwiderstände in einem gemeinsamen Glasgefäß bei der Benutzung der Einrichtung eine zusätzliche Erhitzung des dem Verbraucher vorgeschalteten Halbleiterwiderstandes mit Senkung der Stromspannungskennlinie dieses Widerstandes bewirkt. Dies führt dazu, daß die letztgenannte die dem Verbraucher zugeordnete Widerstandsgerade nicht wie bei gesonderter Anordnung dieses Vorschaltwiderstandes bei einem sehr kleinen Strom schneidet, der nicht ausreichen würde, um den Widerstand zum Zusammenbrechen zu bringen, sondern bei einem wesentlich größeren Strom, so daß es bei der Benutzung der Einrichtung mit Sicherheit zum Zusammenbrechen dieses Vorschaltwiderstandes kommt.

Auf der Zeichnung ist in Abb. 1 eine Einrichtung gemäß der Erfindung schematisch dargestellt.

Abb. 3 zeigt im Schaubild die Stromspannungskennlinie des mit dem Ohmschen Widerstand in Reihe liegenden Halbleiterwiderstandes und

Abb. 3 im Schaubild die Wirkungsweise des dem Verbraucher vorgeschalteten Widerstandes.

An die Netzanschlußklemmen 1 und 2 ist in Reihe mit einem Ohmschen Widerstand 3 ein Halbleiterwiderstand 4 angeschlossen, der durch geeignete Herstellungsart eine waagerechte Stromspannungskennlinie, und zwar die Spannung U in Abhängigkeit vom Strom J, wie in Abb. 2 dargestellt, aufweist. Dieser Widerstand kann in an sich bekannter Weise beispielsweise aus Urandioxyd, Chromoxyd oder Magnesiumtitanat bestehen. Mit den Enden des Widerstandes 4 ist ein Verbraucher, etwa eine Glühkathodenröhre 5, unter Zwischenschaltung eines zweiten Halbleiterwiderstandes 6 verbunden, der aus gleichen oder ähnlichen Stoffen wie der Widerstand 4 bestehen kann, bei dem jedoch in bekannter Weise durch geeignete Regelung des Brennvorganges sowie Regelung der Wärmeableitung durch die anschließenden Stromzuführungen dafür gesorgt ist, daß er eine geringere Wärmeträgheit und eine fallende Kennlinie hat, deren Kuppe höher liegt als die höchsten am Widerstand auftretenden Überspannungen. Beide Widerstände 4 und 6 sind gemeinsam in einem Glasgefäß 7 untergebracht, das entlüftet oder aber auch mit nicht angreifenden Gasen, wie Stickstoff oder Wasserstoff, gefüllt sein kann. Zweckmäßig umschließt der Widerstand 6, wie dargestellt, den anderen Widerstand 4 rohrartig, so daß dieser als Heizkörper im Innern des Widerstandes 6 liegt und diesen besonders schnell und kräftig aufheizt.

Im Schaubild nach Abb. 3 ist mit U_1 die am Widerstand 4 abgegriffene Spannung und mit R die dem Verbraucher zugeordnete Widerstandsgerade dargestellt. Letztere schneidet die Stromspannungskennlinie K, die der kalte Widerstand 6 hat, bei einem so kleinen Strom J_1, daß dieser nicht genügt, um den Widerstand 6 bei der Inbetriebnahme der Einrichtung nach Abb. 1 zum Zusammenbrechen zu bringen. Durch die zusätzliche Erhitzung des Widerstandes 6 durch den Widerstand 4 wird jedoch die Kuppe der Stromspannungskennlinie K bald nach der Einschaltung der Einrichtung so weit gesenkt, daß diese den mit H bezeichneten Verlauf nimmt. Jetzt schneidet die Widerstandsgerade die Stromspannungskennlinie bei dem wesentlich größeren Strom J_2, zu dem der endgültig verbleibende kleine Restwiderstand des Widerstandes 6 gehört. Der Umstand, daß der Widerstand 4 bedeutend wärmeträger als der Widerstand 6 ist, stört die Wirkungsweise des Widerstandes 6 beim ersten Einschalten aus dem kalten Zustande, also das Abfangen des Einschaltüberstromes, zufolge des sich zuerst einstellenden Verlaufes der Stromspannungskennlinie nicht. Da sich andererseits beim Ausschalten der Einrichtung der Widerstand 6 wegen seiner geringeren Wärmeträgheit bedeutend schneller abkühlt als der Widerstand 4, hat er auch beim Wiedereinschalten wieder eine überhöhte, von der Widerstandsgeraden schon bei kleinem Strom geschnittene Stromspannungskennlinie, so daß auch wiederum der Einschaltüberstrom abgefangen wird. Die nach der Wiedereinschaltung schnell eintretende starke Erwärmung des Widerstandes 6 führt jedoch dann wieder dazu, daß der Ohmwert des Widerstandes 6 zusammenbricht, womit dann auch die Stromzufuhr zum Verbraucher nicht unterbunden bzw. unnütz behindert wird.

Figure B.69: Erwin Weise told Allied investigators that he "had demonstrated the possibility of using thin films or control electrodes in semi-conducting materials to provide control of current flow similar to the control of current flow in high vacuum tubes" to create "electronic amplifiers without vacuum."

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PATENTANSPRÜCHE:

1. Einrichtung zur Entnahme gleichbleibender Gleich- oder Wechselspannung aus Netzen mit schwankender Spannung von den Enden eines mit einem Ohmschen Widerstand in Reihe geschalteten Halbleiterwiderstandes mit waagerechter Stromspannungskennlinie, dadurch gekennzeichnet, daß der Halbleiterwiderstand mit waagerechter Stromspannungskennlinie zusammen mit einem dem Verbraucher vorgeschalteten Halbleiterwiderstand mit fallender Stromspannungskennlinie und geringerer Wärmeträgheit in einem Glasgefäß untergebracht ist.

2. Einrichtung nach Anspruch 1, dadurch gekennzeichnet, daß der dem Verbraucher vorgeschaltete Widerstand den anderen zum Verbraucher parallel liegenden Widerstand röhrenartig umschließt.

Hierzu 1 Blatt Zeichnungen

BERLIN. GEDRUCKT IN DER REICHSDRUCKEREI

Figure B.70: Erwin Weise told Allied investigators that he "had demonstrated the possibility of using thin films or control electrodes in semi-conducting materials to provide control of current flow similar to the control of current flow in high vacuum tubes" to create "electronic amplifiers without vacuum."

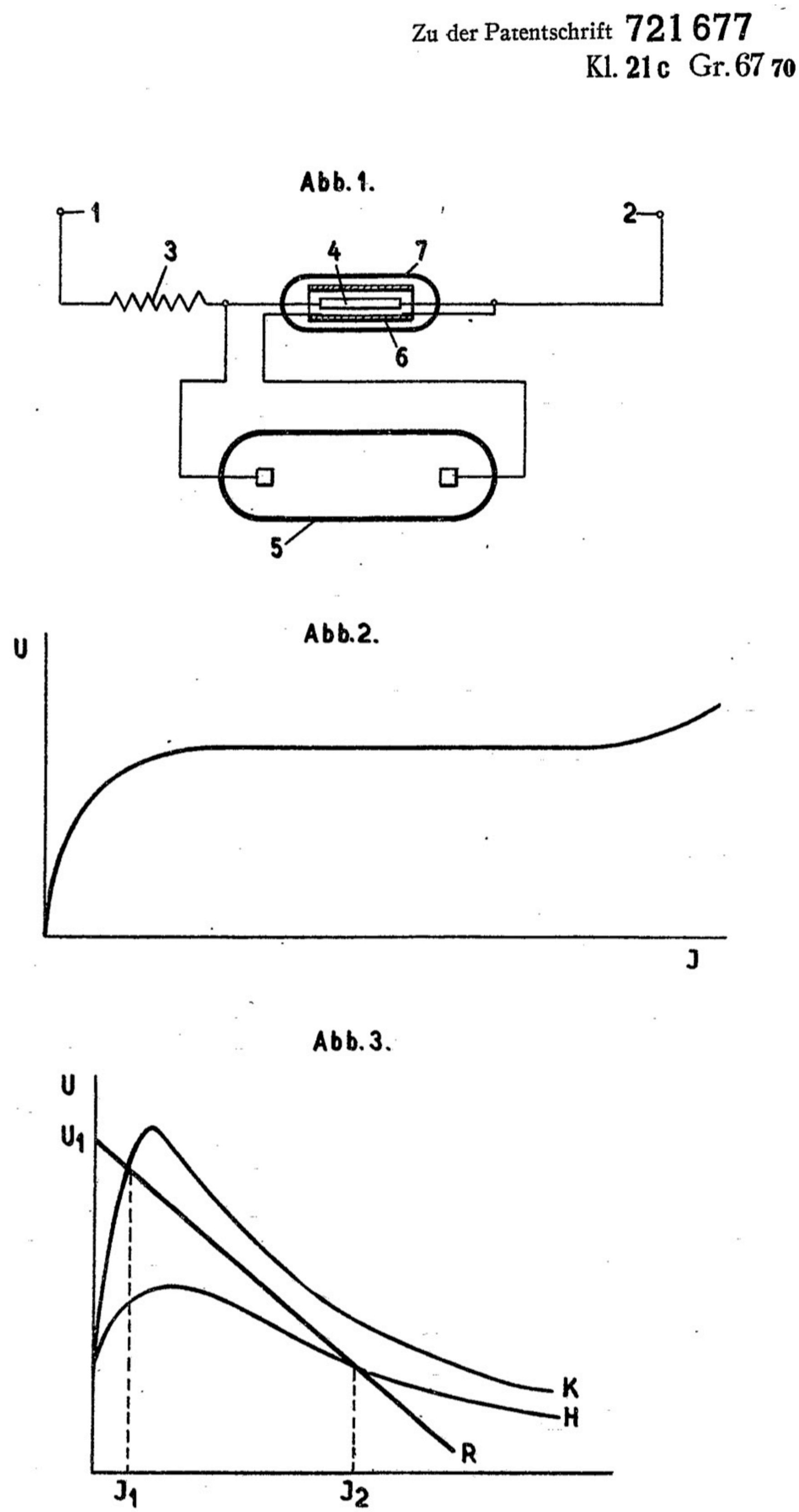

Figure B.71: Erwin Weise told Allied investigators that he “had demonstrated the possibility of using thin films or control electrodes in semi-conducting materials to provide control of current flow similar to the control of current flow in high vacuum tubes” to create “electronic amplifiers without vacuum.”

[**9. Frank Rose (German?, 19??–19??), Eberhard Spenke (German, 1905–1992), and Erich Waldkötter (German?, 19??–19??)** filed detailed patent applications on transistors [Handel 1999]. See for example:

> Eberhard Spenke, Frank Rose, and Erich Waldkötter. Filed in 1949 but likely based on wartime work. U.S. patent 2,648,805. Controllable Electric Resistance Device. (pp. 2735–2744)

Because of the extreme political and financial restrictions on conducting research in Germany after the war, it seems likely that their patent applications were based on wartime work. Indeed, large numbers of patent applications on wartime inventions were filed in 1949 when the West German patent office opened.]

Aug. 11, 1953 E. H. G. SPENKE ET AL **2,648,805**

CONTROLLABLE ELECTRIC RESISTANCE DEVICE

Filed Oct. 21, 1950 3 Sheets–Sheet 1

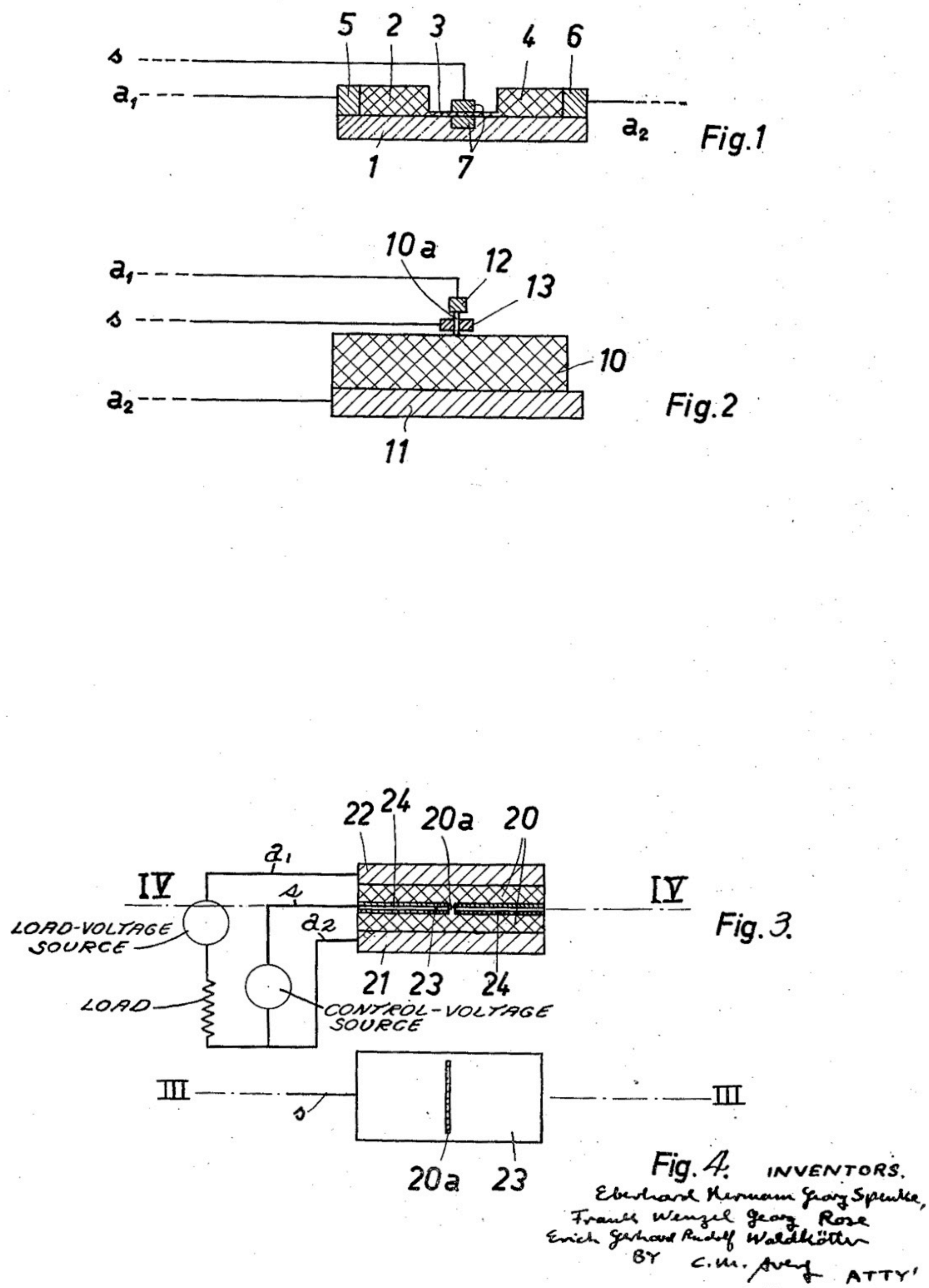

Figure B.72: Frank Rose, Eberhard Spenke, and Erich Waldkötter filed detailed patent applications on transistors in 1949, likely based on wartime work.

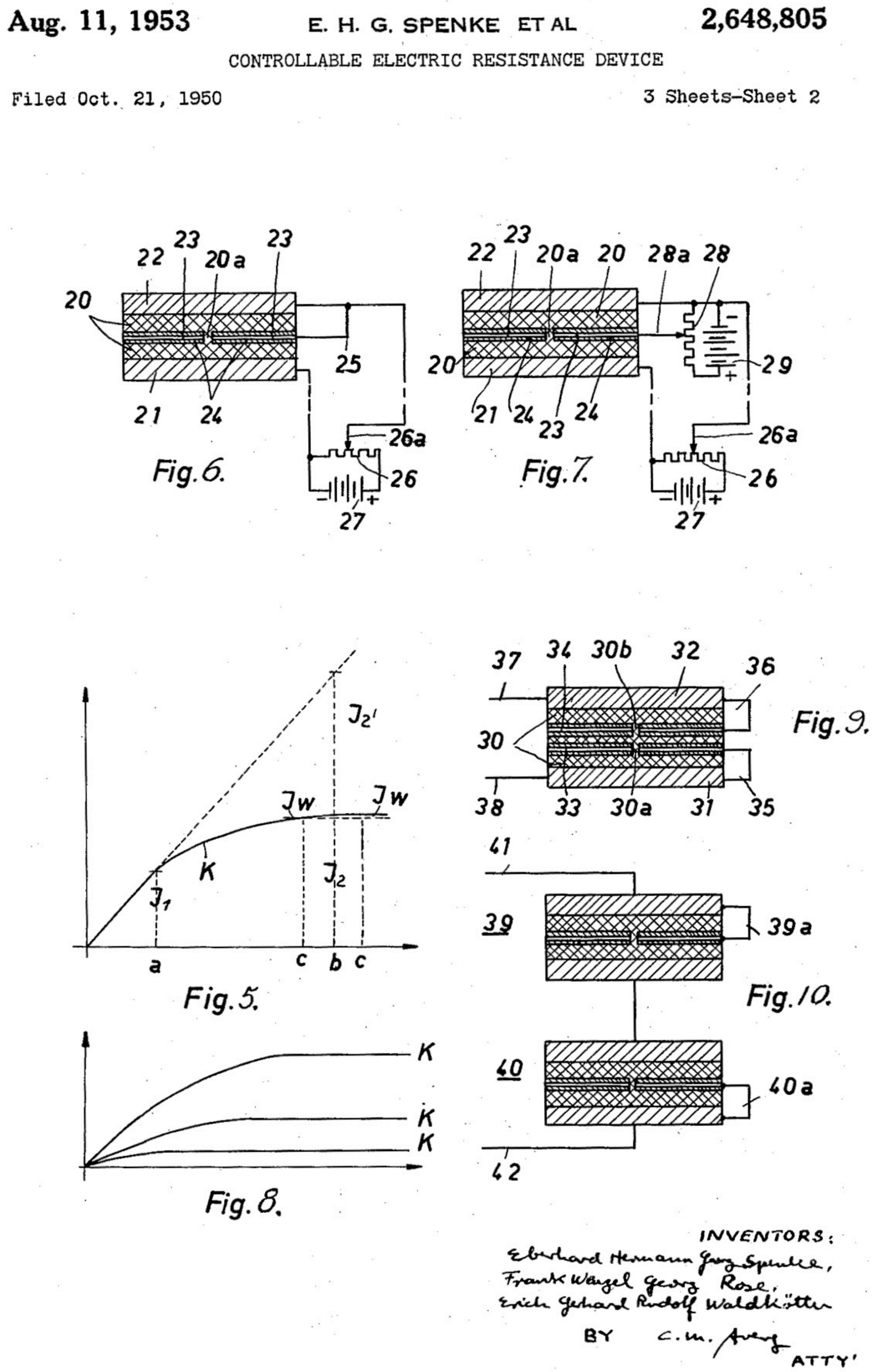

Figure B.73: Frank Rose, Eberhard Spenke, and Erich Waldkötter filed detailed patent applications on transistors in 1949, likely based on wartime work.

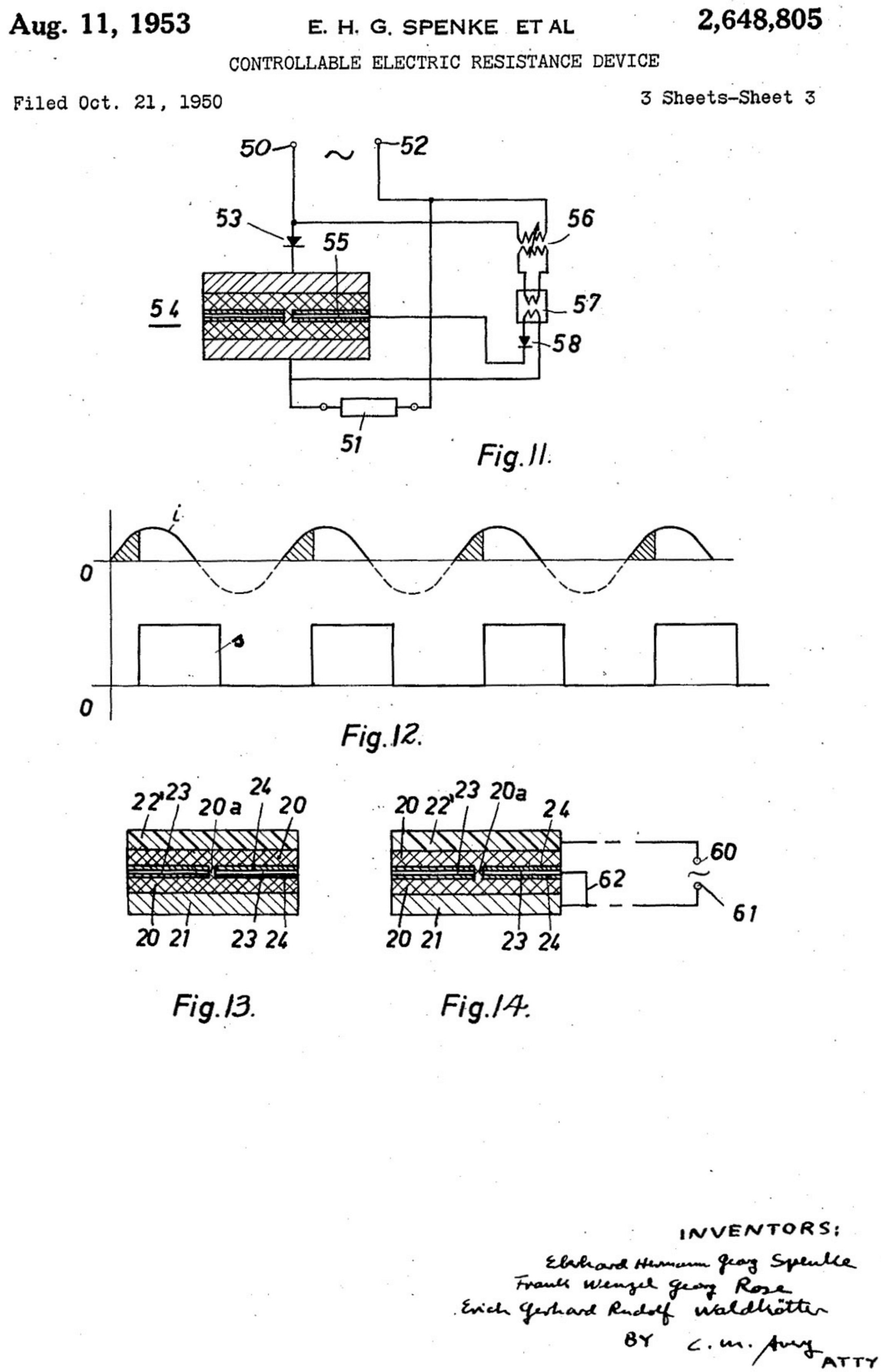

Figure B.74: Frank Rose, Eberhard Spenke, and Erich Waldkötter filed detailed patent applications on transistors in 1949, likely based on wartime work.

Patented Aug. 11, 1953 **2,648,805**

UNITED STATES PATENT OFFICE

2,648,805

CONTROLLABLE ELECTRIC RESISTANCE DEVICE

Eberhard Hermann Georg Spenke, Frank Wenzel Georg Rose, and Erich Gerhard Rudolf Waldkötter, Pretzfeld, Germany, assignors to Siemens-Schuckertwerke, Aktiengesellschaft, Berlin-Siemensstadt, Germany, a corporation of Germany

Application October 21, 1950, Serial No. 191,360 In Germany May 30, 1949

18 Claims. (Cl. 317—235)

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Our invention relates to controllable electric resistors and the like devices for controlling electric circuits.

It is an object of our invention to devise a resistance device of a static type that, though not requiring an electronic vacuum or gaseous discharge, is controllable by the direct application of a control voltage and operates virtually free of inertia, thus being applicable for a large variety of purposes in much the same way as electronic amplifier or control tubes and particularly wherever an electric current path is to be controlled or regulated by minute control energy.

Another object of our invention is to provide a bodily electric resistor of controllable resistance and to obviate the need for providing it with mechanically movable or otherwise mechanically actuated or thermally responsive resistance control members.

It is also an object of the invention to make the resistive behaviour of electric resistors of the solid-material type adaptable to different selectively available resistance characteristics in one or both directions of current flow, a subsidiary object being to secure a characteristic of the saturation type configuration.

An object of the invention is further to devise rectifier units of the dry or junction type that can be controlled by application of control voltage to provide a controllable rectified output.

Another object of the invention is to provide industrially suitable methods of making the novel resistance and rectifier units.

In order to achieve these and the more specific objects apparent from the following, our invention takes advantage of the barrier-layer effect known from semiconductors such as selenium. Such semiconductors and various other substances form a barrier layer where they are in contact engagement with a suitable metal. The barrier layers offer a high resistance to the passage of electric current and are dependent, as regards occurrence and effectiveness, upon the magnitude of the impressed voltage. This behaviour is utilized, for instance, in the so-called dry rectifiers in which a thin semiconductive layer is contacted at one side by a barrier-free contact element and at the other side by a barrier-forming contact element, the so-called barrier electrode. When a voltage of a given direction is applied between the two contact elements, a barrier layer is produced which practically blocks the current passage in this direction or maintains any remaining current flow within very small magnitudes. It has now been observed that the thickness of the barrier layer thus produced is dependent

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upon the magnitude of the impressed voltage. With an increasing voltage, the layer of high resistance expands more deeply into the semiconductive or other resistance material susceptible to the barrier layer effect. The portion of the resistance material not occupied by the barrier layer is consequently diminished by the thickness of the barrier layer.

The just-mentioned phenomenon is utilized by the invention in the following manner. According to the invention, a body of resistance material susceptible to barrier-layer formation is provided with a barrier electrode arranged to form in the resistance body a diaphragm-shaped barrier layer across the current path to be controlled, the dimensions of the diaphragm opening being dependent upon the impressed voltage.

The invention involves a variety of possibilities for the design of such resistance devices. According to one feature of the invention, the resistor proper is a semiconductive body joined with two terminals or connector electrodes, while the barrier diaphragm disposed in the current path of this resistor body is formed by a barrier electrode located at a place where the current path is strongly constricted. The constriction of the current flow lines can be secured by a corresponding shaping of the semiconductive body, preferably by giving the semiconductive body a spot of very small dimensions in one or both directions transverse to the flow direction of the current to be controlled, and locating the controlling barrier electrode at or near this spot and substantially around the constricted current path.

The term "connector electrode" in this specification as well as in the claims refers to the barrier-free contact member or terminal which engages the semiconductive or other resistance body. The terms "barrier electrode" and "diaphragm electrode" refer to electrode members which contact the barrier susceptible resistance body and form together therewith a barrier layer due to impressed voltage.

The foregoing and other features of the invention will be apparent from the following description of the embodiments exemplified by the drawing, in which:

Figs. 1 and 2 show respective resistance devices according to the invention by part sectional front views;

Figs. 3 and 4 show another resistance device according to the invention in a sectional front view and a sectional top view, the respective sectional planes being indicated by the line III—III in Fig. 4 and the line IV—IV in Fig. 3;

Fig. 5 is a coordinate diagram showing a typical

Figure B.75: Frank Rose, Eberhard Spenke, and Erich Waldkötter filed detailed patent applications on transistors in 1949, likely based on wartime work.

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resistance-voltage characteristic of devices according to the invention with reference to the embodiments illustrated in Figs. 6, 7, 9 and 10;

Fig. 6 shows an embodiment of a resistance device according to the invention with appertaining circuit means for adjusting the resistance characteristic;

Fig. 7 shows a similar resistance device with modified circuit means;

Fig. 8 represents a family of resistance-voltage characteristics with reference to the embodiment of Fig. 7;

Figs. 9 and 10 show sectional views of two respective modifications of devices according to the invention having a resistance characteristic controllable in both directions of current flow;

Fig. 11 is the circuit diagram of a controllable rectifying apparatus according to the invention;

Fig. 12 is a coordinate diagram representing typical wave shapes of the current flow and of the control voltage as occurring in rectifying apparatus according to Fig. 9;

Fig. 13 is a sectional view of another embodiment of a controllable rectifying device according to the invention; and

Fig. 14 is a similar view of an embodiment of a controllable rectifying apparatus with a saturation characteristic.

The resistor according to Fig. 1 has an insulating base plate 1 on which a barrier-susceptible or semiconductive resistance body is mounted. This body is composed of three parts 2, 3 and 4 and is intimately contacted by two connector electrodes 5 and 6 also mounted on the insulating plate 1. The intermediate resistor portion 3 has much smaller dimensions than the bordering portions 2 and 4 and is intimately contacted by a barrier electrode 7 which serves to provide a controllable barrier diaphragm. The connecting leads (in Figs. 1 through 4) are denoted by a_1 and a_2, and the control lead is denoted s. As apparent from Fig. 1, the middle part 3 of the resistance body is very thin, although its width in the direction across the plane of illustration may be large. Generally, however, the width of portion 3 in at least one of the directions transverse to the current path (i. e. penpendicular to the plane of illustration) is very small.

For operating the resistance device, the two connector electrodes 5 and 6 are series connected by the respective leads a_1 and a_2 into the circuit to be controlled. The control or regulation of the resistance is effected by means of a control voltage impressed between the barrier electrode 7 and one of the connector electrodes. The electrode 7 contacts the semiconductor 3 in the manner known from the technique of dry rectifiers so that the application of control voltage results in the formation of a barrier layer which extends from the barrier electrode 7 into the body 3. The electrode 7 fully covers the top and bottom sides of body 3, or the electrode fully encloses this body so that the barrier layer, if growing from electrode 7 fully into the body 3, would not leave any free spot for the passage of current. Consequently, the effect is as if a diaphragm of controlled opening area is placed into the resistive current path between the two connector electrodes 5 and 6. The opening width of the barrier diaphragm depends, as explained, upon the magnitude of the impressed control voltage, the thickness of the barrier layer being larger with larger control voltages, so that the available cross section of current flow and hence the effective resistance are varied in the rhythm of the control voltage.

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To form the resistor proper, i. e. the semiconductive body in the embodiment of Fig. 1, of three portions has the purpose to constrict or bunch the lines of current flow at the spot of the diaphragm. This design is based on the consideration that the thickness of the resulting barrier layer as such is very small. It is advisable, therefore, to adapt the transverse dimensions of the resistor body at the diaphragm spot to the order of magnitude of the resulting barrier layer thickness. In other words, it is essential to give the dimension of the current path in the direction of the "diaphragm movement" at the place of the diaphragm electrode a magnitude of only a few multiples, for instance, twice or three times the extent of the barrier layer thickness occurring in the particular resistor substance used, although the dimensions of the constricted resistor portion may be smaller if possible. The term "diaphragm movement" as used in the foregoing and hereafter is intended to refer to the opening and closing directions, i. e. to the growth and decline of the barrier layer under the effect of the control voltage.

In Fig. 2 the resistor proper, consisting of a semiconductor, is denoted by 10. Joined with this resistor is a plate-shaped connector electrode 11. The resistance body 10 has a filament-shaped extension 10a to which is joined a second connector electrode 12 and a barrier electrode 13. The barrier electrode 13 completely surrounds the filament extension 10a. For reasons mentioned in the following, the barrier electrode 13 is insulated from the main resistance body 10 by being somewhat spaced therefrom.

The functioning of the resistance device according to Fig. 2 is largely similar to that of Fig. 1. The special shape of the semiconductive assembly 10, 10a serves the purpose to provide a spot of a strong constriction of the current path lines within the semiconductive body. This is easily achieved by the provision of the filament extension 10a. It may be mentioned that for the sake of lucid illustration the representation in the drawing is not correct according to measure. In particular, the electrode 13 is shown thicker than actually necessary. In reality, this electrode may be very thin. This applies even more to the filament shaped extension 10a. The filament may be produced, for instance, by immersing a glass rod or the like into a molten bath of selenium or another semiconductive or otherwise suitable material and then removing the rod, thus drawing a filament from the bath. By inspecting the filament under a microscope or by other suitable methods, those parts of the filaments are selected which have the desired thickness. The selected pieces of filaments are than used as the filament-shaped extensions 10a. The barrier electrode 13 can be joined with the filament by immersing the filament, or the selected filament section of limited length, in a molten metal or by depositing in vacuum a metal coating on the filament.

Departing from the embodiment of Fig. 2, it is also possible to build up the entire controllable resistance device with the aid of a filament-shaped resistance body of suitable material. This can be done by mounting a barrier electrode in the above-mentioned manner on a limited length of the filament-shaped piece of material and attaching the connector electrodes to the same piece of filament material, for instance, by

Figure B.76: Frank Rose, Eberhard Spenke, and Erich Waldkötter filed detailed patent applications on transistors in 1949, likely based on wartime work.

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clamping the filament piece at both ends in metal holders which then form a barrier-free contact and serve as the connector electrodes.

In the device according to Figs. 3 and 4, the resistance body proper is denoted by **20**, and the spot of strong constriction of the current path lines in the body is denoted by **20***a*. The two appertaining connector electrodes **21** and **22** consist of plates which are joined with the resistance body. The barrier electrode **23** is foil-shaped. It is insulated over most of its surface areas from the adjoining material of the resistance body **20**, this being schematically indicated by insulating layers **24**. In this manner a narrow and thin conductive gap is produced at the spot **20***a* of the resistance body.

The operation of this device is similar to that of the embodiments previously described. The barrier layer diaphragm is formed by the barrier electrode **23** and the constricted current path at **20***a*. The thickness of the gap or current path is dimensioned according to the foregoing explanations so that it amounts to only a few multiples or less of the thickness of the occurring barrier layer. The electric insulation of the barrier electrode **23** from the resistance body **20** by layers **24**, consisting, for instance, of varnish coats or paper inserts, has the purpose to keep the control energy as small as possible. If no insulation were effective, there would be spots which during the occurrence of control voltages would not contribute to the control effect, i. e. to the formation of the barrier layer diaphragm but would rather divert current from the control path. It is, therefore, necessary to avoid such current-diverting spots. For this reason it is also advisable to keep the barrier electrode as small as possible in the direction transverse to the "diaphragm movement" in order to minimize the diversion of control energy.

The control or diaphragm electrode, therefore, is preferably formed by a very thin metal foil. Since, as mentioned, it is infeasible to accurately illustrate all dimensional proportions in the drawing, it will be understood that as regards foil thickness the drawing is not intended to be exactly to scale.

The spot **20***a* of constricted transverse dimension within the resistance body **20** proper can be formed, for instance, by the following method of manufacture. First only the lower portion of the resistance body **20** is joined with the electrode **21**. Then the barrier electrode foil is mounted after a fine cut has been made in that electrode with a fine blade or the like tool. Thereafter the semiconductive or other material used for the resistance body **20** is pressed into the slot formed by the cut. For this purpose the resistance material is previously converted to its liquid or plastic state. After filling the cut with resistance material, the top layer of the resistance body **20** is joined with the bottom portion, and finally the connector electrode **22** is mounted on top of the assembly.

Instead of providing only a single gap in the barrier electrode **23**, as shown in Figs. 3 and 4, it is also possible to provide it with several passageways of rounded or slot-shaped cross section. It is then also preferable to electrically insulate the entire barrier electrode against the resistance body proper with the exception of the inner walls of the perforations that form the current passageways.

As regards the materials best suitable for the electrodes and relative to other matters of manufacture, the known techniques of manufacturing dry rectifiers, for instance, selenium rectifiers, are applicable. It may be mentioned, however, that when using selenium for the resistance body, the barrier electrode may consist of a tin-cadmium alloy, for instance, while the connector electrode may consist, for instance, of nickel, nickel-coated iron plates, or nickel-selenide layers.

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Resistance devices according to the invention can be modified and improved in various ways. According to an improvement feature, the control voltage of the diaphragm electrode is correlated to the voltage of the current path to be controlled, for instance, by a short-circuit connection or by means of other electric coupling members, so as to modify or adapt the resistive behaviour to desired requirements, for instance, for securing a saturation type characteristic. Such a saturation characteristic is desirable for various application purposes. For instance, in telephone systems for automatic selector operation, it is often essential to design certain electric circuits in such a manner that they permit the flow of direct currents only up to a predetermined limit value, while offering a high resistance to superimposed small alternating voltages. Such and similar purposes require a resistance device whose resistance characteristic is approximately as typified by the voltage resistance diagram of Fig. 5. According to Fig. 5, the characterized resistance element has the particularity that the current intensity in the element does not increase in proportion to the voltage impressed across the element. In other words, the resistance of the element is not constant but increases with increasing voltage.

The embodiment shown in Fig. 6 secures a saturation characteristic of the type shown in Fig. 5 with the aid of very simple circuit means. As far as the resistance device proper is concerned, the embodiment of Fig. 6 is in accordance with the above-described device of Figs. 3 and 4, the reference numbers used in Fig. 6 being identical with those of Figs. 3 and 4 for similar respective elements. In Fig. 6, the connector electrode **22** is electrically joined with the diaphragm electrode **23** by a short-circuit connection **25**. The two connector electrodes **21** and **22** are attached across an adjusted portion of a potentiometer rheostat **26** energized from a suitable source of direct current represented by a battery **27**. The short-circuit connection **25** between electrodes **22** and **23** can be made during the manufacture of the resistance device. This can be done, for instance, by placing the connector electrode **22** at its bottom side into direct metallic contact with the top side of the diaphragm electrode **23** so that the two electrodes are practically integrated to a single element. Instead, the connector electrode **22** can be omitted and the barrier electrode **23**, then preferably not insulated at its top side, also assumes the function of the connector electrode **22**.

The operation of the device according to Fig. 6 is as follows: If the tap **26***a* of the potentiometer rheostat **26** is positioned near the negative terminal of source **27**, then the diaphragm electrode **23** and the connector electrode **22** have only a slight positive potential difference relative to the connector electrode **21**, for instance, only the small potential *a* indicated in the diagram of Fig. 5. It will be understood from the preceding explanations that the barrier di-

Figure B.77: Frank Rose, Eberhard Spenke, and Erich Waldkötter filed detailed patent applications on transistors in 1949, likely based on wartime work.

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aphragm is then relatively wide open. Consequently, the resistance effective between the electrodes 21 and 22 is small, and a direct current of the magnitude J_1 (Fig. 5) will flow through the resistance body. If the tap 26*a* is displaced toward the positive source terminal, a correspondingly higher potential is applied to diaphragm electrode 23 and connector electrode 22 relative to the connector electrode 21, for instance, the potential indicated at *b* in Fig. 5. Now the opening of the barrier diaphragm is greatly reduced and the effective resistance between the connector electrodes 21 and 22 correspondingly increased. If this effect had not taken place, then the current due to the increased positive potential would assume the magnitude of J_2' according to the linear characteristic of common resistors. Due to the action of the barrier-layer diaphragm, however, the current has increased only to the value J_2. The embodiment of Fig. 6, therefore, represents a resistance element having a typical saturation characteristic as exemplified by the curve K in Fig. 5.

At high direct-current loads, a device according to Fig. 6 offers a high resistance value to superimposed small alternating-current voltages, as will be elucidated presently. In Fig. 5 is plotted a voltage interval *c*—*c* extending toward both sides from the axis determined by the higher potential *b*. This interval is supposed to represent the positive and negative variations of an alternating voltage wave that may be superimposed on the direct-current potential applied to the resistance device. Since the current flow in the resistance body follows the characteristic curve K, the superimposed alternating current effective at the unidirectional potential *b* has the magnitude T_w. It will be recognized that the current variations due to the superimposed alternating voltage occur along the flat portion of the characteristic K. Consequently, the superimposed alternating voltages have only a slight effect, the alternating component of the resultant direct current remaining extremely small. In other words, within the portion of the characteristic here of interest, the alternating-current resistance of the device according to Fig. 6 is very high.

The embodiment according to Fig. 7 differs from that of Fig. 6 only in that the above-mentioned short-circuit connection 25 is replaced by a potentiometer rheostat 28 with a battery 29 or other source of constant direct-current voltage. The adjustable potentiometer tap is denoted by 28*a*. This device permits adjusting the potential of the diaphragm electrode 23 relative to the connector electrode 22 to any desired value within the available limits. As a result, the device can be adjusted to different saturation characteristics simply by correspondingly positioning the tap 28*a* of rheostat 28. In this manner, for instance, the device may be given any of the different characteristics typified in Fig. 8 by curves K_1, K_2 and K_3. In other respects, the operation of the device shown in Fig. 7 is similar to that of Fig. 6.

It should be understood that the potentiometer rheostats 26 are shown in Figs. 6 and 7 mainly for the purpose of lucid illustration. As a rule, the necessary voltages need not be taken from a potentiometer rheostat. More often, the resistance device according to the invention is connected in given circuits so that the potentials or voltage drops occurring in these circuits and effective at the resistance device take the place

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of the potentiometric arrangements exemplified on the drawing.

Devices according to Figs. 6 and 7 secure the desired modification or adaptation of the resistance characteristic, for instance, for obtaining a saturation type behaviour, only in one given direction of current flow. Hence, such devices have a valve effect when impressed by alternating voltage and are also applicable for rectifying purposes.

However, resistance devices according to the invention can also be designed to secure the above-explained effect on the resistance characteristic in both directions of current flow. This is of interest for applications where the direct current flowing through the resistance device does not always have the same direction and is also of advantage for alternating-current uses of the resistance devices.

An example of a device active to modify the resistance characteristic in both directions of current flow is shown in Fig. 9. A semiconductive layer 30 consisting, for instance, of selenium is joined with two connector electrodes 31 and 32. Two barrier electrodes 33 and 34 are disposed within the semi-conductive layer 30 and have respective constricted current paths at 30*a* and 30*b*. Both barrier electrodes are electrically insulated at their respective upper and lower surfaces from the material of the semiconductive layer 30 except at the places of the controlled and constricted paths 30*a* and 30*b*. The insulation consists, for instance, of a coat of varnish or a layer of paper. The barrier electrode 33 is connected with the connector electrode 31 by a short-circuit connection 35. Accordingly, the barrier electrode 34 is connected with the connector electrode 32 by a short-circuit connection 36. It will be recognized that the two barrier electrodes and their respective gaps are arranged in series relation to each other relative to the flow of current passing between the connector electrodes.

When a voltage of one polarity is applied across the leads 37 and 38 of the device, the barrier electrode 33 with gap 38 is effective to produce the above-mentioned modification of the resistance characteristic, while a voltage of the opposite polarity will cause the other barrier electrode 33 to have a similar effect. Consequently, the resistance characteristic of a device according to Fig. 9 differs from the ordinary linear characteristics in both directions of current flow.

The effect obtained with devices according to Fig. 9 can also be secured by connecting two resistance units according to Fig. 6 and/or Fig. 7 in series with each other and with mutually opposed polarities of the respective connector electrodes that are electrically joined with the appertaining barrier electrode.

In Fig. 10, showing such a series opposed connection of two resistance units, the two units are denoted by 39 and 40. The appertaining short-circuit connections corresponding to the device of Fig. 6 are denoted by 39*a* and 40*a*. The terminal leads 41 and 42 are to be connected in the circuit to be controlled or regulated by the series connected two units.

If in a circuit according to Fig. 10 the two series connected resistance units are adjusted for respectively different characteristics, which can be done, for instance, by using one or two units according to Fig. 7, then the arrangement has not only different respective characteristics for

Figure B.78: Frank Rose, Eberhard Spenke, and Erich Waldkötter filed detailed patent applications on transistors in 1949, likely based on wartime work.

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the two directions of current flow, but has also a rectifying operation.

Apparatus according to the invention can also be designed to operate as controllable rectifying devices. To this end, according to another feature of the invention, a device having a barrier diaphragm as explained in the foregoing is series connected with a dry or junction type rectifier.

The just-mentioned feature is embodied in the apparatus shown in Fig. 11. The circuit to be controlled has terminals 50 and 52 across which an alternating voltage is impressed. The circuit extends from terminal 50 through a dry rectifier 53, a controllable resistance device 54 and through the load 51 to terminal 52. The resistance unit 54 is designed in accordance with the principles explained previously and has a diaphragm electrode 55 essentially as explained in conjunction with Figs. 3 and 4. The control voltage for the diaphragm electrode 55 is taken from the circuit to be controlled through an adjustable phase shifter 56 and a transformer 57. Transformer 57 has the characteristic needed to provide a secondary output voltage of rectangular wave shape. The secondary circuit of transformer 57 is connected across the barrier electrode 55 and one of the connector electrodes of the resistance unit 54 through a valve 58 which suppresses the negative pulses or half waves supplied from the transformer. Consequently, the pulses of control voltage impressed on the controllable resistance unit 54 correspond essentially to the curve *s* shown in the voltage-time diagram of Fig. 12. Fig. 12 also shows a curve *i* which exemplifies the current pulses in the load 51 assuming that the barrier diaphragm is always open. The phase position of the voltage curve *s* relative to the current curve *i* can be adjusted with the aid of the phase shifter 56. The phase shifter 56 and/or the transformer 57 transform the voltage taken from the load circuit to be controlled so as to impress on the resistance unit a control voltage of the desired magnitude.

The operation of the device according to Fig. 11 can be explained as follows. If the resistance unit 54 in the circuit to be controlled were omitted, the positive half waves according to curve *i* in Fig. 11 would substantially fully pass through the load as is the case in conventional non-controllable rectifying apparatus. Due to the presence of the controlled resistance unit 54, however, part of each positive current half wave can be cut off. The control voltage impressed upon the diaphragm electrode 55 through the circuit elements 56, 57 and 58 has the effect that the barrier diaphragm is closed at some moment within the duration of the individual rectangular pulses of the curve *s*. As a result, the duration of current flow in the load circuit during the positive half waves of current curve *i* can be enlarged and diminished by adjusting the phase shifter 56. In Fig. 12, the flow periods, i. e. the portions of the positive current half waves in which the current is effective in the circuit to be controlled, are marked by cross hatching. It will be recognized that by correspondingly displacing the curve *s* relative to curve *i* the current flow can be augmented up to the full value of the positive current half wave, and can be diminished to the zero value by a phase displacement in the opposite direction.

The series connection of a valve such as a dry rectifier with a controllable resistance unit of the type previously described thus results in controllable rectifying devices suitable for highly diversified applications similar to those heretofore served by gas-discharge devices, mercury-arc rectifiers, electronic tubes, etc. It will be obvious, therefore, that the control circuits applicable for the invention may be similar to those known from the techniques and applications of the just-mentioned other rectifying devices. In particular, many different circuits are known and suitable for providing an impulse sequence of rectangular, trapezoidal or the like wave shape similar to curve *s* in Fig. 12. For that reason, further details of the very many available circuit connections and arrangements need not here be given.

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While in the above-described rectifying apparatus according to Fig. 11 the dry rectifier 53 and the series connected controllable resistance device 54 represent individual units, it is possible, and for many applications preferable, to join both devices into a single structural unit. Fig. 13 shows an embodiment of this type.

The device according to Fig. 13 involves a controllable resistance unit designed essentially in accordance with Figs. 3 and 4. In contrast, however, one of the connector electrodes, i. e. the electrode denoted in Fig. 13 by 22′ consists of a barrier-forming metal or alloy. For instance, when selenium is used as a barrier-susceptible material, the electrode 22′ may consist of a tin-cadmium alloy as used for the barrier electrode of conventional junction-type rectifier units. All other elements of the device shown in Fig. 13 are in accordance with Figs. 3 and 4 and denoted by similar respective reference numbers. In the unit according to Fig. 13, the two electrodes 22′ and 21 with the intermediate body 20 of semiconductive material may be looked upon as representing a conventional dry rectifier. By virtue of the inserted diaphragm electrode 23 with the appertaining slotted insulation 24, a barrier diaphragm is inserted into this dry rectifier. Consequently, the unit of Fig. 13 as a whole functions in a manner similar to a series arrangement of a dry rectifier and a controllable barrier type resistance device. Hence, in circuits otherwise designed in accordance with Fig. 11, the unit of Fig. 13 may be used instead of the two circuit elements denoted in Fig. 11 by 53 and 54.

The barrier layer diaphragm in a unit according to Fig. 13 may also be used not for the purpose of control in the sense of a steady or periodic control performance, but for imparting to the unit a saturation type characteristic, thus obtaining a rectifier with a saturating rectifying characteristic.

An embodiment of this type is illustrated in Fig. 14. The controllable unit as such is identical with that shown in Fig. 13 and has its elements denoted by the same respective reference numerals. However, according to Fig. 14, the two connector electrodes are attached to terminals 60 and 61 for connection to an alternating-current source or circuit. The diaphragm eletcrode 23 is connected through a short-circuit connection 62 with the connector electrode 21. The performance of this arrangement will be understood if one considers that the flow direction of a valve or rectifier is from the connector electrode to the barrier electrode. With an increasing voltage in the flow direction, the current of an ordinary dry rectifier increases continuously with the voltage although not in a linear dependence. In apparatus according to Fig. 14, the flow area of the barrier diaphragm increases continuously with

Figure B.79: Frank Rose, Eberhard Spenke, and Erich Waldkötter filed detailed patent applications on transistors in 1949, likely based on wartime work.

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an increasing voltage in the flow direction with the result that the otherwise existing dependence between current and voltage is modified in the sense of achieving a saturation characteristic.

The same effect can be achieved in the opposite, i. e. in the blocking direction of the unit if the diaphragm electrode **23** is connected, through a short-circuit connection **62**, not with the electrode **21** but with the barrier-forming electrode **22**. While, as a rule, a saturation characteristic in the blocking direction is not essential, such a characteristic has the advantage that minimizes any undesired back flow of current, i. e. current flowing in the blocking direction.

We claim:

1. A controllable electric resistance device, comprising a resistance body of barrier-layer-forming material forming a current path and having a spot of constricted conductance in said path, current supply means comprising a connector electrode and being conductively joined with said body to pass current through said path, and a barrier electrode joined with said body substantially around said spot and spaced from said connector electrode to permit impressing a voltage across said electrodes.

2. A controllable electric resistance device, comprising a semiconductive body forming a path for current to be controlled, two current supply terminal means joined with said body, said body having a portion of constricted cross section between said terminal means, and a barrier electrode joined with said body and fully surrounding said constricted portion.

3. A controllable electric resistance device, comprising a resistance body, conductor means joined with said body for passing current therethrough, and a barrier electrode joined with said body and forming together with said body a constricted passage for producing a barrier layer in said passage, said passage having transverse to the current flow direction of said passage a width of at most a few multiples of that of said layer.

4. An electric resistance device, comprising a resistance body of barrier-layer-forming material having a constricted portion, two mutually spaced terminal electrodes joined with said body outside of said constricted portion to pass current therethrough, a barrier electrode joined with said body at said constricted portion for producing a voltage-responsive barrier layer in said body, said barrier electrode being spaced from one of said terminal electrodes and being electrically connected with said other terminal electrode to assume a potential of given relation to that of said other terminal electrode.

5. An electric resistance device according to claim 4, comprising a short-circuit connection between said barrier electrode and said other terminal electrode whereby the device has a saturation type resistance characteristic.

6. An electric resistance device according to claim 4, comprising means for controlling the resistance characteristic of the device in both directions of current flow.

7. An electric resistance device, comprising a semiconductive body of barrier-layer-forming material, two mutually spaced terminal electrodes joined with said body to pass current therethrough, said body having two constricted portions in electric series relation to each other between said terminal electrodes, two mutually insulated barrier electrodes joined with said body at said respective constricted portions, one

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of said barrier electrodes being electrically joined with one of said terminal electrodes to have a correlated potential, and said other barrier electrode being electrically joined with said other terminal electrode to have a potential correlated to that of said other terminal electrode, whereby said device has voltage-responsively shaped resistance characteristics in both directions of current flow.

8. An electric resistance device, comprising two series-connected units, each unit having a semiconductive body of barrier-layer-forming material and two terminal electrodes and an intermediate barrier electrode, each of said bodies having between its two terminal electrodes a constricted portion with which the pertaining barrier electrode is joined, the barrier electrode of each unit being electrically joined with one of the appertaining terminal electrodes, and said two units being poled in opposed relation to each other, whereby said device has voltage-dependent resistance characteristics in both directions of current flow.

9. A controllable electric resistance device, comprising a semiconductive body, having two relatively large outer portions and an intermediate portion joining said two outer portions and having a constricted cross section compared with said outer portions, conductor means joined with said respective outer portions for passing current through said body, said conductor means including a connector electrode, and a diaphragm electrode adapted to form a voltage-responsive barrier layer in said body, said diaphragm electrode being spaced from said connector electrode to permit impressing a voltage across said electrodes and substantially surrounding said constricted portion in intimate contact therewith.

10. A device according to claim 9, comprising a barrier layer rectifier valve series connected with said resistance device for the rectification of current under control by said voltage.

11. In a device according to claim 9, said connector electrode consisting at its juncture with said body of barrier-forming material to form a valve together with said body, whereby the device is operable as a controllable rectifier unit.

12. A device according to claim 9, comprising barrier layer valve means electrically series related to said body and to said diaphragm electrode means and having its barrier-free side electrically connected with said diaphragm electrode means to provide a rectifying effect of a saturation characteristic in the flow direction.

13. The method of manufacturing an electric resistance device which comprises the steps of coating an unperforated barrier electrode on both sides with insulating material, perforating the insulated electrode, placing the perforated electrode onto the surface of a body portion of barrier-forming semiconductive material, placing another body portion of similar material onto said electrode and joining both portions through the perforation of the electrode.

14. A controllable electric resistance device, comprising a semiconductive body of barrier-layer-forming material having a constricted portion, a barrier electrode joined with said body at said constricted portion and substantially surrounding said constricted portion, and current supply means joined with said body to pass current through said constricted portion.

15. In a controllable electric resistance device according to claim 14, said constricted portion of said semiconductive body consisting of a fila-

Figure B.80: Frank Rose, Eberhard Spenke, and Erich Waldkötter filed detailed patent applications on transistors in 1949, likely based on wartime work.

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ment, and said barrier electrode being joined with said filament body at a place between said contact means and fully surrounding said filament.

16. A controllable electric resistance device, comprising a flat body of semiconductive material, two connector electrodes coaxially joined with said body at opposite sides thereof and in face-to-face contact therewith, a foil shaped barrier electrode embedded in said body to produce a barrier layer, said barrier electrode extending substantially parallel to said connector electrodes and partitioning said body into two portions, said barrier electrode having at least one opening through which said body portions are joined with each other, said opening having a width in the order of a few multiples of the depth of said barrier layer.

17. A controllable electric resistance device, comprising a resistance body of barrier-layer-forming semiconductive material forming a path for current to be controlled, current supply means comprising a connector electrode and being conductively joined with said body to pass said current through said body, and a barrier electrode of flat shape traversing said resistance body and partitioning it into two portions, said barrier electrode having duct means through which said two portions are joined with each other, said barrier electrode being electrically insulated from said resistance body with the exception of the inner wall of said duct means.

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18. A controllable electric resistance device, comprising a resistance body of barrier-layer-forming semiconductive material forming a path for current to be controlled, current supply means comprising a connector electrode and being conductively joined with said body to pass said current through said body, and a barrier electrode of flat shape traversing said resistance body and partitioning it into two portions, said barrier electrode having duct means through which said two portions are joined with each other, said barrier electrode being designed as a foil and having a minute foil thickness in the flow direction of said current.

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FRANK WENZEL GEORG ROSE.
ERICH GERHARD RUDOLF WALDKÖTTER.

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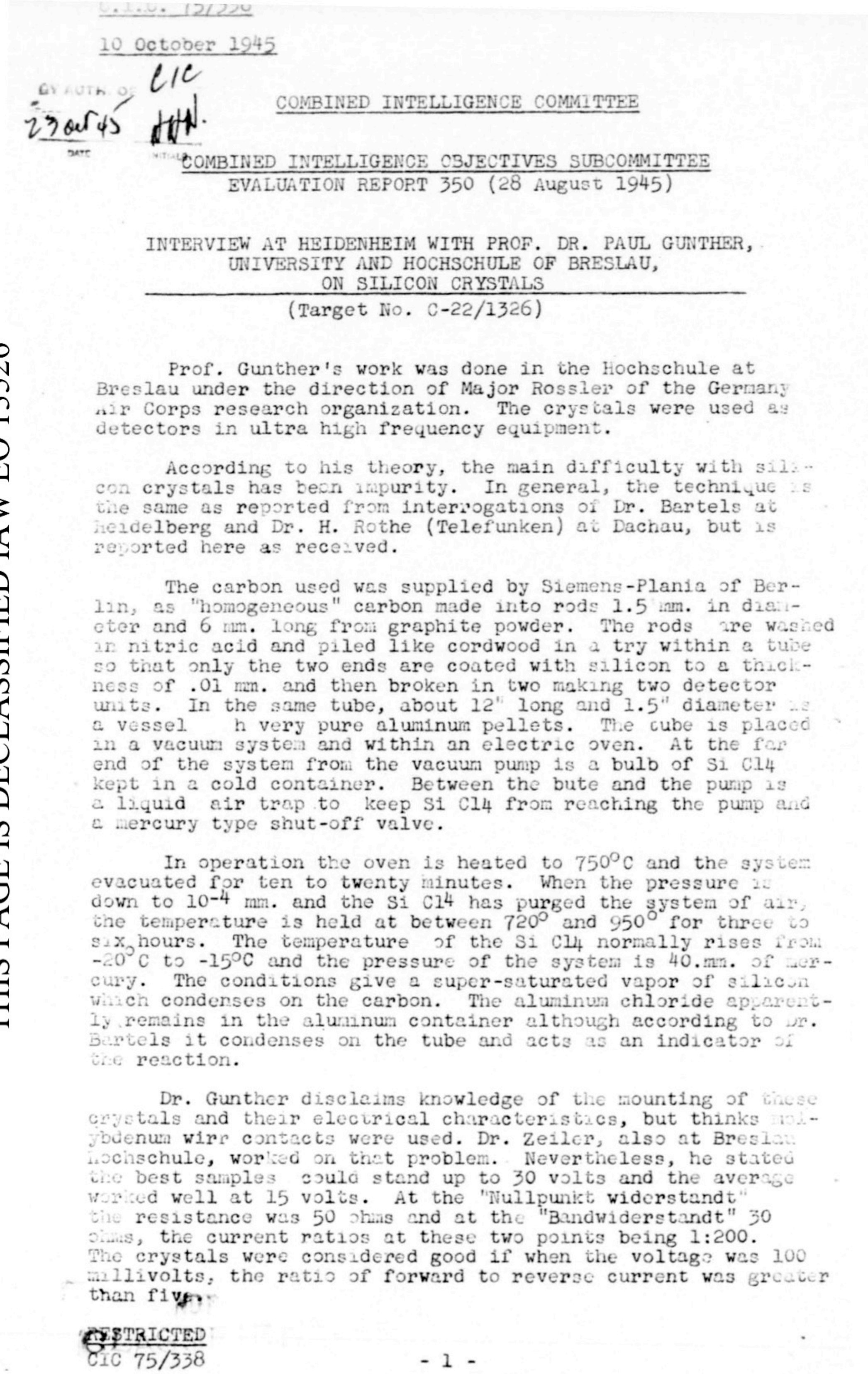
Figure B.81: Frank Rose, Eberhard Spenke, and Erich Waldkötter filed detailed patent applications on transistors in 1949, likely based on wartime work.

[**10. Karl Seiler (German, 1910–1991), Paul Ludwig Günther (German, 1892–1969), and others** developed methods for designing and fabricating silicon semiconductor devices throughout the war and into the postwar period [Handel 1999]. Their work was applied to transistors after the war, and it may have been used for that purpose during the war.

See for example:

> CIOS ER 350. *Interview at Heidenheim with Prof. Dr. Paul Günther, University and Hochschule of Breslau, on Silicon Crystals.* (pp. 2746–2747)
>
> Karl Seiler. Filed in 1950 (but apparently based on wartime work). U.S. patent 2,701,216. Method of Making Surface-Type and Point-Type Rectifiers and Crystal-Amplifier Layers from Elements. (pp. 2748–2751)
>
> Paul Ludwig Günther and Franz Kerkhoff. Filed in 1954 (but apparently based on wartime work). U.S. patent 2,876,400. Composite Electrodes for Directional Crystal Devices. (pp. 2752–2754)]



C.I.O.S. 15/556

10 October 1945

BY AUTH. OF CIC

23 Oct 45

COMBINED INTELLIGENCE COMMITTEE

COMBINED INTELLIGENCE OBJECTIVES SUBCOMMITTEE
EVALUATION REPORT 350 (28 August 1945)

INTERVIEW AT HEIDENHEIM WITH PROF. DR. PAUL GUNTHER,
UNIVERSITY AND HOCHSCHULE OF BRESLAU,
ON SILICON CRYSTALS

(Target No. C-22/1326)

Prof. Gunther's work was done in the Hochschule at Breslau under the direction of Major Rossler of the Germany Air Corps research organization. The crystals were used as detectors in ultra high frequency equipment.

According to his theory, the main difficulty with silicon crystals has been impurity. In general, the technique is the same as reported from interrogations of Dr. Bartels at Heidelberg and Dr. H. Rothe (Telefunken) at Dachau, but is reported here as received.

The carbon used was supplied by Siemens-Plania of Berlin, as "homogeneous" carbon made into rods 1.5 mm. in diameter and 6 mm. long from graphite powder. The rods are washed in nitric acid and piled like cordwood in a try within a tube so that only the two ends are coated with silicon to a thickness of .01 mm. and then broken in two making two detector units. In the same tube, about 12" long and 1.5" diameter is a vessel h very pure aluminum pellets. The cube is placed in a vacuum system and within an electric oven. At the far end of the system from the vacuum pump is a bulb of Si Cl4 kept in a cold container. Between the bute and the pump is a liquid air trap to keep Si Cl4 from reaching the pump and a mercury type shut-off valve.

In operation the oven is heated to 750°C and the system evacuated for ten to twenty minutes. When the pressure is down to 10^{-4} mm. and the Si Cl^4 has purged the system of air, the temperature is held at between 720° and 950° for three to six hours. The temperature of the Si Cl4 normally rises from -20°C to -15°C and the pressure of the system is 40.mm. of mercury. The conditions give a super-saturated vapor of silicon which condenses on the carbon. The aluminum chloride apparently remains in the aluminum container although according to Dr. Bartels it condenses on the tube and acts as an indicator of the reaction.

Dr. Gunther disclaims knowledge of the mounting of these crystals and their electrical characteristics, but thinks molybdenum wirr contacts were used. Dr. Zeiler, also at Breslau Hochschule, worked on that problem. Nevertheless, he stated the best samples could stand up to 30 volts and the average worked well at 15 volts. At the "Nullpunkt widerstandt" the resistance was 50 ohms and at the "Bandwiderstandt" 30 ohms, the current ratios at these two points being 1:200. The crystals were considered good if when the voltage was 100 millivolts, the ratio of forward to reverse current was greater than five.

RESTRICTED
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Figure B.82: Karl Seiler and Paul Ludwig Günther designed and fabricated silicon electronic devices during the war, and filed patents on silicon transistors after the war (likely based on wartime work) [CIOS ER 350].

Gunther had also worked on Fe S_2 as a detector but found crystals of it variable. He had commenced an investigation to determine whether their detector action at high frequency breaks down because of chemical or physical changes.

Gunther was interested in work done at Munich by Heinrich Welker under Clusus on Germanium crystals. Using similar reactions and technique to those he had used with silicon, Gunther had found that the dual conductivity of the resulting crystals was caused by the presence of up to 20% of aluminum in the crystals. When he succeeded in getting good crystals, they were good detectors with resistances ranging from 15,000 to 20,000 ohms. The good crystals were obtained by exposing GE Cl_4 to a stream of H_2 at 700°C.

There seemed to be some evasiveness on the part of Dr. Gunther because when there were questions concerning the growing of quartz crystals, he did not mention the work of E. J. Chytrek of Breslau, one of his students who was experimenting with growing quartz crystals in a solution of sodium carbonate.

28 July 1945

R. H. McCarthy
J. R. Townsend
P. Mertz
Consultants

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CIC 75/338

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Figure B.83: Karl Seiler and Paul Ludwig Günther designed and fabricated silicon electronic devices during the war, and filed patents on silicon transistors after the war (likely based on wartime work) [CIOS ER 350].

Feb. 1, 1955 K. SEILER **2,701,216**

METHOD OF MAKING SURFACE-TYPE AND POINT-TYPE RECTIFIERS
AND CRYSTAL-AMPLIFIER LAYERS FROM ELEMENTS
Filed April 5, 1950

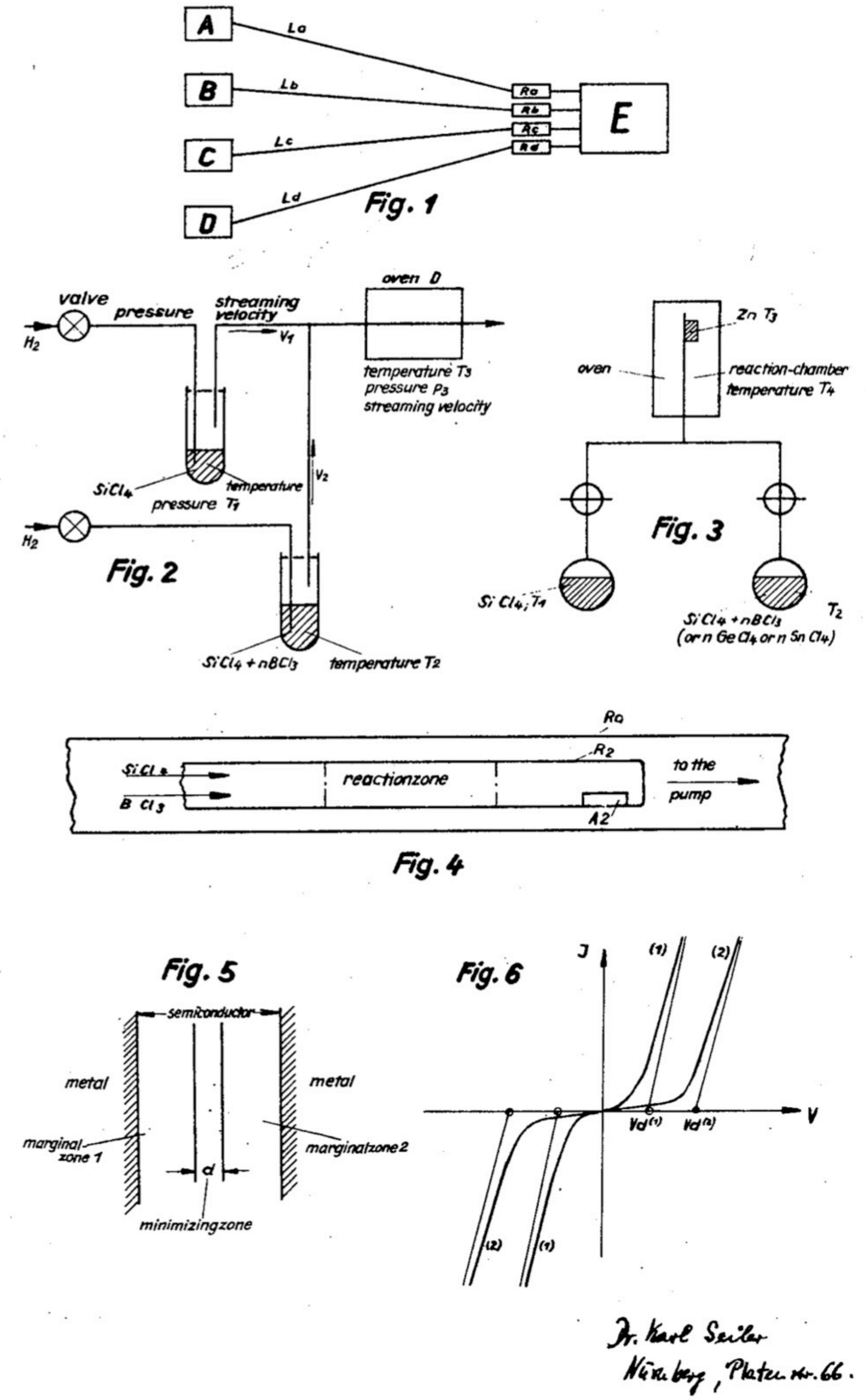

Figure B.84: Karl Seiler and Paul Ludwig Günther designed and fabricated silicon electronic devices during the war, and filed patents on silicon transistors after the war (likely based on wartime work).

United States Patent Office

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Patented Feb. 1, 1955

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METHOD OF MAKING SURFACE-TYPE AND POINT-TYPE RECTIFIERS AND CRYSTAL-AMPLIFIER LAYERS FROM ELEMENTS

Karl Seiler, Nurnberg, Germany, assignor to International Standard Electric Corporation, New York, N. Y., a corporation of Delaware

Application April 5, 1950, Serial No. 154,064

Claims priority, application Germany April 6, 1949

4 Claims. (Cl. 117—106)

Unlike the large variety of point-type rectifiers (crystal diodes) there are only a few combinations of metals and semiconductors which exhibit a surface-type rectifying effect. Schottky's analysis of semiconductor rectification (see f. i. Zeitschrift für Physik, vol. 118, 1942, pp. 539–592) sets forth several reasons which may serve to clarify this fact.

(1) The relative impurity concentration throughout the semiconductor should be a minimum in the zone of increased resistance immediately adjacent the metallic electrode, in order to avoid short-circuits. Any increase in the number of impurities in this zone means great probability of short-circuits due to so-called by-passes.

(2) In the adjacent semi-conducting zone, however, adequate conductivity has to be provided by lattice-disturbing (impurity) atoms sufficient in number to greatly accentuate the zone mentioned in paragraph (1) where the so-called borderline effects take place.

To fulfil this requirement the disassociation level of the impurity atoms should be low (the impurity atoms should not diffuse readily), while the mobility of the electric carriers should be high. That only a few surface-type rectifications effects have been realized so far, derives from the fact that these two demands have not, or have hardly, been possible of fulfilment so far, for the known methods of making specified layer patterns are based exclusively on such processes where the space distribution of the impurities, is only obtained by modifications introduced by a secondary process by removing impurities at a suitable temperature, by chemical reaction (f. i. dissolving, lacquer-layers applied later on, etc.). Hence in making some specified layer pattern, the substances intended to produce the desired effects are placed at their respective locations in a first operation where no attention can be paid as to obtaining any specified space distribution of impurities, while that specified distribution, essential for proper performance, is brought about only subsequently in a second process governed by laws different from those of the first one. Thus one has been forced to simply accept as given whatever impurity concentration and distribution resulted from that second process without the possibility of introducing such corrective action of one's own as might be desirable to secure optimum distribution of impurities across the layer. With regard to the fact that very delicate arrangements are involved with layers present only as extremely thin films, it is obvious that the probability of inadequate results is rather large if these two essential processes are practiced one after the other.

In rectifiers involving compound-type semiconductors (in particular cuprous oxide) this fact is particularly pronounced as here the change in impurity concentration is caused by a chemical reaction which in turn is to introduce the stoichiometric unbalance of the semiconductor compound.

Generally a high impurity concentration is provided in the zones of the semiconductor more remote from the metallic electrode. But a certain maximum impurity concentration should not be exceeded in the zone of the semiconductor immediately adjacent the metallic electrode. This means that along the main direction of current flow the impurity concentration will have to obey a specified functional law, i. e. the dependence of the impurity concentration at a particular layer level will depend on the distance between that layer and the metallic electrode. This distance, however, is extremely small so it is obvious that rather erratic results are liable to occur in the few processes available for controlling the impurity concentration.

The drawbacks of the known methods are avoided in this invention by providing that the ultimate structure of the layer pattern is no longer obtained from two independent individual processes, but that the basic and the impurity substances are deposited simultaneously on the provided foundation, and that the specified relative impurity concentration is controlled to fit the needs of each particular layer while the layer is being built, so the desired space distribution of impurities is brought about.

It is known that the elements boron, silicon, germanium, and tellurium have semiconducting properties. In view of the delicacy of the processes to be controlled, the degree of chemical purity of the substances coated on the foundation electrode is of outstanding importance in making rectifiers.

In order to achieve uniform results and to control the porportion of the impurity admixture, it might seem desirable to vaporize the semiconductor materials and the impurity substances and deposit them from the vaporous state onto a suitable foundation. However, due to the high vaporizing temperatures of the materials involved there is induced the hazards of chemical reactions of the basic material or even the impurity contents with the material of the crucible which would produce uncontrolled and undesirable effects on the rectifying properties.

In order to avoid such high temperatures in production, one starts out in the known way from a liquid compound of the elements involved which by chemical rectification and customary chemical purifying methods can be prepared with a very high degree of purity and which in turn may be reduced chemically under proper conditions upon reaction with some equally pure reducing agent. Simultaneously with this reduction, the impurity substance may be treated in the same manner. With the relatively ample choice present in selecting admixtures to semiconducting elements, there is usually found some suitable chemical reaction mechanism which enables simultaneously synthesizing the impurity admixture. In a functional schematic, the nature of the process to be adopted is indicated in Fig. 1. A, B, C, and D refer schematically to devices where the substances needed for assembling the rectifying layer are obtained in their purest form by available processes according to what has been described above. As indicated schematically, these substances are then fed through pipes L_a, L_b, L_c, and L_d to the device E where the layer pattern is formed. In Fig. 1, these pipes L_a and L_b directly feed the device E with no prior intermixing of the substances being possible. Of course, one, two, or even all of the pipes could be joined in a common duct whenever intermixing of the substances is desired or permissible at such a relatively early stage of the production process. Equally in a schematic manner are shown control mechanisms R_a, R_b, R_c, and R_d at some arbitrary point along the ducts which allow any desired decrease or increase in the feeding rate of any of the ingredients while the semiconducting system is being built up. It is by no means essential that these controlling devices be inserted somewhere between the units A and E, B and E, etc., these controlling facilities may as well be incorporated straight in the units A, B, C, D or any additional units that might be present. Care will have to be taken, however, to prevent undesired reactions on the other devices B, C, D whenever at the junction of the pipes or individual pipe ducts the gas or vapor rate of device A is increased.

To practice this method, the elements boron, silicon, germanium, or tellurium may be used because of the high mobility of their electric carriers. To provide optimum efficiency, the impurity concentration at the back or counterelectrode is chosen large enough to prevent virtually any barrier layer from forming there.

As an example of the preparation of the semiconducting substance in building of a layer pattern, silicon may be reduced with hydrogen from silicon, tetrachloride or with zinc, in order to obtain pure silicon.

It is also known that the elements which are left and

Figure B.85: Karl Seiler and Paul Ludwig Günther designed and fabricated silicon electronic devices during the war, and filed patents on silicon transistors after the war (likely based on wartime work).

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right, respectively, of silicon in the periodic table of elements act as acceptors and donors, respectively, in the semiconductor. To synthetize a surface-type rectifying silicon layer, the basic material (silicon) and the impurity admixture (for example boron) are reduced simultaneously under the equations

$$SiCl_4+2H_2 \rightarrow Si+4HCl$$
$$2BCl_3+3H_2 \rightarrow 2B+6HCl$$

The production setup will have about the appearance outlined in Fig. 2. In the reaction oven O, the reaction product deposits on a conducting foundation, (for example, carbon, or other high-melting material not alloying with the basic material) or on some insulating foundation (aluminum oxide, or similar substances).

As boron is used in very low concentrations only, one preferably uses a mixture of boron chloride and silicon tetrachloride in the second feeder current.

Silicon may be provided with a small percentage of tin or germanium by adding $SnCl_4$ or $GeCl_4$ to the flow of $SiCl_4$.

Other methods of introducing into the reaction the impurity material may consist for example of thermal decomposition out of a suitable compound or in adding it as an element to the outgoing flow.

The essential feature is that the impurity concentration is open to any programmed control during the building-up of the semi-conducting layer.

In a similar way one may make surface-type rectifying discs from germanium, by reducing germanium tetrachloride along with tin tetrachloride or silicon tetrachloride or boron chloride in the presence of hydrogen, or by adding arsenic or antimonium to the current in the shape of a compound of these elements, with hydrogen.

The reducing agent will be so chosen that small amounts of it when dissolved, in the semiconductor will not result in any marked degree of conductivity, or that if such is the case they will cause if possible the kind of conductivity that is wanted anyhow when adding the impurity. Hydrogen is a reducing agent of relatively very neutral character.

In case some metal having relatively high vapor pressure is being reduced, such as zinc, one may operate without a flow. In Fig. 3, O refers to an electrically-operated tubular oven with two separate windings in series-connection. In the rear section, zinc vapor is generated which flows in the opposite direction to the mixture of silicon tetrachloride and boron chloride, or silicon tetrachloride and germanium tetrachloride, the fractional composition of which may be varied any time. In the reaction zone are again the bases on which the semiconducting material deposits. These mentioned methods may be extended to boron as well.

Another example is illustrated in Fig. 4, which however shows only the part indicated by E in Fig. 1. In the inner tubing R_i, closed at one end—when required it may also be open at either end—there is fed from one side simultaneously some halogen compound or halogen compounds of the basic material as well as of the impurity material at suitable rates which undergo control during the reaction process as desired, and they are brought to reaction with some material reacting with either halogen (i. e. with that of the basic material as well as with that of the impurity material) so they deposit on bases placed in the reaction zone at a point where reducing material is not, or almost entirely not, deposited.

Thus pipe R_i may for instance be entered from the left by silicon tetrachloride and boron chloride while at the right aluminum is vaporized, so that from the right aluminum vapor or low-order aluminum halogens flows in a current opposing that of the aforenamed compounds. In the reaction zone, aluminum chloride is formed which has to flow left through the open end of the tube in a countercurrent to the entering substances. The carriers or bases are then placed in such a section of the reaction zone where no aluminum deposits as in this process it is boron that has to serve as the impurity admixture. If required, even tin or germanium may be deposited as impurity substances.

Tube R_i is surrounded by some outer shell R_a to which the vacuum pump connects at the right. The entire assembly is accommodated in an oven (not shown).

As obviously the halogens entering the tube and those leaving it pass each other in opposite directions, it is convenient to direct these opposite flows by appropriate

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partitions. One may thus for example, partition the tube up to the reaction zone by a horizontal wall to feed silicon halogen and boron halogen in the lower half while the upper half serves for the return of the formed aluminum chlorides. Again, one may take to a concentric subdivision of tube R up to the reaction zone, in order to feed through the inner tube silicon tetrachloride and boron chloride, and to remove through the concentric ring space the halogens produced in the reaction. But one may even avoid this opposite current pattern by designing all of the rectifier-making process as a like-current operation, with all of the agents participating in the reactions passing through the tube left or right in the same direction of flow. In this case, and in the selected example, aluminum or low-order chlorides of aluminum would be fed from the left to the reaction zone in a vaporized state through an extra duct, while all of the ingredients and those substances as are set up leave to the right with of course the depositing pure basic and impurity substances settling out somewhere at a suitable place on appropriate deposit-carriers. With the described process, one not only can expect uniformity of the output material, but there is further facilities for making rectifiers with optimum properties by varying the percentages of the mixing basic and impurity substances.

In addition to aluminum, as a reducing agent there may be used zinc, hydrogen, etc. With aluminum as a reducing agent, the drawback is encountered that tube R_i in Fig. 4, which is conveniently made of quartz, is corroded by aluminum so it becomes useless before long. This even introduces changes in the reaction conditions which even may lead to a displacement of the reaction zone. To avoid this, the aluminum is conveniently inserted in a short tubular socket of sintered corundum—aluminum oxide—so the quartz tubing is protected.

The process of the present invention permits making surface-type rectifiers with entirely symmetrical electrical characteristics (so-called limiters), if the local impurity concentration is held low not at the outside (i. e. the interface to an adjacent electrode) but in the center-layer of the semi-conductor. Fig. 5 shows the overall structural pattern of such a limiter where the impurity concentration is minimized in the center-layer over a layer thickness d. The thickness of the marginal zone bordering at the low-concentration zone is some 10^{-7} centimeters, or a few atoms across.

The effect of the thickness d of the low-concentration zone on the properties of the limiter, i. e. on the diffusion voltage level V_d (cutoff-voltage) is shown in Fig. 6. The current J has been plotted versus the voltage, and this for two different values of d. Herewith, $d^{(2)}$ exceeds $d^{(1)}$, so even $V_d^{(2)}$ exceeds $V_d^{(1)}$.

Particularly interesting is a layer pattern which results in a transistor effect. To this end it is essential that the type of electric carriers changes right under the surface. Electron-conducting germanium crystals (n-type) which at the surface are modified for hole-conduction (p-type) have been described. This structure gives rise to a barrier layer at the interface of the n-type and p-type conducting germanium layers so the current of the emitter electrode is forced radially into the surface. It is only then that the barrier layer under the collector is so affected that the known power-amplifying control of same takes place.

In making such a transistor, known techniques start from solid n-type conducting germanium and then the surface is made p-type conducting by some particular treatment thereof. Such surface treatment obeys laws of its own, so only in the most exceptional cases will it perform the conversion from the n-type to the p-type in the way required for optimum transistor operation. Hence, it is advantageous as provided in this invention to assemble a transistor from its basic elements so that on the foundation there is first applied the layer of the basic material (such as germanium), along with a donor causing electron conduction, with the change in the type of conduction subsequently brought about in that the donor, at a specified stage of the layer-assembly, is replaced by an acceptor, which causes hole-conduction in the basic material when it is deposited along with the latter. One also may begin by making a p-type conducting foundation to coat it subsequently with a thin n-type conducting film.

I claim:

1. In the method of making semi-conductors each having a plurality of different conductivity zones therein, the

Figure B.86: Karl Seiler and Paul Ludwig Günther designed and fabricated silicon electronic devices during the war, and filed patents on silicon transistors after the war (likely based on wartime work).

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steps of simultaneously depositing from the vapor state onto a base material a semi-conducting substance commingled with an impurity substance selected from a group consisting of donor and acceptor impurities, and varying the proportion of said substances while applying them to the base in the form of a composite layer of said substances graduated in its cross-section as between amounts of the two substances applied.

2. Method according to claim 1, in which the semi-conducting substances are chosen from the group consisting of boron, silicon, germanium and tellurium.

3. Method according to claim 1, in which the highest amount of impurity substance is applied adjacent the base material.

4. Method according to claim 1, in which the lowest amount of impurity substance is placed in the center portion of the layer.

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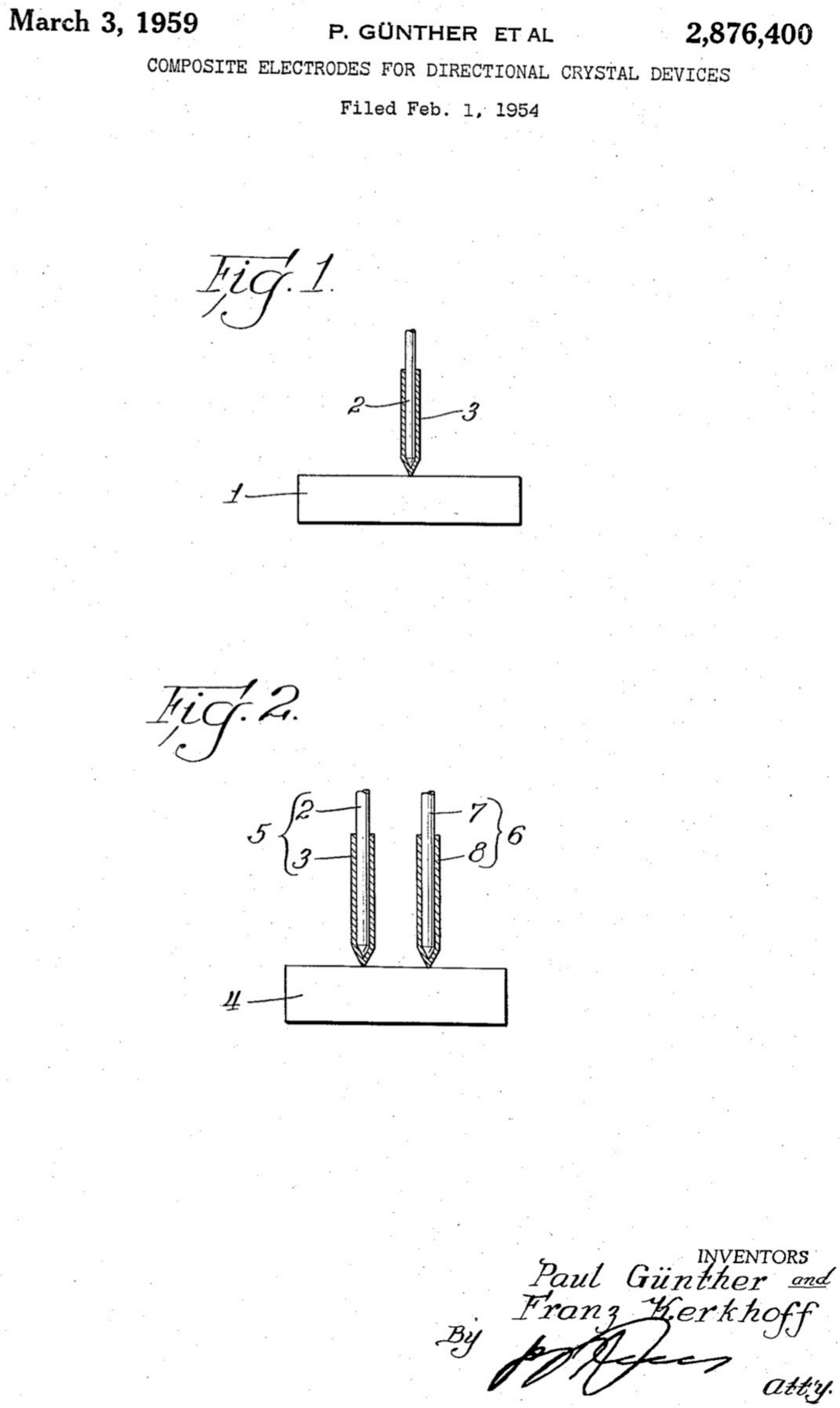
Figure B.87: Karl Seiler and Paul Ludwig Günther designed and fabricated silicon electronic devices during the war, and filed patents on silicon transistors after the war (likely based on wartime work).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COMPOSITE ELECTRODES FOR DIRECTIONAL CRYSTAL DEVICES

Filed Feb. 1, 1954

Figure B.88: Karl Seiler and Paul Ludwig Günther designed and fabricated silicon electronic devices during the war, and filed patents on silicon transistors after the war (likely based on wartime work).

United States Patent Office

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Patented Mar. 3, 1959

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COMPOSITE ELECTRODES FOR DIRECTIONAL CRYSTAL DEVICES

Paul Günther and Franz Kerkhoff, Munich, Germany, assignors to Siemens & Halske Aktiengesellschaft, Munich, Germany, a corporation of Germany

Application February 1, 1954, Serial No. 407,196

Claims priority, application Germany February 27, 1953

11 Claims. (Cl. 317—235)

This invention is concerned with composite electrodes for directional devices comprising semi-conductors, for example, transistors and the like.

Composite electrodes for the purpose and of the type noted above are generally known. It is likewise known to form on such electrodes preferably point-shaped or knife-edge contacts of a hard core which is provided with a coating of another generally softer material, the latter being more suitable than the core material to form electrical contact engagement with a semi-conductor crystal. Such a known electrode may, for example comprise a tungsten wire plated with platinum. The drawback of such structure is that it is impossible to provide upon tungsten a sufficiently uniform platinum coating and that it is consequently impossible to produce such electrodes with the required uniformity in the course of customary mass production processes.

It has been found by research lying in back of the invention that the above mentioned drawbacks can be avoided by using other particular materials. In accordance with the invention, electrodes of the previously indicated type which comprise at least two different materials, for example, a core or carrier and a coating, are made of metals from the first, fourth, fifth and/or eight groups of the periodic table of elements. More specifically a hard material as for example niobium, tantalum, iron or alloys of such materials, for example, hard bronze of the type of phosphor-beryllium-bronze or the like may be used primarily for the core of the electrode; and for the coating may be used primarily materials of high output capacity, for example, rhodium, palladium, iridium, also platinum or, under some circumstances alloys of these materials. In the case of using in a transistor a plurality of electrodes, for example, two or three electrodes, the selection of the material for the surface coating will depend upon whether the electrode is to be employed as a collector or an emitter.

The invention will now be described with reference to the accompanying drawings showing in diagrammatic representation examples thereof. In these drawings,

Fig. 1 shows a germanium crystal coacting with a single point contact electrode; and

Fig. 2 illustrates a transistor comprising a germanium crystal coacting with two point contact electrodes.

In Fig. 1, numeral **1** indicates the germanium crystal. In contact engagement with the surface of the crystal is a point electrode comprising a wire **2** of phosphor-beryllium-bronze provided with a platinum coating **3**. The electrode is produced by providing upon the bronze wire, for example, in an alkaline ammonia phosphorous platinum bath of platinum coating in galvanic manner.

Fig. 2 shows a transistor comprising a germanium crystal **4** coacting with two point contact electrodes **5**

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and **6**. Between the electrodes, a p-n layer is provided in a known manner. The electrode **5** is made like the electrode of Fig. 1, comprising a bronze core with a platinum coating **3**. The other electrode **6** comprises a steel core **7** covered by a copper coating **8**.

The coatings may be applied or provided in different manner than galvanic, for example, by vaporization, by cathode vaporization, or in mechanical manner, for example, by spraying or rolling. Burning such as is usually applied in the production of mirrors, ceramics, etc., is recommended for mass production.

What is believed to be new and desired to have protected is defined in the appended claims.

We claim:

1. A transistor comprising a crystal, in electrode in point contact with said crystal, said electrode including a core and a coating surrounding said core, said core formed from one or more metals of the group consisting of niobium, tantalum, iron, copper, tin, zinc, phosphorous, beryllium and alloys of the aforesaid metals, said coating formed from one or more metals of the group consisting of rhodium, palladium, iridium, platinum and alloys of the aforesaid metals, and said coating of said electrode in point contact with said crystal.

2. A transistor according to claim 1, wherein said core of the electrode comprises a hard bronze of the type of phosphor-beryllium-bronze.

3. A transistor according to claim 1, wherein said core of the electrode is formed of a hard bronze of the type of phosphor-beryllium-bronze, and said coating is formed of platinum.

4. A transistor comprising a crystal, at least two electrodes in point contact with said crystal, p-n layer provided in said crystal between the electrodes, one of said electrodes comprising a phosphor-beryllium-bronze core and a platinum coating, the other of said electrodes comprising a steel core and a copper coating, and said coatings of said electrodes in point contact with said crystal.

5. A composite electrode for a directional crystal device, said electrode provided with a point at one end for point contact with a crystal and comprising a core and a coating surrounding said core, said core formed from one or more materials of the group consisting of tantalum, phosphor-beryllium-bronze and steel, said coating formed from one or more materials of the group consisting of the elements of group eight of the periodic table of elements and consisting of rhodium, palladium, iridium and platinum.

6. A composite electrode according to claim 5, wherein said composite electrode may be used in a diode.

7. A composite electrode according to claim 5, wherein said composite electrode may be used as an emitter in a transistor.

8. A composite electrode for a directional crystal device said electrode formed with a point at one end for point contact with a crystal and comprising a steel core and a copper coating surrounding said core.

9. A composite electrode for use as a collector, said electrode comprising a core and a coating surrounding said core, said core formed from one or more materials of the group consisting of tantalum, phosphor-beryllium-bronze and steel, and said coating comprising one or more materials of the group consisting of copper and tin.

10. A semi-conductor device of the transistor type including a directional crystal, a composite electrode for point contact with said directional crystal, said composite electrode comprising a phosphor beryllium-bronze

Figure B.89: Karl Seiler and Paul Ludwig Günther designed and fabricated silicon electronic devices during the war, and filed patents on silicon transistors after the war (likely based on wartime work).

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core and a platinum coating surrounding said core, and said coating complementally formed to said core and formed for point contact with said directional crystal.

11. A semi-conductor device according to claim 10, comprising a second composite electrode for point contact with said directional crystal, said second composite electrode comprising a steel core and a copper coating surrounding said core, and said coating of said second composite electrode complementally formed to said core and formed for point contact with said directional crystal.

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Figure B.90: Karl Seiler and Paul Ludwig Günther designed and fabricated silicon electronic devices during the war, and filed patents on silicon transistors after the war (likely based on wartime work).

[**11. Helmar Frank (Moravian, 1919–2015) and Jan Tauc (Bohemian, 1922–2010)** worked in very large, highly secret, German-run laboratories in Tannwald (now Tanvald, Czech Republic) during the war [Lojek 2007]. When Czechoslovakia salvaged what was left of those laboratories and restarted them after the war, one of the first actions that Frank and Tauc carried out was to produce and demonstrate transistors. Those postwar Czech transistors were based at least in part, and quite possibly entirely, on wartime German work. See for example:

pp. 1050–1072

pp. 2756–2757

p. 3983

p. 5503

p. 5513

p. 5549

Both Frank and Tauc continued to develop semiconductor and microelectronics technologies in Czechoslovakia for many years. Frank was interrogated by the United States in 1945 regarding his knowledge of advanced electronics technologies. Tauc eventually moved to the United States.

12. Bernhard Gudden (German, 1892–1945) and Kurt Lehovec (Bohemian/Austrian/ Czech, 1918–2012) ran a secretive and well-funded group that was developing advanced semiconductor devices at Charles University in Prague during the war [Lojek 2007]. After the war, Gudden refused to assist Russian or Russian-backed forces and died in a Czech prison. Lehovec was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits. His first U.S. patent application on transistors covered a design that had several advantages over the transistors from Bell Laboratories, and that may well have been based on wartime work that he and Gudden had been conducting. See for example:

p. 1074

p. 1097

pp. 2757–2763

pp. 2818–2832

pp. 2895–2910

Historians should conduct much more archival research on the history and accomplishments of the wartime microelectronics programs at Bohemian/Moravian/Czech laboratories such as those where Helmar Frank, Jan Tauc, Bernhard Gudden, and Kurt Lehovec worked. Historians should also investigate the many ways that numerous countries benefitted after the war from scientists, information, and materials from those wartime programs.]

Czech National Library of Technology. Professor Helmar Frank. English translation. [https://www.techlib.cz/cs/84002-profesor-helmar-frank]

Helmar Frank was a Czechoslovak physicist of German nationality. He graduated in the Czechoslovak Republic and the Protectorate of Bohemia und Moravia, worked at the German University in Prague, the Institute of Physics of Charles University in Prague, the Research Institute of Communication Technology in Prague and since 1968 he worked as associate professor and later professor at the Faculty of Nuclear and Physical Engineering Technical University in Prague.

He created the first Czechoslovak semiconductor amplifying component—the point-contact germanium transistor—and developed, initiated and helped to introduce production of semiconductor materials and components in many Czechoslovak factories. [...]

1940–1942 scientific assistant at the Institute of Physics of the German University in Prague

1942–1945 lecturer Prof. Gudden at the Institute of Physics of the German University in Prague

1945–1947 detained by the Czechoslovak army in the framework of reparations

1947–1950 employed as a civil contract employee of the Military Technical Institute with a workplace in the Institute of Physics of Charles University

1950–1968 employed as an independent researcher at the Research Institute for Electro (tech) Physics. (VÚPEF, later VÚST)

1968–1983 Associate Professor, Department of Solid State Engineering, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague (KIPL FJFI ČVUT)

1972–1981 Head of the Department of Solid State Engineering

1973 appointed Chairman of the Board for the Defense of Candidate Dissertations, Chairman of the State Examination Board for the State Final Examinations, elected Vice-Dean for Science and Foreign Relations;

1983–2008 professor at FNSPE CTU

1950–2009 lectures and cooperation Faculty of Mathematics and Physics, Charles University in Prague, Technical University of Dresden, University of Regensburg, GSF Munich, Slovak Technical University in Bratislava, cooperation with CKD Semiconductors Prague, Tesla Vrchlabi, Prumet Sumperk, Tesla Roznov, Tesla Piestany

***Jan Tauc 1922–2010.* National Academy of Sciences 2011 [https://nas.nasonline.org/site/DocServer/Tauc_Jan.pdf]**

Jan's first job after graduation was at a government-supported research institute with a mission to develop electronic technologies (such as television and microwaves), using equipment and documentation left behind by the German army and declassified information from the West that became available after the war. The institute was located first in Tanvald, a mountainous region of northern Bohemia, which was the location of the former German army center. There Jan became involved in microwave detectors that the Germans had developed for the 10 cm wavelength band, using germanium. When the news of the invention of the transistor reached Prague, he used the germanium of those detectors to build the first point-contact transistor in Czechoslovakia and decided to stay in that field.

Bo Lojek. 2007. *History of Semiconductor Engineering.* Berlin: Springer. pp. 195–204.

Czech-born Kurt Lehovec started his career during World War II at Charles University in Prague as a Ph.D. student of Prof. B. Gudden (B. Gudden graduated and worked under Prof. Pohl). Kurt's Ph.D. study focused on lead-selenide as an infrared detector. During the course of this research, he noticed that Thallium diffused into Selenium very rapidly and the "blocking effect" of the rectifier was significantly improved. Süddeutsche Apparate Fabrik in Nüremberg supported Lehovec's study. This association let Lehovec attend a secret scientific conference about "Material X" in 1942 in Munich. The code name, Material X, was used for Germanium, and Lehovec did not know what Material X was.

German military research maintained two research groups working on semiconductors in occupied Czechoslovakian "Böhmen und Mähren" territory: The Prague group headed by Prof. B. Gudden worked on the rectifying diode; a second and larger group worked in the small town of Tanvald in the North of Bohemia on microwave point contact diode and radar research. Many members of the German research groups, including Prof. Gudden, were killed in May 1945 during the liberation of Czechoslovakia by the Red Army. A major part of the Tanvald research facility was confiscated by the Soviet army and transferred to the Soviet Union; the rest of the inventory was set on fire and destroyed.

Several kilograms of Germanium survived the fire and were used by Jan Tauc and Helmar Frank to build the first European [sic—actually the first Czech] transistors in 1949. Jan Tauc later immigrated to the United States. Helmar Frank, who was also a student of Prof. Gudden at Charles University, directed post-war semiconductor research sponsored by the Czechoslovakian Army at the former Philips Laboratories in Prague.

During the war the British Intelligence Assault Unit 30AU identified prominent scientists involved in German research. [...] At the end of the war, the CIA and KGB quickly joined the British effort and transferred several researchers from the Prague and Tanvald research groups to their respective countries. The CIA with U.S. Joint Intelligence Objectives Agency (JIOA) executed the Project Paperclip, and picked up Kurt Lehovec. Under very dramatic circumstances, when the Red Army began the liberation of Prague, and when hours not days made a difference, Lehovec peddled on a bicycle with his tennis racquet from Prague to the American occupied zone. Later, he was deported as a Paperclip item in a U.S. Navy ship to the Squier Laboratory at U.S. Signal Corps in Fort Monmouth in New Jersey.

The thinking behind project Paperclip was exemplified in a letter Major General Hugh Knerr, Deputy Commanding General for Administration of U.S. Strategic Forces in Europe, wrote to Lieutenant General Carl Spatz in [June] 1945: "*Occupation of German scientific and industrial establishments has revealed the fact that we have been alarmingly backward in many fields of research, if we do not take this opportunity to seize apparatus and the brains that developed it and put this combination back to work promptly, we will remain several years behind while we attempt to cover a field already exploited.*"

[...] Lehovec arrived at the U.S. Signal Corps with physical chemists, Dr. Rudolf Brill and Ernst Baers, physicists; Horst Kedesti, Georg Hass, Georg Goubau, Günter Guttwein, and electrical engineers; Hans Ziegler, Eduard Gerber, and Richard Guenther. From 210 Paperclip scientists the Signal Corps utilized 24 scientists, all involved in radar and communication research. The rocket scientists ended up in White Sands.

[...] In 1959, Ziegler became the Chief Scientist of U.S. Army Signal Corps' Laboratories at Fort Monmouth, N.J. After the Army's re-organization, he was appointed in 1963 to Deputy for Science and Chief Scientist of the US Army Electronics Command and in 1971 to Director of the U.S. Army Electronics Technology & Devices Laboratory. Dr. Ziegler was also a Fellow of the IEEE and the American Academy of Science. The Army recognized his achievements with two Meritorious—and the coveted Exceptional—Civil Service Awards. [...]

Lehovec asked the chief scientist of Squier Laboratory, Dr. Golay, what his research project should be, and he received the answer: "*you can do whatever you want, we need everything.*" Lehovec was one of the youngest members of the Paperclip team, and he worked very hard from day one. His group was assigned to the "Institute of Advanced Study" and had about 10 members. In 1948, Lehovec was sent to Purdue University to visit Prof. Lark-Horovitz's group to discuss ongoing research with the Signal Corps. With Dr. Harold A. Zahl, the Chief Scientist of the Signal Corps, Lehovec visited Bell Laboratories and started the Army's research on silicon and germanium devices, primarily on the problems of light emission from solids.

From his Prague studies he was familiar with the work of Russian scientist O. Lossew on "cold" light emission, first observed in silicon carbide in 1907. This effect, which was manifested by passing current through selected crystals of silicon carbide, showed a type of light emission which remained unexplained. Dr. Carl A. Accardo remembered when he was approached by Lehovec with an inquiry "*if I would be interested in studying the effects with him and his co-worker Edward Jamgochian.*" Their research indicated that the produced light was due to the recombination of electrons and holes across a so-called p-n junction. The two articles authored by Lehovec, Accardo and Jamgochian appeared in Physical Review and were presented at the American Physical Society in New York. The articles provided the theoretical background and an explanation of what later become known as LED's, or light emitting diodes.

Lehovec was a principal and reviewer of Semiconductor Research Contract DA36-0390SC 71131 between the U.S. Signal Corps and Prof. Karl Lark-Horovitz's group at Purdue University. During 1949–1950 Lark-Horovitz and R. Bray investigated the effect of strong electric fields on the observed spreading resistance of metal-germanium point-contact rectifiers. Some of these experiments closely resembled the work carried out simultaneously at Bell Telephone Laboratories by Bardeen, Brattain, and Shockley. [...]

Lehovec set up laboratory production in record time and he was on a mission. His goal was not to duplicate Bell Telephone Laboratories devices. He wanted to be an innovator, not a follower. He noticed already at the Signal Corps that the only drawback of the silicon devices was lower mobility of free carriers, which would make the devices somewhat slower compared to the germanium devices. Kurt Lehovec realized that the only way to overcome this disadvantage was to make the device smaller. However, to manufacture small devices in the beginning of the nineteen fifties was not an easy task. In addition, Sprague's management philosophy was, "*if this is any good, Bell would have done it already.*"

Lehovec found two basic problems with the Bell point contact transistor which the Sprague Company licensed:

1) Tedious labor to manipulate under a microscope two tiny wires to the correct position.

2) The possibility of sliding of the wires during the handling the device.

Lehovec came up with an ingenious solution to these problems which Armen Fermenian put into practice, a narrow sheet of beryllium copper was guided over a ceramic frame and glued to it. Two metal chisels cut the sheet within the frame providing the triangular shapes with sharp points facing to each other. A plunger then bent the tips of the triangles into vertical position at the desired spacing of the point contacts.

Lehovec visited Bell Labs and showed a transistor to Jack Morton. Morton was very impressed with Sprague technology and considered an order of a large number of devices for Western Electric. The deal was, however, aborted by Sprague management. The next major improvement of transistor technology was the introduction of new "capillary alloying" for junction transistor. This method allowed to calculate the amount of germanium dissolved in the indium from the germanium-indium phase diagram at the given temperature, and thus to control the junction depth. In addition, the surface-melt technique enabled the production of multiple junctions in a single slice of semiconductor. The method was superior to the BTL and TI grown-junction transistor process, which could produce only PNP or NPN structures. [...]

Another of Lehovec's major inventions, junction isolation, had a very interesting background. Lehovec attended a workshop at Princeton University in the end of 1958. Torkel Wallmark of RCA presented in this workshop a visionary presentation about the next generation of electronics. Wallmark listed problems that needed to be solved before integrated circuits could be designed. One of these limitations was device isolation. Lehovec, educated from his work on the surface-melt multiple-junction devices found a solution while driving his red Corvette—PN junction isolation.

The engineering problem was solved; the bigger problem remained to be overcome. At that time nobody had heard anything about integrated circuits, so only visionaries could have appreciated the importance of Lehovec's invention. The Sprague Company did not have visionaries and they did not want to file a patent application. Sprague's patent attorney, Hillary Sweeney, explained at great length to Lehovec, that a patent needed to have a docket number and must be in sequence with previous disclosures, and that he was too busy to do it. Lehovec wrote the patent application himself and mailed it to the Patent Office. After months, a persistent Lehovec finally prevailed. His patent was approved and issued by the Patent Office without a major objection. Immediately after the patent 3,029,3662 was issued, Al Bower, of the patent firm Connolly & Hutz that handled the Sprague patents, called Lehovec that Texas Instruments is suing Sprague for patent interference. [...]

Texas Instruments set up the interference proceeding hearing in a large conference room and equipped Kilby with double digits of TI's attorneys. Sprague Company was represented by Attorney at Law, Mr. Hutz, and Kurt Lehovec. [...]

The whole Texas Instruments séance ended as a complete debacle, and attorney Hutz was asked to deliver a written summary of arguments presented at the hearing. Three weeks later the U.S. Patent Office decided that Lehovec was entitled to all patent claims and was awarded patent priority.

Harold Zahl, a retired Director of the U.S. Army's Fort Monmouth laboratory [Zahl 1968, pp. 108–109]

On "Project Paperclip" it was not pieces of equipment or missiles which were brought over from Germany, it was people—scientists, engineers, and families. In the cruel years immediately following the war there were many very able scientists and engineers who wished to leave Western Europe and make a new home in the United States.

"Screening" offices were accordingly set up in Europe, and applications studied very carefully as to ability and previous political interests. Simultaneously military laboratories in this country were asked whether they wished any of these people, and their dossiers were made available for decision purposes.

As most elsewhere, at Monmouth we had two problems: First, the war still remained very fresh in the memories of our people; and second, we were still releasing relatively unskilled American citizens. But the superb talent available through "Paperclip" suggested once-in-a-lifetime opportunities, and much of the top American talent was straining to get out of the military environment back to their teaching jobs or to industry.

Demonstrative of the type of talent we were dealing with, on each request the requester had to sign a statement to the effect that the equivalent to the person he was asking for was not available in the U.S. The problem of asking for this type of talent, or rather the decision as to whether we should, was put squarely up to me as director of research. I recommended "Yes, let's try it with 25 people," and we were in business. This was probably one of the most important decisions I have ever made.

The men and their families then started coming over, most of them with all their worldly possessions and hardly any money. The title of "Doctor" soon grew commonplace at Monmouth. In coming over, they were signed for a two-year contract, with our option to return them in six months if we for any reason found them unsatisfactory. After the contract expired, Civil Service regulations allowed them to change to what was called Schedule-A, a form of Civil Service which would be finalized once citizenship had been achieved.

I have in my office a photo of the first 16 which came over, hands up, swearing allegiance to the United States, as they moved into Schedule-A. Of these 16, now twenty years later, 11 still remain at the Monmouth laboratory, all in very high positions, and one in the very highest. It was a wonderful experience to see the old "Melting Pot" in action.

In retrospect, throughout the country we see thousands of our best citizens, able engineers, scientists, and administrators, with a byproduct of tens of thousands of brilliant children in our schools . . . the results of "Paperclip." Surely this country is better and stronger because of that decision, made by a few men more than two decades ago.

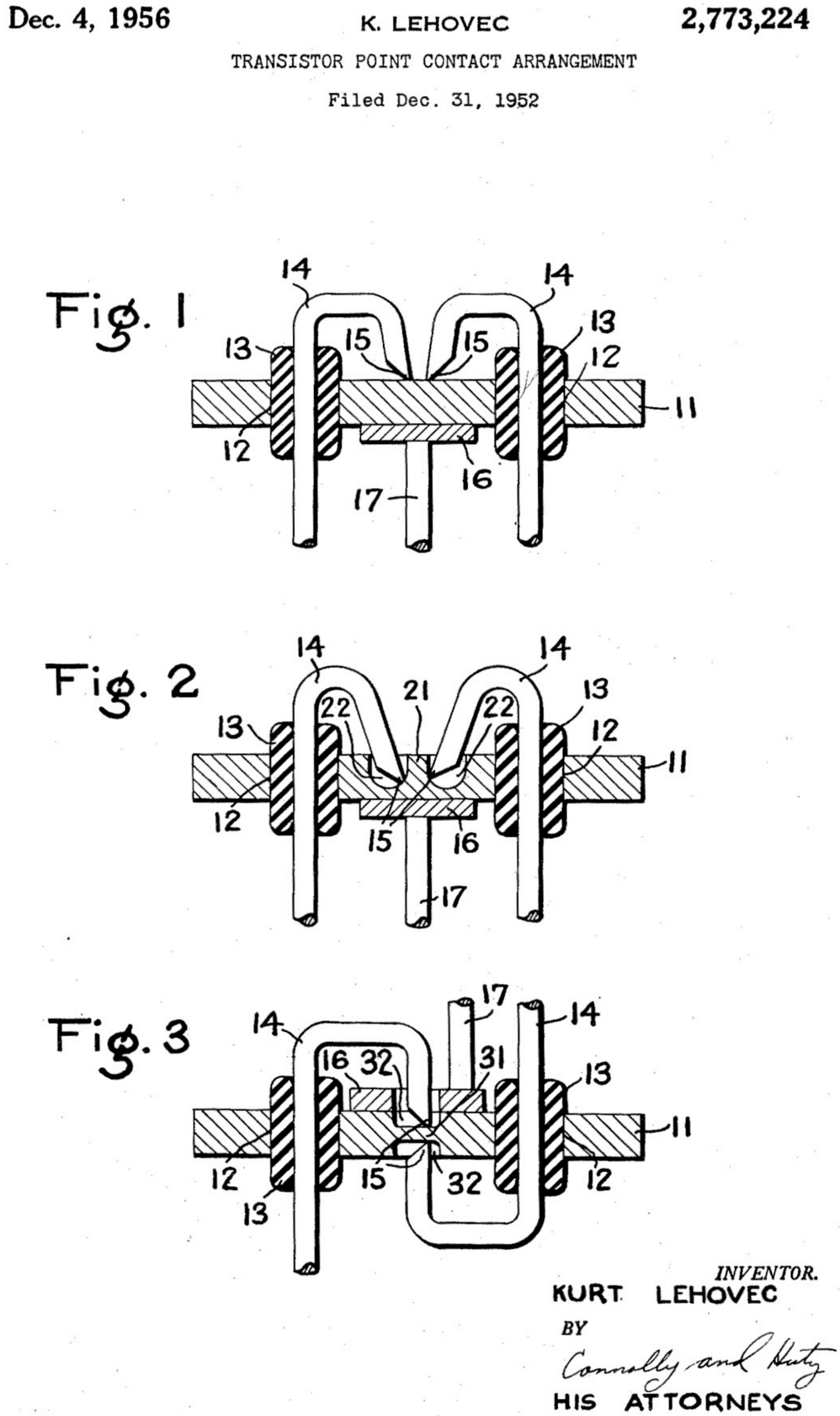

Figure B.91: Kurt Lehovec developed semiconductor devices for Germany during the war. After the war he was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits. In 1952, he filed a patent application on a transistor design that had several advantages over the transistors from Bell Laboratories.

United States Patent Office 2,773,224 Patented Dec. 4, 1956

1

2,773,224

TRANSISTOR POINT CONTACT ARRANGEMENT

Kurt Lehovec, Williamstown, Mass., assignor to Sprague Electric Company, North Adams, Mass., a corporation of Massachusetts

Application December 31, 1952, Serial No. 328,948

6 Claims. (Cl. 317—235)

The present invention relates to new and improved point contact constructions for transistors.

The field of transistors is now so well known that it is not deemed necessary to devote any of the present specification to purely descriptive matter relating to this subject. In this connection, reference is made to the text "Holes and electrons in semiconductors" by Schockley, the entire November 1952 issue of the Proceedings of the Institute of Radio Engineers, as well as other publications.

One type of transistor which presently shows a great deal of promise requires the use of two point contacts termed the emitter and the collector bearing against a single crystal of a metal such as germanium, silicon, or other related semiconducting materials. A third low resistance electrical connection is made to such a crystal. In order to obtain satisfactory operating characteristics with this type of construction the two point contacts must be positioned relatively close, and must remain in a comparatively fixed position.

It is now a common procedure to hold these point contacts or probes in place by the use of a small amount of tension and a stiff gel-like filler material. Other means for accomplishing the same result have been suggested. These include the use of stiff fabric-like inserts through which the probes are inserted; the use of an adjacent wall upon which the point contacts are mounted; and other means. The number of suggestions made on the subject of positioning wire probes in itself indicates the ineffectiveness of the presently used procedures.

An object of the present invention is to improve upon the aforegoing and related methods for positioning wire point contacts against a body of a semiconducting material used in a transistor. A further object is to produce new and improved transistor constructions. These and other aims of the invention, as well as the advantages of it will be apparent from the following description and claims, as well as the accompanying drawings in which:

Figure 1 diagrammatically illustrates a transistor formed in accordance with this disclosure; and

Figure 2 is a diagrammatic view of a modified construction of the invention; and

Figure 3 is a diagrammatic view of a still further modified construction. In all figures like numerals designate like parts.

In Figure 1 of the drawings a simple transistor construction is shown in which a small semiconducting wafer **11** such as, for example, a germanium crystal about 30 x 50 x 150 mils in size is provided with two apertures **12** through which wire probes **14** project. Each of these probes **14** is insulated from the wafer **11** by an insulating sleeve **13** of polyethylene or the like, and is bent so that the point contacts **15** touch the same face of the crystal quite close to one another. Preferably a space of from 1 to 5 mils separates them. A low resistance contact **16** of known type is made to the wafer **11** through the wire **17**.

The modification shown in Figure 2 of the drawing

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differs from the construction of Figure 1 solely in that the adjacent point contacts **15** are positioned upon opposite sides of a wall **21** in small cavities **22** formed within the wafer **11**. Preferably, this wall **21** should be from about 1 to about 5 mils thick. The construction shown in this figure has the advantage that with it the point contacts are not apt to be dislodged due to handling, as when encasing the entire unit in a protective insulating resin.

The same advantage is derived from the construction illustrated in Figure 3. Here the wire probes **14** are inserted through the holes **12** in the wafer **11** from opposite directions so that the point contacts **15** project towards one another within the cavities **32**, but are separated by the wall **31** which is preferably of the thickness previously indicated.

The various apertures and holes or cavities herein indicated can be found in a variety of methods known to the art, such as, for example, by the use of dental abrasive equipment.

The herein described invention has a number of advantages. Perhaps one of the most important of these is comparative ease with which it adapts itself to large scale production techniques. By one procedure a comparatively large flat body of a semiconductor can be provided with the apertures, holes, and/or cavities for a large number of transistors at the same time, the appropriate connections and probes indicated can be placed in position, and then the individual transistors actually formed by cutting the larger body. If desired, the initial block can be scored or perforated so as to assist in separating the individual units. Various known steps, not specifically indicated herein, such as, for example, etching can be carried out at any convenient stage in forming the units of the invention. Also, a construction similar to that shown in Figure 1 can be formed utilizing a very thin wafer with the point contacts positioned upon opposite sides of it in the broad manner indicated.

As many apparently widely different embodiments of this invention may be made without departing from the spirit and scope hereof, it is to be understood that the invention is not limited to the specific embodiments hereof except as defined in the appended claims.

What is claimed is:

1. A transistor comprising a body of a semiconducting material, means defining at least two closely-spaced apertures through said body, wire probe means passing through said apertures, insulating means separating said wire means from said body in said apertures, point contact means formed on the tips of said probe means, said point contact means forming rectifying contacts with parts of said body about 1 to 5 mils apart.

2. A transistor as defined in claim 1 wherein said contacts are both on the same face of said body.

3. A transistor comprising a body of a semiconducting material, means defining at least two closely-spaced apertures in said body, wire probe means passing through said apertures, insulating means separating said wire means from said body in said apertures, point contact means formed on the tips of said probe means and positioned within cavities upon the same face of said body, said point contact means forming rectifying contacts with adjacent parts of said body.

4. A transistor comprising a body of a semiconducting material, means defining at least two closely-spaced apertures in said body, wire probe means passing through said apertures, insulating means separating said wire means from said body in said apertures, point contact means formed on the tips of said probe means positioned upon opposed sides of said body, said point contact means forming rectifying contacts with adjacent parts of said body.

Figure B.92: Kurt Lehovec developed semiconductor devices for Germany during the war. After the war he was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits. In 1952, he filed a patent application on a transistor design that had several advantages over the transistors from Bell Laboratories.

2,773,224

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5. A transistor as defined in claim 4 wherein said point contact means are positioned within cavities.

6. A transistor sub-assembly comprising a body of a semi-conducting material, means defining at least two closely spaced apertures through said body, contact means passing through said apertures and contacting said body about 1 to 5 mils apart, and insulating means separating said contact means from said body in said apertures.

4

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UNITED STATES PATENTS

2,538,593	Rose	Jan. 16, 1951
2,547,386	Gray	Apr. 3, 1951
2,560,579	Kock et al.	July 17, 1951
2,648,805	Spenke et al.	Aug. 11, 1953

Figure B.93: Kurt Lehovec developed semiconductor devices for Germany during the war. After the war he was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits. In 1952, he filed a patent application on a transistor design that had several advantages over the transistors from Bell Laboratories.

B.2 Printed Circuits and Multi-Pin Connectors

[While moving from large vacuum tubes to small transistors greatly helped to miniaturize and simplify electronics, the development of printed circuit boards was another major step in microelectronics. In printed circuits, electronic components are attached to an insulating board that is covered with etched metal lines for wires, avoiding the labor and bulkiness involved in connecting separate physical wires to each component. A closely related technological development was multi-pin connectors, which could be used without printed circuits but became even more advantageous when used together with printed circuits.

As shown on pp. 2766–2777, Albert Hanson (German, 18??–19??) filed patent applications on printed circuits and multi-pin connectors in 1902 and 1903. From the available documentation, it is not clear how far he got in implementing his designs, although the highly detailed nature of the patents suggests that he may well have built and tested printed circuits and multi-pin connectors.

Mathias Nowottnick, an engineering professor at the University of Rostock, noted that printed circuit technology, apparently based on Hanson's patents, was being used by at least three German companies by 1927–1932 [Nowottnick 2014, p. 4]:

1927 Telefunken, Verdrahtung von Bauteilen mittels Messingstreifen.

1930 Hescho-Werke in Hermsdorf Aufdrucken von Leiterzügen auf Keramiksubstrat mittels Siebdrucktechnik (stellt heute noch die Grundlage für die Dickschichttechnik dar!)—"Gedruckte Schaltung".

1932 erste Leiterplatte mit genieteten Metallstreifen, Sachsenwerk Licht und Kraft AG [Fig. B.106]

1927 Telefunken, wiring of components using brass strips.

1930 Hescho Works in Hermsdorf Imprinting of conductors on ceramic substrate using screen printing technology (still the basis for thick-film technology today!)—"printed circuits."

1932 first printed circuit board with riveted metal strips, Sachsenwerk Light and Power AG [Fig. B.106]

Wolfgang Scheel, a longtime department head of the Fraunhofer Institute, named additional German companies that were among the first to use printed circuits [Manfred Frank 2003, p. 2]:

Lassen Sie mich zunächst feststellen, dass die Leiterplatte in diesem Jahr [2003] ihren 100. Geburtstag feiert. Der Berliner Hanson hat dafür das Patent 1903 angemeldet. Ferner möchte ich anmerken, dass als Pionierfirmen auf dem Gebiet der Leiterplattenentwicklung in Deutschland die Sachsenwerk Licht und Kraft AG Niedersedlitz, die Ruwelwerke Geldern, die Lackwerke Peters in Kempen und die Isola AG in Düren zu nennen sind.

Let me first note that the printed circuit board celebrates its 100th birthday this year [2003]. Hanson from Berlin filed the patent for it in 1903. I would also like to note that the pioneering companies in the field of printed circuit board development in Germany are Sachsenwerk Licht und Kraft AG Niedersedlitz, Ruwelwerke Geldern, Lackwerke Peters in Kempen and Isola AG in Düren.

Paul Eisler (Austrian, 1907–1992) studied engineering at the University of Vienna, graduated in

1930, and worked in electrical engineering, during which time he apparently became familiar with then-current German and Austrian printed circuit technologies that were based on Hanson's original patents. In 1936 Eisler fled to the United Kingdom, taking his knowledge of printed circuit technologies with him, and he immediately began building printed circuits upon his arrival there [Eisler 1989; Medawar and Pyke 2000].[4]

Eisler brought printed circuit technology to the attention of the British government during World War II and filed patent applications on it in 1944 (pp. 2779–2795). Some U.S. officials discovered Eisler's work and incorporated simple printed circuits into proximity fuses for artillery shells that were used in late 1944 and 1945, but otherwise Allied countries do not seem to have harnessed the potential of printed circuits during the war.

In contrast, as shown on pp. 2796–2799, printed circuits were in "wide use" in wartime Germany (apparently having grown far beyond just Telefunken, Hescho-Werke, and Sachsenwerk since ∼1930), and all of that printed circuit technology was transferred to the United States on a large scale after the war by people such as longtime Bell Telephone Laboratories engineer Todos Odarenko.

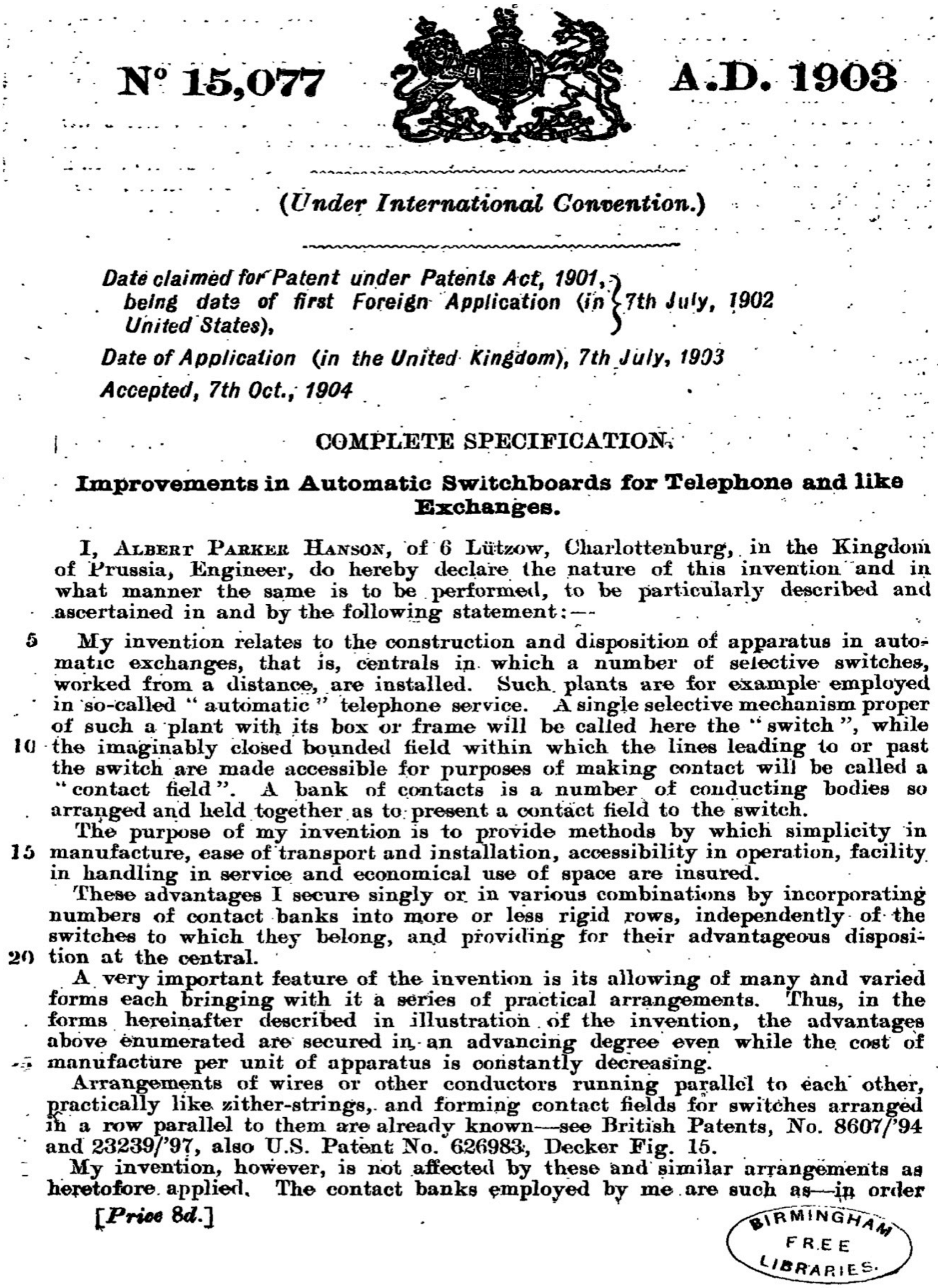
The final step in the development of printed circuits came when Rudolf Strauss (German, 1913–2001) developed the wave soldering method for the fully automated manufacturing of printed circuits, or surface mount technology (SMT), from 1951 to 1955; see pp. 2800–2806 [rondinax.wordpress.com/2014/01/31/rudolf-strauss-1913-2001-a-key-player-in-the-rondinax-and-rondix-story/]. (Was Strauss truly the original creator of wave soldering, or did he bring that method with him from the German-speaking world, just as Eisler apparently brought printed circuits?)

Boris Chertok, who led some of the Soviet missions removing German technologies after World War II, mentioned the widespread German use of sophisticated multi-pin connectors. Those likely went along with printed circuits, since printed circuits were in wide use and both multi-pin connectors and printed circuits traced back to Albert Hanson's inventions. Chertok also described the transfer of many other advanced electronics technologies to the Soviet Union (pp. 2807–2812).

The figure on p. 2813 shows a panel of multi-pin connectors from an A-4 (V-2) rocket produced during the war [Peenemünde Archive, Folder ARK 41].

Much more archival research is needed to reconstruct the detailed history and extent of research and development of printed circuits in the German-speaking world, as well as how that work was transferred to other countries during and after the Third Reich.]

[4]Note that many historians have described Eisler as the inventor of printed circuits. While Eisler played a critical role in transferring printed circuit technology out of the German-speaking world and producing the first printed circuits in Allied countries, it seems clear from the historical record that Albert Hanson was the original inventor in 1902, and that multiple companies in the German-speaking world were building and selling printed circuits several years before Eisler ever built his first printed circuit board. From both his studies and his work as an electrical engineer, presumably he would have been familiar with those technologies before he left the German-speaking world.



Nº 15,077 **A.D. 1903**

(Under International Convention.)

Date claimed for Patent under Patents Act, 1901, being date of first Foreign Application (in United States), } *7th July, 1902*

Date of Application (in the United Kingdom), 7th July, 1903

Accepted, 7th Oct., 1904

COMPLETE SPECIFICATION.

Improvements in Automatic Switchboards for Telephone and like Exchanges.

I, Albert Parker Hanson, of 6 Lützow, Charlottenburg, in the Kingdom of Prussia, Engineer, do hereby declare the nature of this invention and in what manner the same is to be performed, to be particularly described and ascertained in and by the following statement:—

My invention relates to the construction and disposition of apparatus in automatic exchanges, that is, centrals in which a number of selective switches, worked from a distance, are installed. Such plants are for example employed in so-called "automatic" telephone service. A single selective mechanism proper of such a plant with its box or frame will be called here the "switch", while the imaginably closed bounded field within which the lines leading to or past the switch are made accessible for purposes of making contact will be called a "contact field". A bank of contacts is a number of conducting bodies so arranged and held together as to present a contact field to the switch.

The purpose of my invention is to provide methods by which simplicity in manufacture, ease of transport and installation, accessibility in operation, facility in handling in service and economical use of space are insured.

These advantages I secure singly or in various combinations by incorporating numbers of contact banks into more or less rigid rows, independently of the switches to which they belong, and providing for their advantageous disposition at the central.

A very important feature of the invention is its allowing of many and varied forms each bringing with it a series of practical arrangements. Thus, in the forms hereinafter described in illustration of the invention, the advantages above enumerated are secured in an advancing degree even while the cost of manufacture per unit of apparatus is constantly decreasing.

Arrangements of wires or other conductors running parallel to each other, practically like zither-strings, and forming contact fields for switches arranged in a row parallel to them are already known—see British Patents, No. 8607/'94 and 23239/'97, also U.S. Patent No. 626983, Decker Fig. 15.

My invention, however, is not affected by these and similar arrangements as heretofore applied. The contact banks employed by me are such as—in order

[*Price 8d.*]

Figure B.94: Albert Hanson filed detailed patent applications on printed circuits and multi-pin connectors in 1902–1903.

to prevent the fields assuming too great extension in one direction—are of a construction suited to the presentation of contacts distributed over a field having extension in more than one direction.

When I hereinafter refer to contact fields or contact banks "of the nature described" it is understood that I mean contact fields such as just described or contact banks presenting such fields.

In the accompanying drawings, contact banks with curved contact fields are chosen as an example for illustration. The rows however may be straight or of any nature or, better, the single contact fields may be planes or may take any form and may consist of one or of any number of rows of contacts. The switches too may be of any nature and may be designed for electrical or mechanical (pneumatic, for example) operation.

Figures 1 to 3 show each a row of contact banks.

Figure 4 indicates a method of support of banks and switches.

Figure 5 shows a double row of contact banks with support.

Figures 6 and 7 show details of a method of fastening the contact banks to the supports.

Figure 1 shows a row of contact banks *a, a, a,* united by means of bank wires *j, j,* each contact of any bank being connected with the corresponding contact of all the other banks, all in the well known manner. By fastening the banks *a, a,* upon a suitable support *b*, the whole is given rigidity which greatly facilitates its being handled as a unit in transport, in mounting and in being removed from its position at the central; firstly, because in the transport and handling of such a row of contact banks alone, the bank wires are not exposed to breakage as is the case in many systems heretofore in use, thus rendering it unnecessary to fasten the contact banks at the factory to the row of switches already mounted in frames as has heretofore been the case, and secondly, because it is no longer necessary to fasten each contact bank so securely to its individual switch as heretofore, an arrangement which renders the removal of the switches or a row of contact banks much easier than heretofore. A simple method of fastening or hanging can be adopted for the row as a whole. In order to illustrate a method in which such a row of banks might be employed a contact field X is indicated on the bank farthest towards the right and a switch represented by a frame *c* with the rod *r* bearing the contact arm *s*, shown in proper working relation to the field.

In the arrangement here shown (Figure 1) a further advantage is obtained by the abolishment of the cumbersome metal framing for each contact bank so often employed in systems now in use. The radially arranged contact pieces which, extending outward on either side of the contact field like spreading fingers, make a wide spacing between the fields necessary are also abolished. Both the framing and the radial contacts are shown in English Patent No. 22,545, 1898, Figs. 1 & 6 and 4 & 8. Further, the switches are arranged along beside the row not wholly or partly between the single banks as is the case in some systems. Under this arrangement the single contact fields as well as the switches can be brought close together and thus a very considerable economy of space and shortening of the bank wires *j, j,* is attained.

Figure 2 shows the same row arrangement as before with the difference that the contact banks, instead of being single, are manufactured in one continuous whole. The angle iron *b* of Figure 1 may here be dispensed with as the row is of such material and so constructed as to possess in itself the rigidity required.

Figure 3 illustrates a form similar to the last but with a different arrangement of the bank wires *j, j.* The figure gives an example of how it is possible to construct a row of contact banks alone or with the addition of the bank wires *j, j,* in one more or less rigid piece. By the insertion of stiff card-board or insulated metal between the layers of cable proper a high degree of stiffness can here be attained.

One form of contact piece employed by me, one which is very instrumental

Figure B.95: Albert Hanson filed detailed patent applications on printed circuits and multi-pin connectors in 1902–1903.

in attaining many of the advantages sought is shown in this figure (3). It consists of a piece properly formed at one end for making contact and then extending backward, practically parallel with its neighbours in such a manner as to be accessible for soldering or other connection with one of a series of longitudinally running wires arranged practically in a plane behind the contacts, they may be further extended as shown to facilitate testing or the like. The arrangement allows the bank wires to be stretched straight thus shortening their length and rendering the whole more accessible in building up and more compact.

The vertical arrangement of banks and switches shown in Fig. 4 is to be recommended for general adoption, but especially in cases where a plant is to be installed in narrow or irregular rooms or rooms broken by pillars or the like as, in such cases, the cost of erecting a given large number of switches is less than would be the case with the horizontal arrangement. For example, given a case where a space two feet square and five or six feet high is available, a vertical column with twenty-five or fifty switches attached could easily and advantageously be erected in it, while the utilization of the same space where short horizontal units were employed each carrying two, three or four, switches and arranged one over the other, would be impracticable owing to the large number of wire and cable connections necessary from unit to unit. As vertical columns of somewhat less than a man's height can be erected in almost any room and easily arranged in conformity with other objects in the room such as tables or the like, it would seldom be necessary in manufacturing the apparatus to depart from a given standard of length, a feature of importance in manufacturing on a large scale.

The Figure (4) shows further, a row of contact banks with support and variation of details. As shown here the contact bank row *a*, *a*, may, where advisable, be secured upon supports compounded of various materials, for example an iron strip *h*, and a wooden support *g*. The number, nature and form of the supports are immaterial, but, as illustrated in the figure, I would preferably design them with a view to insuring the switches against damage and dust besides securing additional stiffness in the whole. The switch is here enclosed in a casing from out of which only the contact rod *r* bearing the contact arm *s* projects. Certain parts or sides of the casing, as for example the back, may be dispensed with when the supports *h* and *g*, in forming the channel *f* partly enclose the switches or, when, by arrangement of the switches contiguously one immediately over the other, a mutual protection is obtained, in which case the top of each casing would be rendered dispensible.

Again, the facilities for rapidly inserting and fastening or removing the switch mechanisms are of importance. In the example here given the screw *n* enters the slit *o* of the strip *h* forming a guide upon the insertion of the switch into its position, until, the projecting side *m* of the casing, meeting the edge *q* of the strip *h* forms a stop and one or two turns of the screw *n* suffice to secure the switch in its position.

The insertion and removal of the switch is further facilitated by providing means for closing the battery and other working circuits without the attendant having to fasten or unfasten the wires here concerned. The means here shown as an example are the springs *p* (Figure 4), three for each switch, each connected with the proper conductor upon the column and each making contact with a proper button or other arrangement fastened upon the body of the switch and not here shown, upon the insertion of the latter in its working position.

Figure 5 shows a further development of the arrangement in the preceding figure, two rows of contact banks *a*, *a*, *a*, *a*, being here united into a unit. This arrangement brings with it greater simplicity, only one strip *h* and one support *g* being necessary for two rows of contact banks. A still greater advantage of this double arrangement is obtained in cases where the contact banks are served by their bank wires arranged in any way similar to that shown in Figure 3. Bank wires of a given length and a given number of soldered joints here suffice

Figure B.96: Albert Hanson filed detailed patent applications on printed circuits and multi-pin connectors in 1902–1903.

4 **No. 15,077.—A.D. 1903.**

Improvements in Automatic Switchboards for Telephone and like Exchanges.

to serve double the number of contact banks and hence double the number of switches. In cases of this kind I use elongated contact pieces as described above in connection with Figure 3 but form them in such a manner as to present a contact at either end.

The advantages of this arrangement are apparent. It is characteristic thereof that the switches employed with it would preferably vary in construction in so far as some of their movements would be in opposite directions, *i.e.;* the switches would be paired or manufactured as rights and lefts.

Figures 6 and 7 show modifications of the strip *h* hereby any deformity of the whole which might arise, for example from unequal expansion of the various materials employed to form the support, is prevented and an easy separation of these parts is provided for.

In Figure 6 the slits 1 and the elongated form of the screw holes *i* for the countersunk fastening screws allow of a relative movement of the iron plate *h* and the wooden support *g* not shown in the figure.

In Figure 7 the strip h is divided into shorter pieces so supported upon the wooden support *g* by by means of a dove-tailed arrangement *k* that, besides permitting a relative motion, the strip *h* can easily be removed from the support *g* by sliding it upwards lengthwise of the latter. In order to secure the proper position of the switch mechanisms relatively to their respective banks of contacts, it is advisable in all cases where any considerable motion might be expected, to secure the switches directly upon the contact banks or upon the metal strip *h* not however upon the wooden support.

It is understood that any or all of the illustrations given above are merely examples of the application of my invention and that I do not confine myself in any way to the examples here shown.

Having now particularly described and ascertained the nature of my said invention and in what manner the same is to be performed, I declare that what I claim is:—

1. A plurality of contact banks of the nature described arranged in a more or less rigid row independently of the mechanisms to which they belong in such a manner as to facilitate their manufacture, transport or handling in service as a unit.

2. The arrangement of a plurality of contact fields of the nature described in a more or less rigid row, one close beside the other.

3. In contact banks of the nature described the employment of contact pieces so formed as to present a contact at one end and extend backward from this in *a manner enabling it to cross the connecting wires practically in a plane* parallel to theirs and be connected to one or more of them.

4. In contact banks for automatic exchanges the employment of double contact pieces so disposed as to present contact fields to switches of right and left (symmetrical) construction.

5. In an exchange of the nature indicated, the arrangement of more than one row of contact banks parallel to each other and united into a more or less firm unit, independently of the switches to which they belong.

6. An arrangement of contact banks of the nature described, characterised by having a plurality of banks united, in the nature of their construction, into a row without the aid of special supports.

7. Contact banks of the nature described, built up of layers of contacts and insulation, the layers extending through and being common to several contact banks.

8. A series of contact banks of the nature described, in which the contact banks and their connecting leads are united into a compact whole.

9. A series of contact banks of the nature described, characterized by being built up of layers into a more or less rigid whole each layer being composed of

Figure B.97: Albert Hanson filed detailed patent applications on printed circuits and multi-pin connectors in 1902–1903.

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several groups of contacts together with the connecting leads and proper insulation, all arranged practically in a plane.

10. In an automatic exchange employing switch mechanisms designed to be removed independently of their contact banks the disposition of the supports or other parts adjacent to the mechanisms in such a manner as to partially enclose the same and thus offer protection against damage.

11. In an automatic exchange, the providing of contact bodies upon the switch supports, to correspond with contact bodies upon the switches in closing the working circuits of the switches upon the latter being inserted into position.

12. In an automatic exchange the provision of guides or stops or both, so disposed as to facilitate the insertion of the switch into position.

13. In an exchange of the nature described, the employment of supports compounded of various materials or parts, so disposed as to admit of a relative motion of the various parts in order to prevent deformity arising from unequal expansion of the parts or from other causes.

14. In plants of the nature described the employment of a web or strip which serves as a common object upon which to fasten both switches and contact banks.

15. In plants of the nature described, the employment of means for enabling the rows of contact banks, to be easily separated from their supports by sliding the former upon the latter.

16. In an automatic exchange, employing switches enclosed in a casing and designed to be removed independently of their contact banks the disposition of the switches and their supports in such a manner that parts of the casings can be dispensed with, being supplanted or rendered unnecessary by adjacent surfaces of the support or of an adjacent switch.

17. In an automatic exchange, the disposition of the banks together with their switches upon vertical supports.

18. In contact banks for automatic exchanges constructed substantially as described with reference to Fig 3 of the drawings the employment of contact pieces so formed as to extend away from the contact fields, cross the connecting wires and appear upon the opposite side of the latter for purposes of testing or the like.

Dated this 3rd. day of July, 1903.

ALBERT PARKER HANSON,
Inventor.

Redhill: Printed for His Majesty's Stationery Office, by Love & Malcomson, Ltd.—1904.

Figure B.98: Albert Hanson filed detailed patent applications on printed circuits and multi-pin connectors in 1902–1903.

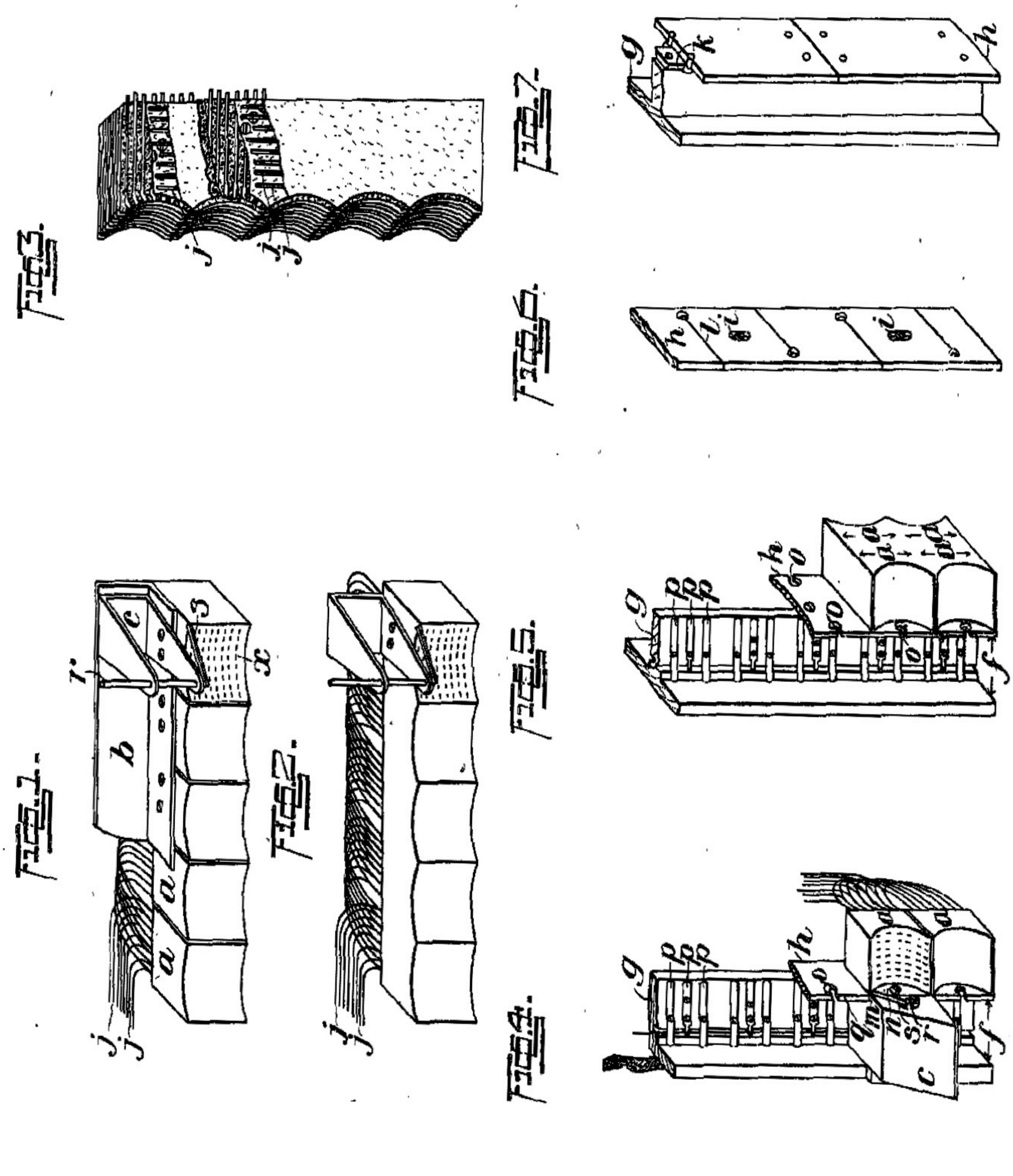

Figure B.99: Albert Hanson filed detailed patent applications on printed circuits and multi-pin connectors in 1902–1903.

N° 4681 A.D. 1903

Date of Application, 27th Feb., 1903

Complete Specification Left, 28th Dec., 1903—Accepted, 27th May, 1904

PROVISIONAL SPECIFICATION.

Improvements in or connected with Electric Cables and the Jointing of the same.

I, ALBERT PARKER HANSON, of 43 Dorotheenstrasse, Berlin, in the Kingdom of Prussia, Engineer, do hereby declare the nature of this invention to be as follows:—

My invention relates to improvements in or connected with electric cables and the jointing of the same, by means of which certain advantages are obtained; and it is specially though not exclusively applicable for telephone exchange purposes where it is desirable to have a large number of conductors led to the switch boards or switching devices within very small compass and yet with each conductor or group of conductors readily accessible for jointing, replacing or other purposes.

A cable constructed under my invention may be broadly stated to be one in which a number of conductors are arranged between layers of paper or other suitable material the said material being when desired perforated or arranged so as to leave gaps or openings for jointing or other desired purposes.

In order that the nature of my invention may be more readily understood I shall proceed to briefly refer to certain contemplated forms thereof which will I anticipate give good results in practice. In all the forms hereinafter mentioned the conductors may be bare or insulated in any convenient manner and they may be arranged singly or in pairs for working on metallic circuit and they may be crossed at intervals for the purpose of avoiding induction sounds.

In one contemplated form, the conductors are spaced apart and glued or cemented to sheets of paper and these are built up so that the cable consists of alternate layers of separated wires and of paper paraffined or otherwise treated when desired. Instead of paper, fabric or tissue of any desired material may be employed.

In another contemplated form instead of separating the conductors by flat strips or sheets of paper or other material they may be separated by a single sheet or strip which is folded or corrugated longitudinally. The wires are then placed at the bottoms of the folds or corrugations and the upper parts of the said material are then bent over laterally so that each conductor lies in a kind of elongated pocket and is completely separated from its neighbours.

In a third form the conductors may simply rest between two layers of insulating material without being either cemented to or folded into the said material.

In a fourth contemplated form instead of separating the conductors by continuous lengths of paper or other material I use a number of short strips or layers of the latter spaced some distance apart so as to leave the conductors visible and accessible at intervals.

In a fifth contemplated form instead of using flat strips or layers, whether long or short, I employ corrugated strips or sheets, either long or short, and

[*Price 8d.*]

Figure B.100: Albert Hanson filed detailed patent applications on printed circuits and multi-pin connectors in 1902–1903.

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with the corrugations lying either longitudinally or transversely with respect to the conductors. In this case, and when the corrugations are longitudinal, the conductors lie in the depressions but without having the elevations folded over them as in the second case hereinbefore mentioned.

In a sixth contemplated form the conductors are wound helically round an insulating body, such for example as paper or twine, and then placed between layers as aforesaid.

To permit of access to the conductors for jointing or other purposes, orifices or perforations may be made in the layers of paper or other material or the same object may be attained by using short lengths of material as aforesaid and leaving intervals between the respective lengths. Not only may joints be made at these openings or intervals but the conductors themselves may be led out thereat and passed through other orifices or intervals to other layers of the cable. Or, the conductors of contiguous layers may be jointed together at these orifices or intervals in any desired manner. It is not necessary that the conductors of each layer should lie parallel to one another as they may be made to cross one another at any desired angle.

Instead of the separate wires being crossed at intervals pairs or groups of wires may be so crossed and either with or without a separating layer of paper or other material.

The perforations, orifices or intervals hereinbefore mentioned may be so spaced that instead of being coincident they may "break joint" as it is termed, and the same remark applies to the joints twists and crossings of the conductors and separating material. By this means cables of more uniform thickness throughout their length are obtained besides being more convenient for jointing.

The cables may be sheathed or armoured in any of the usual ways. The conductors themselves may be wires of any desired shape in cross section and when desired may be formed *in situ* by electro-deposition or by mechanical deposition as for example by printing with metallic powder in a suitable medium.

I desire it to be understood that the several forms hereinbefore referred to are to be taken as typical or illustrative of modified forms which it is not necessary to describe in detail.

Dated this 27th day of February 1903

For the Applicant
J. G. LORRAIN, M.I.E.E., &c.
Norfolk House, Norfolk Street, London, W.C.
Chartered Patent Agent.

COMPLETE SPECIFICATION.

Improvements in or connected with Electric Cables and the Jointing of the same.

I, Albert Parker Hanson, formerly of 43 Dorotheen Strasse, Berlin, now of Lützow 6, Charlottenburg, in the Kingdom of Prussia, Engineer, do hereby declare the nature of this invention and in what manner the same is to be performed, to be particularly described and ascertained in and by the following statement:—

My invention relates to improvements in or connected with electric cables and the jointing of the same, by means of which certain advantages are obtained; and it is especially though not exclusively applicable for telephone and like

Figure B.101: Albert Hanson filed detailed patent applications on printed circuits and multi-pin connectors in 1902–1903.

exchange purposes where it is desirable to have a large number of conductors led to the switchboards or switching devices within very small compass and yet with each conductor or group of conductors brought out or made accessible at regularly recurring intervals for purposes of connecting them to the contacts, jack springs or other apparatus in connection with which the cable is used.

A cable constructed under my invention may be broadly stated to be one in which a number of conductors are arranged and held upon a layer of paper or other suitable material or embedded into the same, said layer where desirable being perforated or arranged so as to leave openings or gaps which permit of other wires or conductors being connected to the cable wires or through which the cable wires protrude for the purpose stated.

In my Provisional Specification I describe several contemplated forms. I have since discovered that the first and third of these forms are not novel and I desire it to be understood that I make no claim to them whatever. The second, fourth, fifth and sixth contemplated forms as well as the manner of rendering the conductors accessible, I consider new and claim as my invention.

In order that my invention may be more readily understood, I shall refer to the accompanying drawings which illustrate certain forms. In these forms the conductors may be bare or insulated in any convenient manner, preferably with a thin coating of varnish or the like, and they may be arranged singly or in pairs for working on metallic circuit. Where desirable the two wires of a pair or several wires of a group may be so spaced relatively to each other and to other wires or they may be so twisted together or regularly transposed as to diminish or eliminate disturbances from induction.

In the form illustrated in Fig. 1 the conductors *a a* are spaced apart and glued or cemented to the ribbon of paper *c*. Where desirable a second ribbon of paper *d* is glued or otherwise held upon the first in order the better to hold the wires *a a* in position and to give the cable more stability. Where such a covering (*d*) is used, it is, of course, not necessary to attach the wires *a a* to the ribbon *c*. The paper may be waterproofed, paraffined or otherwise treated or, when desired, layers of other suitable substance may be employed in its stead. The layer *c* is provided with openings *e e* through which the wires $a_1\, a_1$ may be brought into contact with and connected to the cable wires *a a*.

In Fig. 2 is shown at the left a form in which a single elongated opening *e* in, and on the right a complete severing of, the ribbon *c* serves the purpose of rendering the wires *a a* accessible for the attachment of the wires $a_1\, a_1$.

In Fig. 3 sheets or cross running strips of insulating material *c c* are employed instead of a continuous ribbon running lengthwise of the wires *a a*.

In Fig. 4 is shown a cable in which the layers of insulating material enclosing the wires *a a* are corrugated in such a manner that the bare wires *a a* come in contact with the sheets of insulating material *c d* at a few points only, thus securing good insulation and reducing the capacity of the single wires. The corrugations may be made to run in any desired direction or arranged in any suitable way, one object sought, being as stated to have the conductors come in contact with the insulating material at as few points as possible. Another object in corrugating the paper or insulating material is to give the cables a certain desired thickness without adding much to their weight, an advantage of importance when cables are laid one upon the other and it is desired to space them properly to correspond with the thickness of the jacks or other apparatus with which they are used.

This form of cable with or without cross leads $a_1\, a_1$ and openings *e e* is the form referred to in my Provisional Specification as the fifth contemplated form. It offers advantages not hitherto obtained in any form of cable, is new and I claim it as my invention

As shown in Figure 4 the wires *a a* run in the hollows of the longitudinal corrugations of the layer *d* but touch the latter at very few points—theoretically not at all—being lifted away from *d* by the cross leads $a_1\, a_1$, which are attached

Figure B.102: Albert Hanson filed detailed patent applications on printed circuits and multi-pin connectors in 1902–1903.

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to the wires *a a* through the openings *e e*. The cross leads a_1 a_1 lie in the corrugations of the layer *c*, either being straight and lying flat upon the upper side of *c* throughout its breadth or, as shown in the figure, being bent downward where the connections are to be made and thus themselves only touching the layer *c* for short distances on either side of the openings. The corrugations of the layers *d* and *c* may, however, as stated above be transverse or lie at any angle to the direction of the wires *a a* in which case the wires *a a* rest upon the ridges of the corugations and consequently touch the layers only at predetermined points. The cross leads a_1 a_1 are then preferably laid in the hollows of the corrugations of the upper layer *c*.

In Fig. 5 the two wires *a* & *b* of each pair are wound helically around a piece of thick soft string, a strip of paper or other suitable body, or, properly insulated single wires may be twisted together and, properly spaced, held between the layers *c* and *d*. This form of cable is also new and I desire to claim it. Openings *e* may be made in the layer *c* through which both wires of a pair *a b* are made accessible, or one of the wires of the pairs may be made accessible through openings in the layer *c* while the other is made accessible from the other side of the cable through openings in the layer *d*.

In Fig. 6 the wires *a a* themselves protrude through openings or orifices in the layer *c*. In this form the end of the protruding loops may for example be soldered directly to jack springs, contacts or other wires or the loops may be so arranged as to barely extend over the edge of the insulating material *c* where, held firmly by the whole being pressed between the layers of any suitable material or in any other manner, the wires may serve directly as contacts, such as are used in many systems of automatic telephony. Banks of such contacts containing several rows each may be produced by superimposing several cables one upon the other and compressing them into a complete whole.

In Fig. 7 although the wires of the cable *a a* are entirely enclosed, only one sheet of insulating material has been used. The wires having been deposited in longitudinal corrugations or pockets in the insulating material *c* and this material folded over in the manner shown. This form of cable is that referred to in my Provisional Specification as a second contemplated form.

In Fig. 8 the wires *a a* of the cable are embedded in a layer of insulating material such as paper pulp, cellulose, guttapercha or the like. At regular intervals the wires are laid bare through the openings *a a* in order to permit of the cross leads a_1 a_1 being connected to them.

In the construction of these cables I have employed conductors of round and flat cross sections or I have even formed the conductors *in situ* by electrodeposition or by mechanical deposition as for example by ruling lines of metallic powder in a suitable medium directly upon the layer of insulating material.

In many instances such for example as where the cables are used for connecting the multiple jacks in an ordinary telephone exchange or the bank contacts of an automatic exchange, it is desirable to lay up the cables one above the other.

In such cases layers of sheet metal may be interposed between the several cables to prevent induction between the wires of the cables so separated or each cable may be sheathed or armoured in any of the usual ways to attain the same end or to render them more fire or moisture proof.

I desire it to be understood that the several forms hereinbefore described are taken as typical or illustrative of modified forms many of which would arise in various applications of my invention.

Having thus particularly described and ascertained the nature of my said invention and in what manner the same is to be performed, I declare that what I claim is:

1) An electric cable composed of a plurality of wires held between bands or sheets of insulating material corrugated in such a way that the wires come

Figure B.103: Albert Hanson filed detailed patent applications on printed circuits and multi-pin connectors in 1902–1903.

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in contact with the insulating material only at certain points along their length, substantially as described.

2) An electric cable composed of pairs or groups of wires twisted together or wound about a supporting body and enclosed between strips or sheets of insulating material or embedded in the same, substantially as described.

3) An electric cable, consisting of a plurality of wires laid singly or in groups in longitudinal corrugations or pockets in a strip or sheets of insulating material and having these corrugations closed above the wires, substantially as described.

4) In an electric cable or arrangement of wires a common insulating body provided at intervals with orifices or openings which permit of other wires being connected to the cable wires or through which the cable wires are looped out, substantially as described.

5) In an electric cable a plurality of conductors each insulated from the other and each looped or brought to the outside of the cable in proper order relatively to other conductors so brought out, and laid bare for the purpose of serving as a contact, as for example in connection with automatic exchange switching mechanism.

Dated this 24th day of December 1903

ALBERT PARKER HANSON,
Applicant.

Redhill: Printed for His Majesty's Stationery Office, by Love & Malcomson, Ltd.—1904.

Figure B.104: Albert Hanson filed detailed patent applications on printed circuits and multi-pin connectors in 1902–1903.

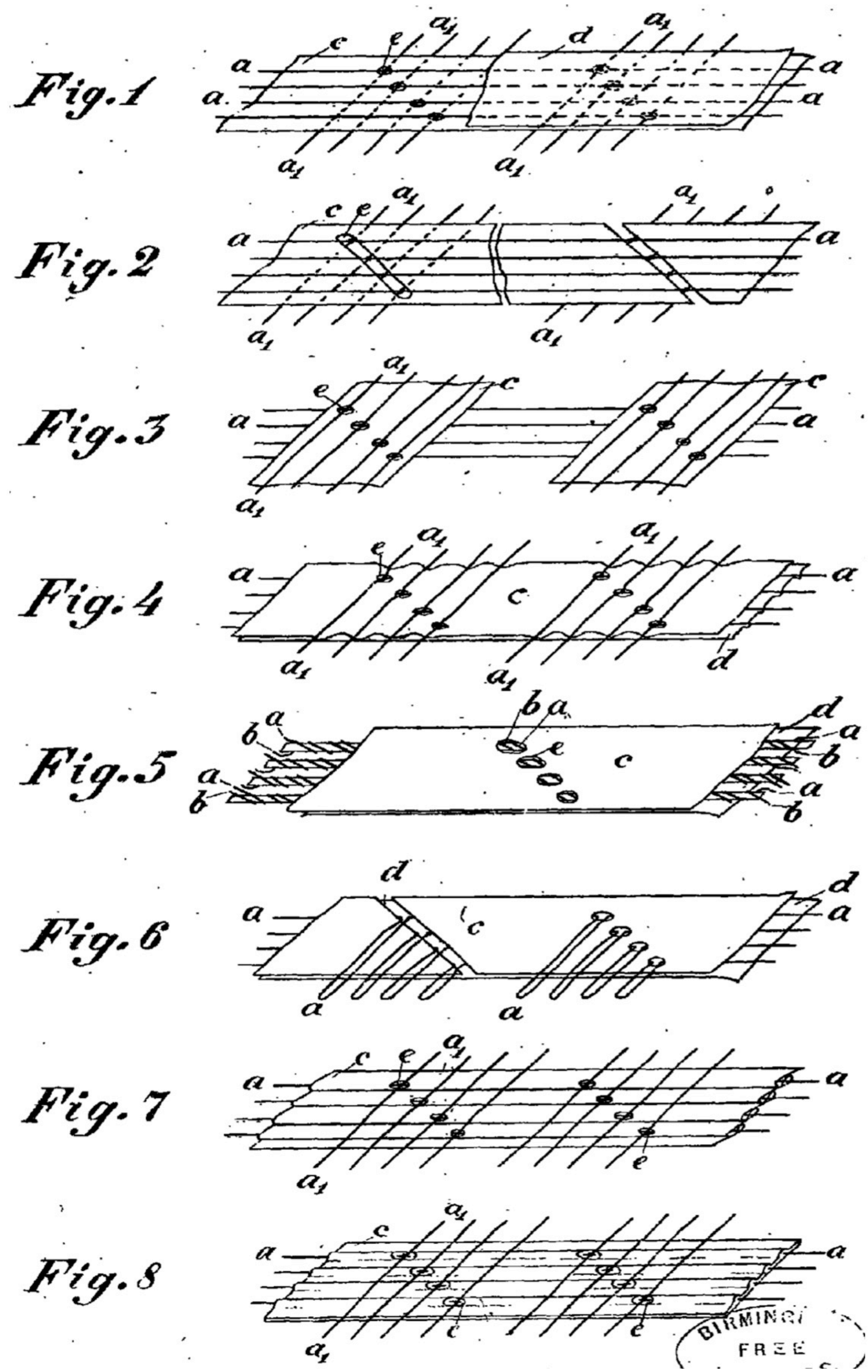

Figure B.105: Albert Hanson filed detailed patent applications on printed circuits and multi-pin connectors in 1902–1903.

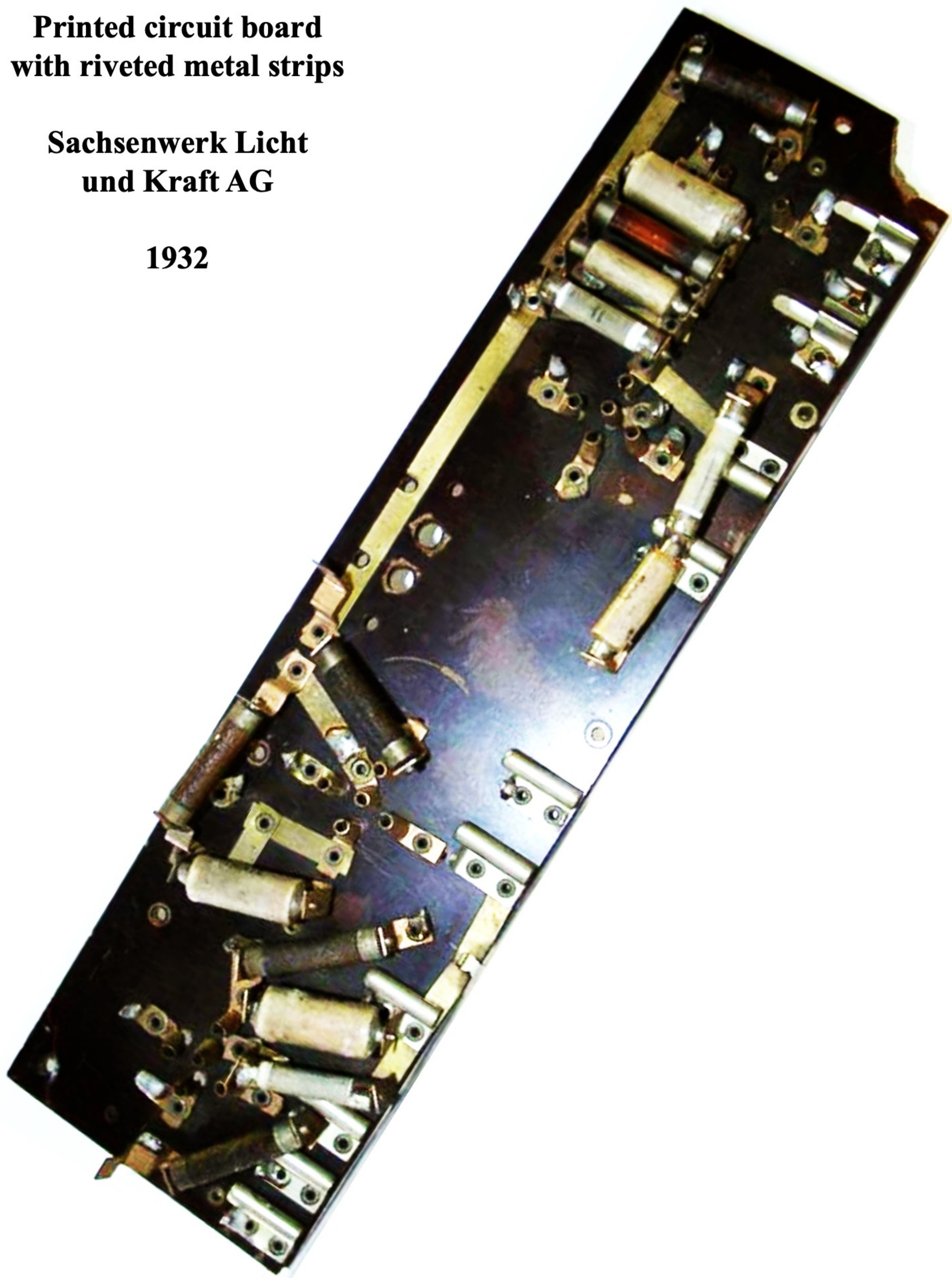

Figure B.106: Printed circuit board with riveted metal strips, Sachsenwerk Licht und Kraft AG, 1932.

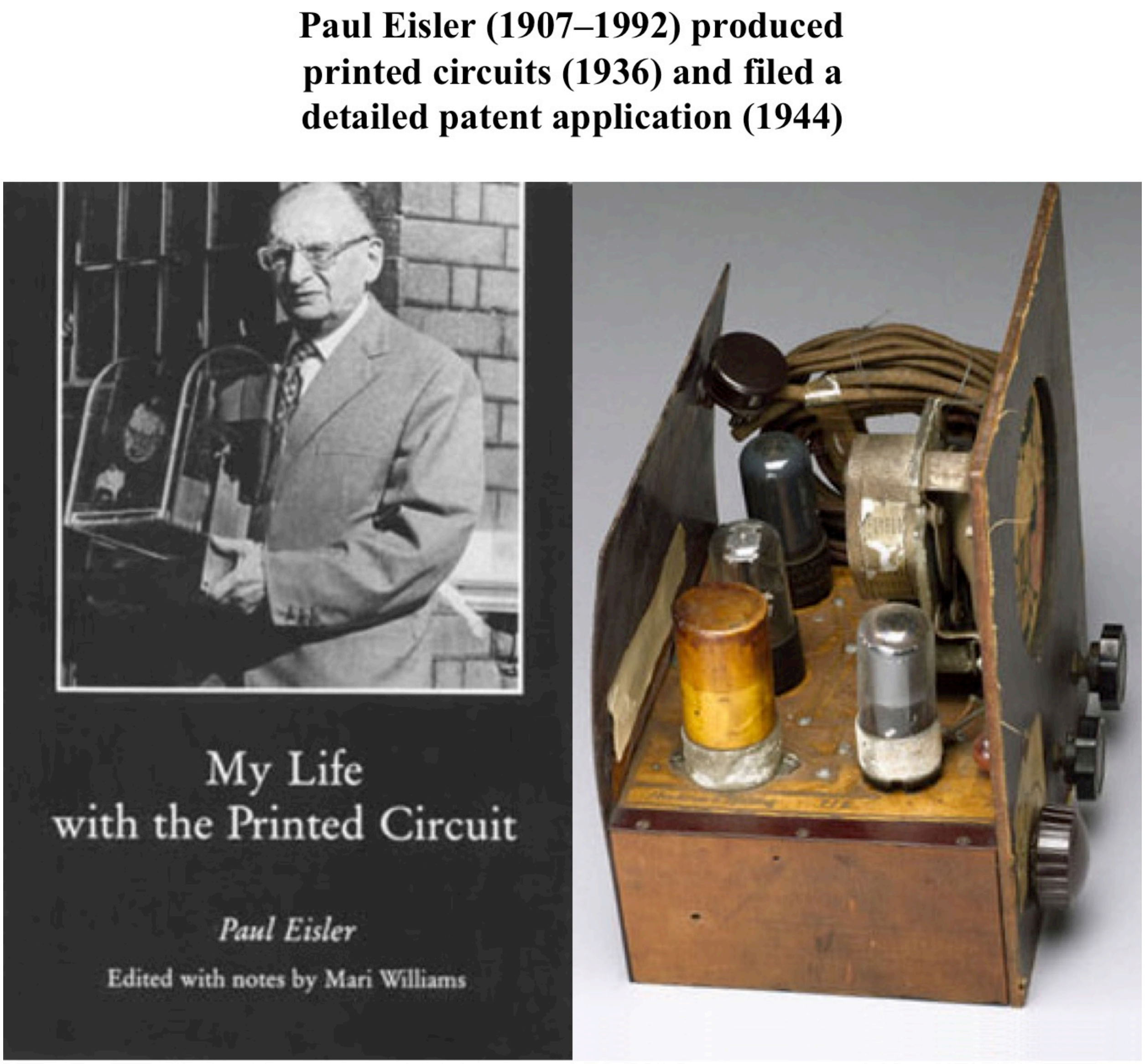

Figure B.107: Paul Eisler produced printed circuits in 1936 and filed a patent application on them in 1944. At least three German companies produced printed circuits several years before Eisler, and he was presumably familiar with their technology from his studies and work as an electrical engineer in the German-speaking world.

May 25, 1948. **P. EISLER** **2,441,960**

MANUFACTURE OF ELECTRIC CIRCUIT COMPONENTS

Filed Feb. 3, 1944 8 Sheets-Sheet 1

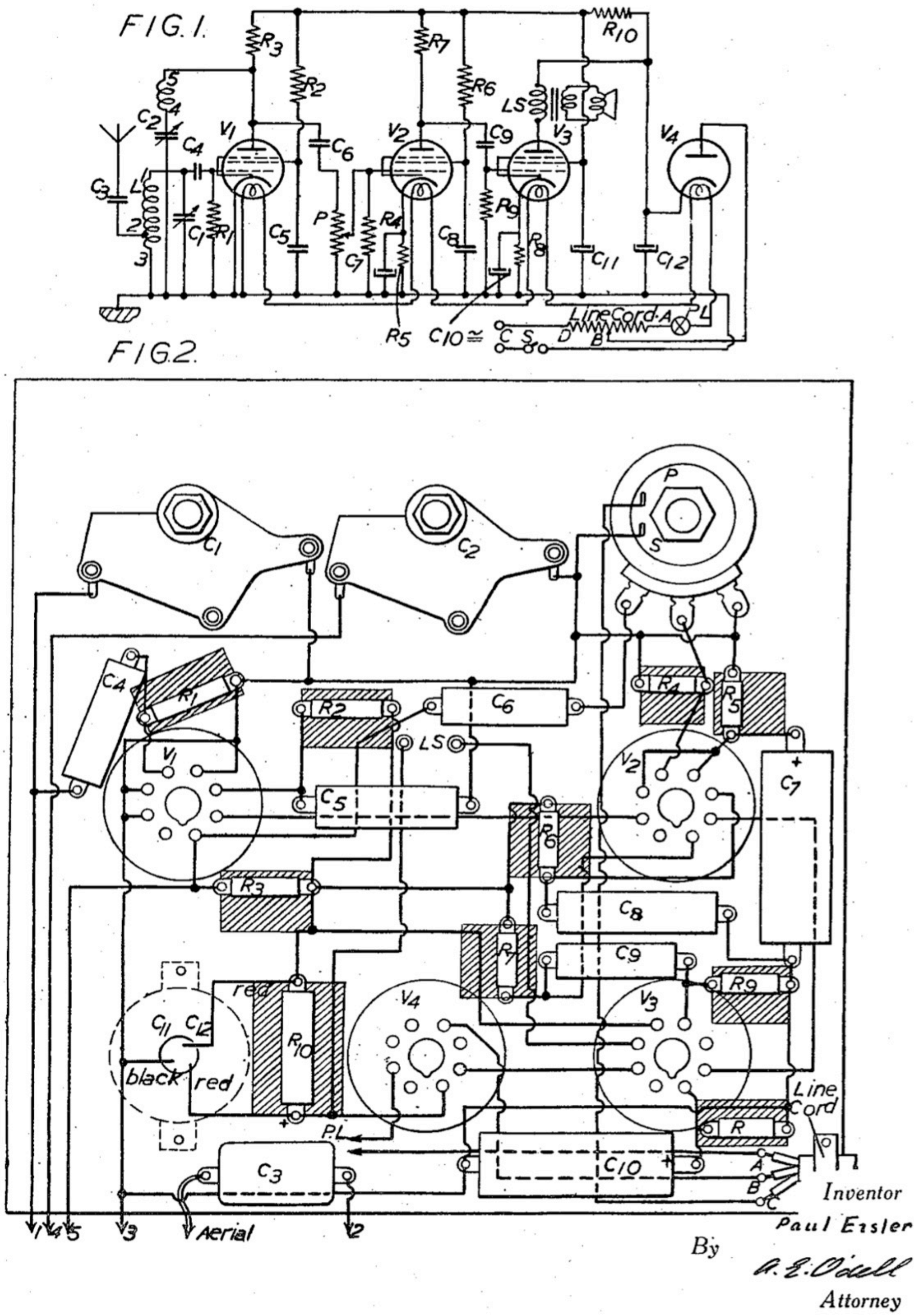

Figure B.108: Paul Eisler produced printed circuits in 1936 and filed a detailed patent application in 1944.

May 25, 1948. **P. EISLER** **2,441,960**

MANUFACTURE OF ELECTRIC CIRCUIT COMPONENTS

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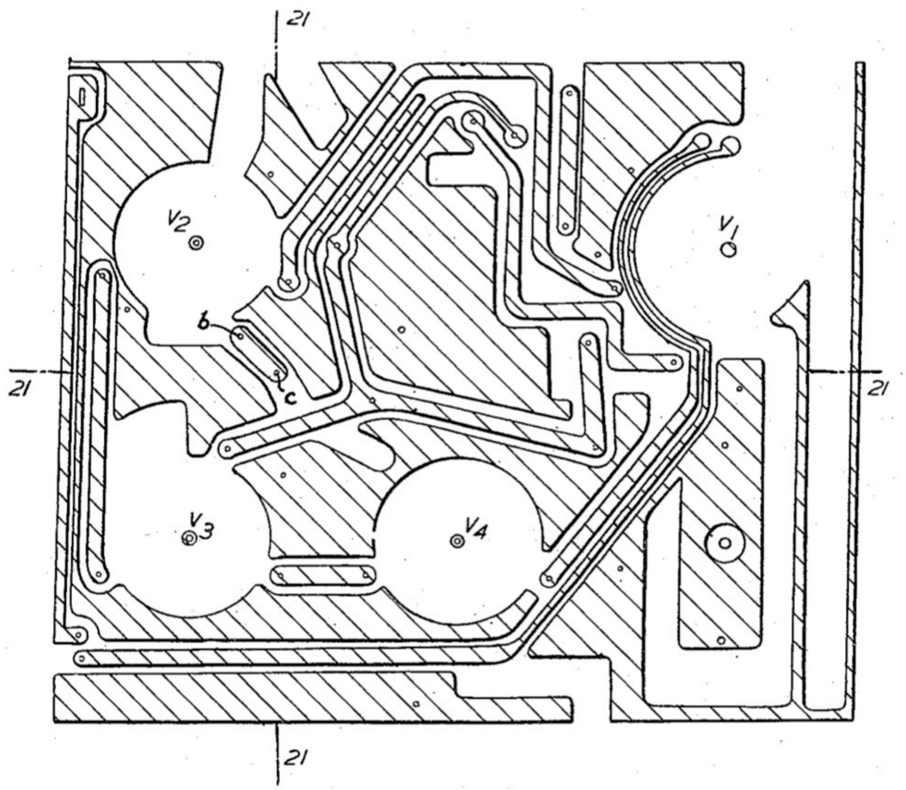
FIG.3.



Inventor
Paul Eisler
By
A. E. Odell
Attorney

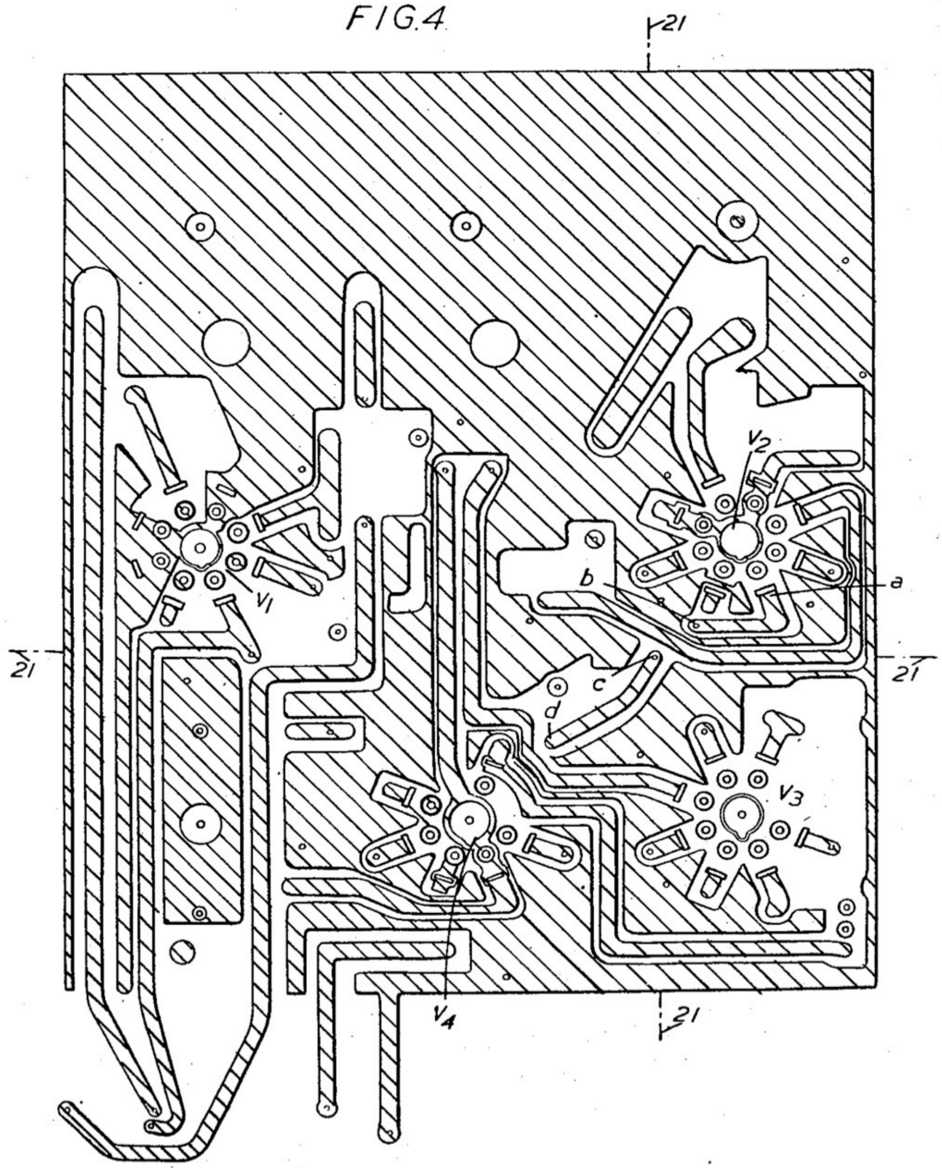
Figure B.109: Paul Eisler produced printed circuits in 1936 and filed a detailed patent application in 1944.

May 25, 1948. **P. EISLER** **2,441,960**

MANUFACTURE OF ELECTRIC CIRCUIT COMPONENTS

Filed Feb. 3, 1944 8 Sheets-Sheet 3

FIG. 4



Inventor
Paul Eisler
By
A. S. Odell
Attorney

Figure B.110: Paul Eisler produced printed circuits in 1936 and filed a detailed patent application in 1944.

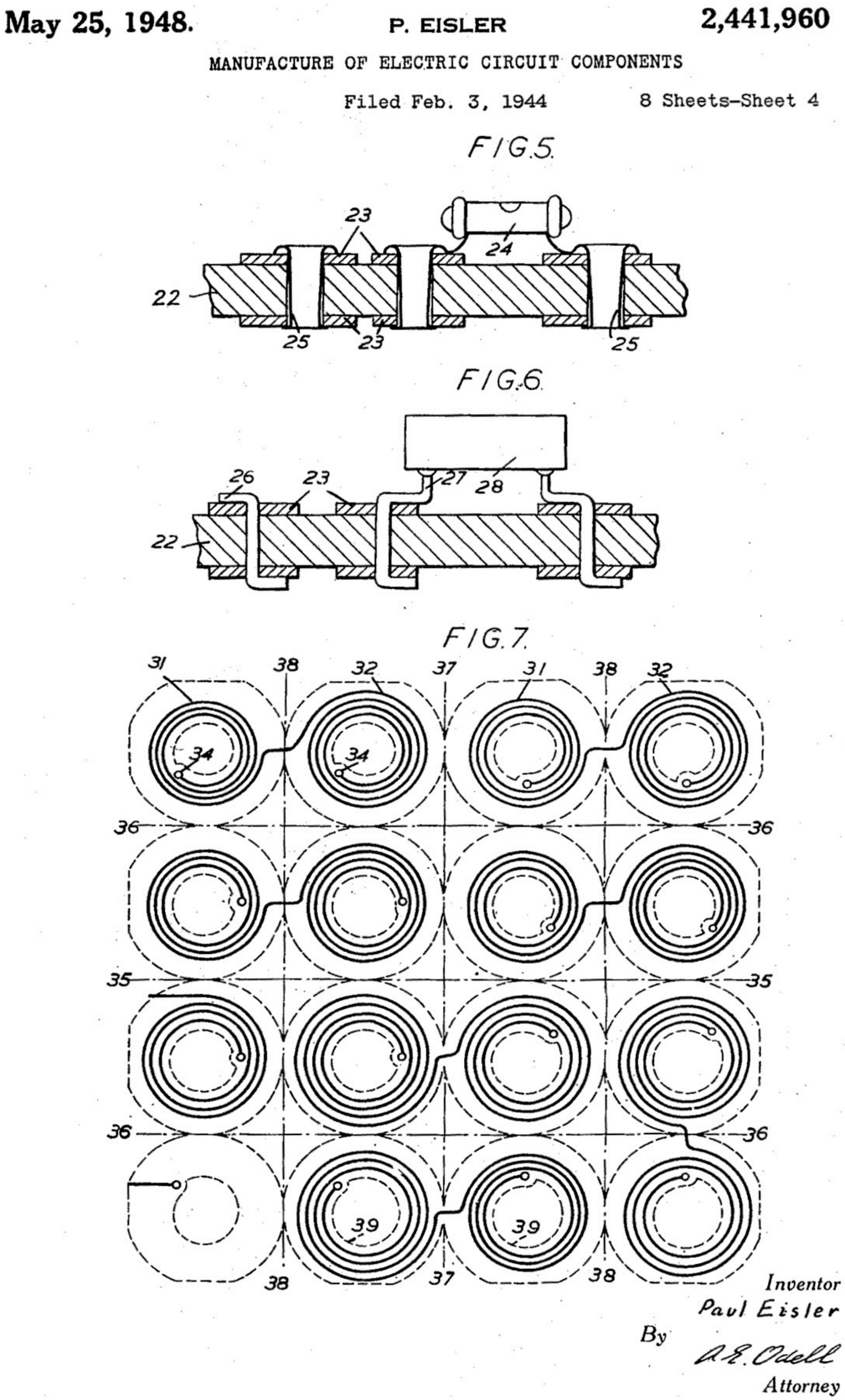


Figure B.111: Paul Eisler produced printed circuits in 1936 and filed a detailed patent application in 1944.

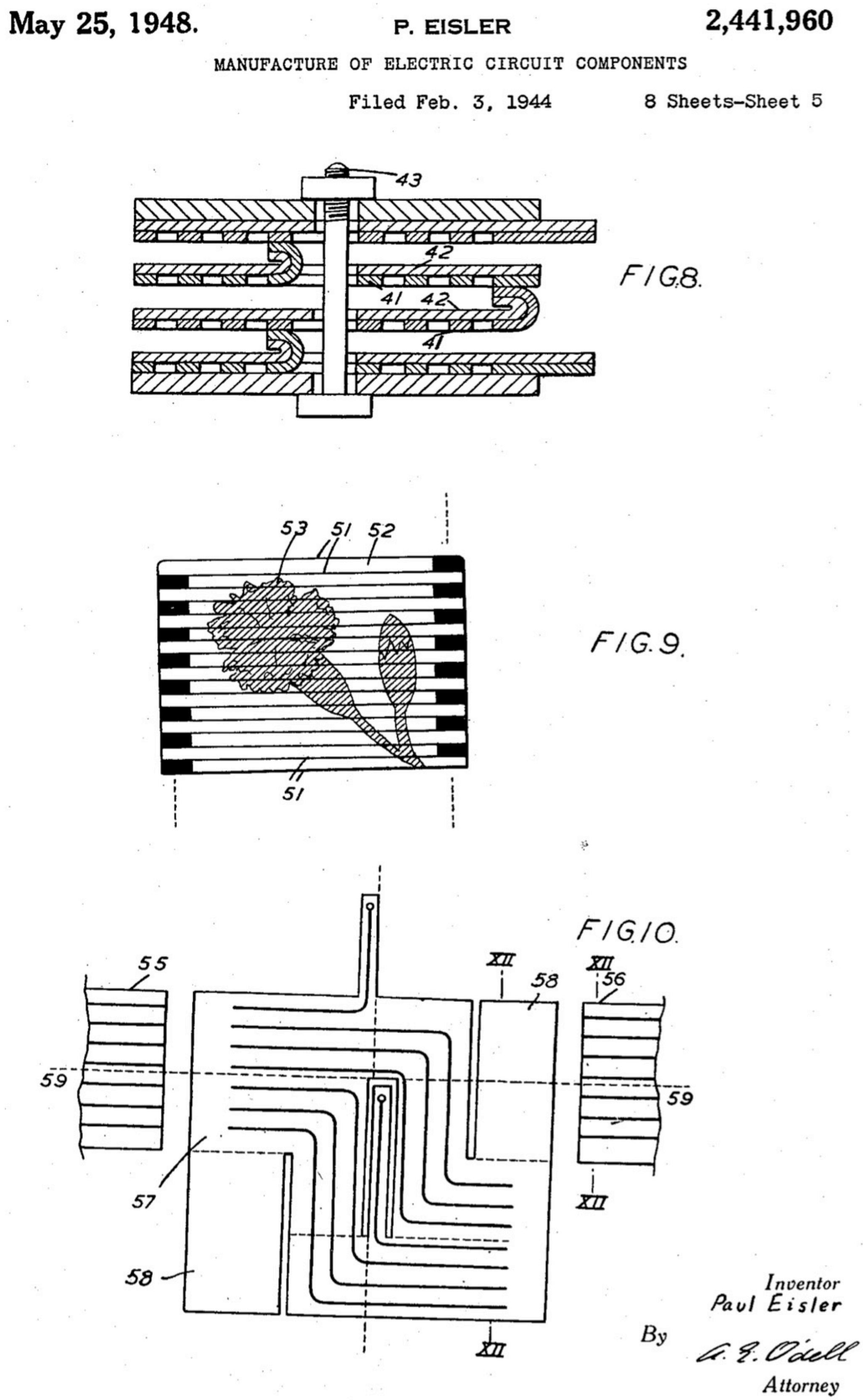


Figure B.112: Paul Eisler produced printed circuits in 1936 and filed a detailed patent application in 1944.

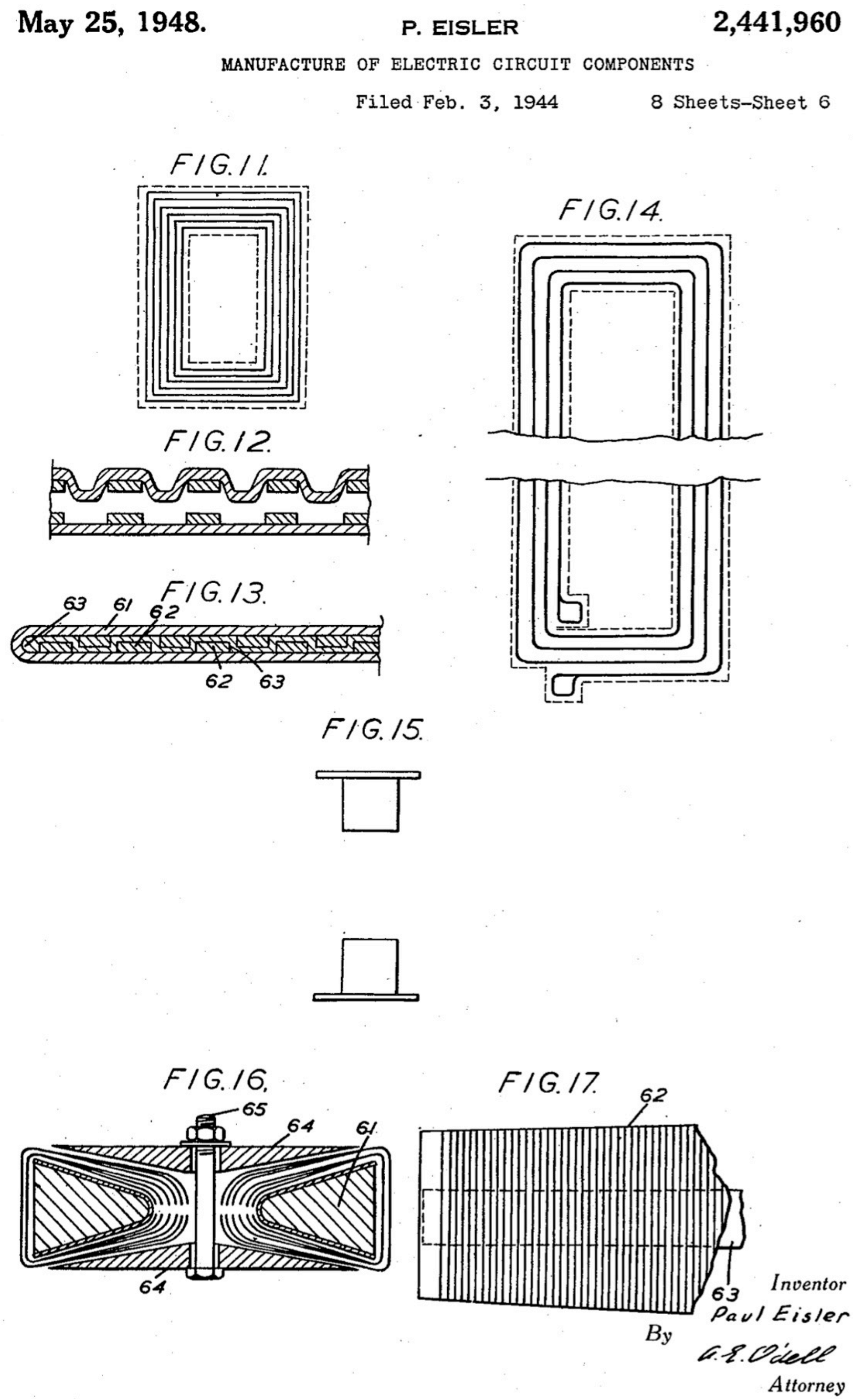


Figure B.113: Paul Eisler produced printed circuits in 1936 and filed a detailed patent application in 1944.

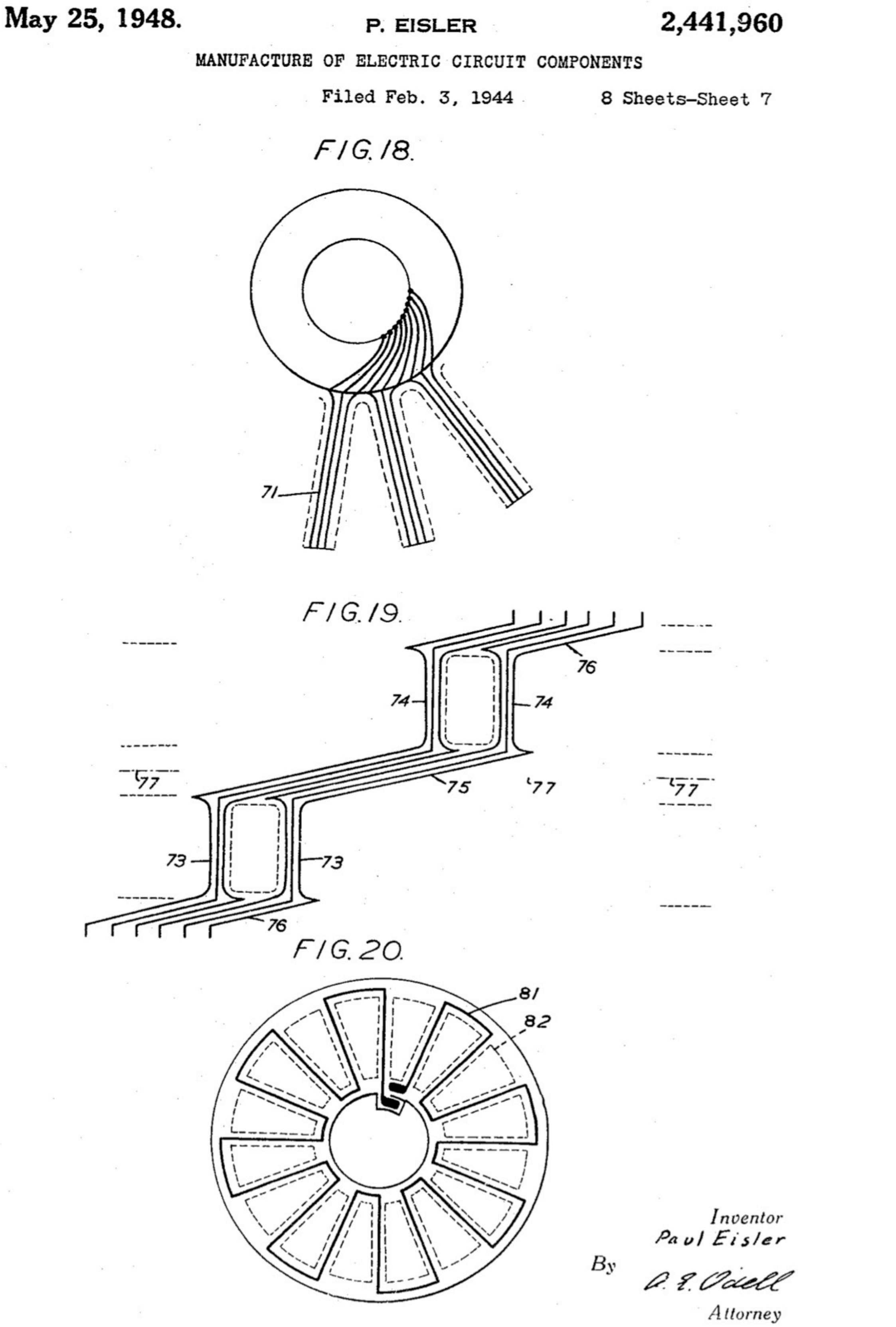


Figure B.114: Paul Eisler produced printed circuits in 1936 and filed a detailed patent application in 1944.

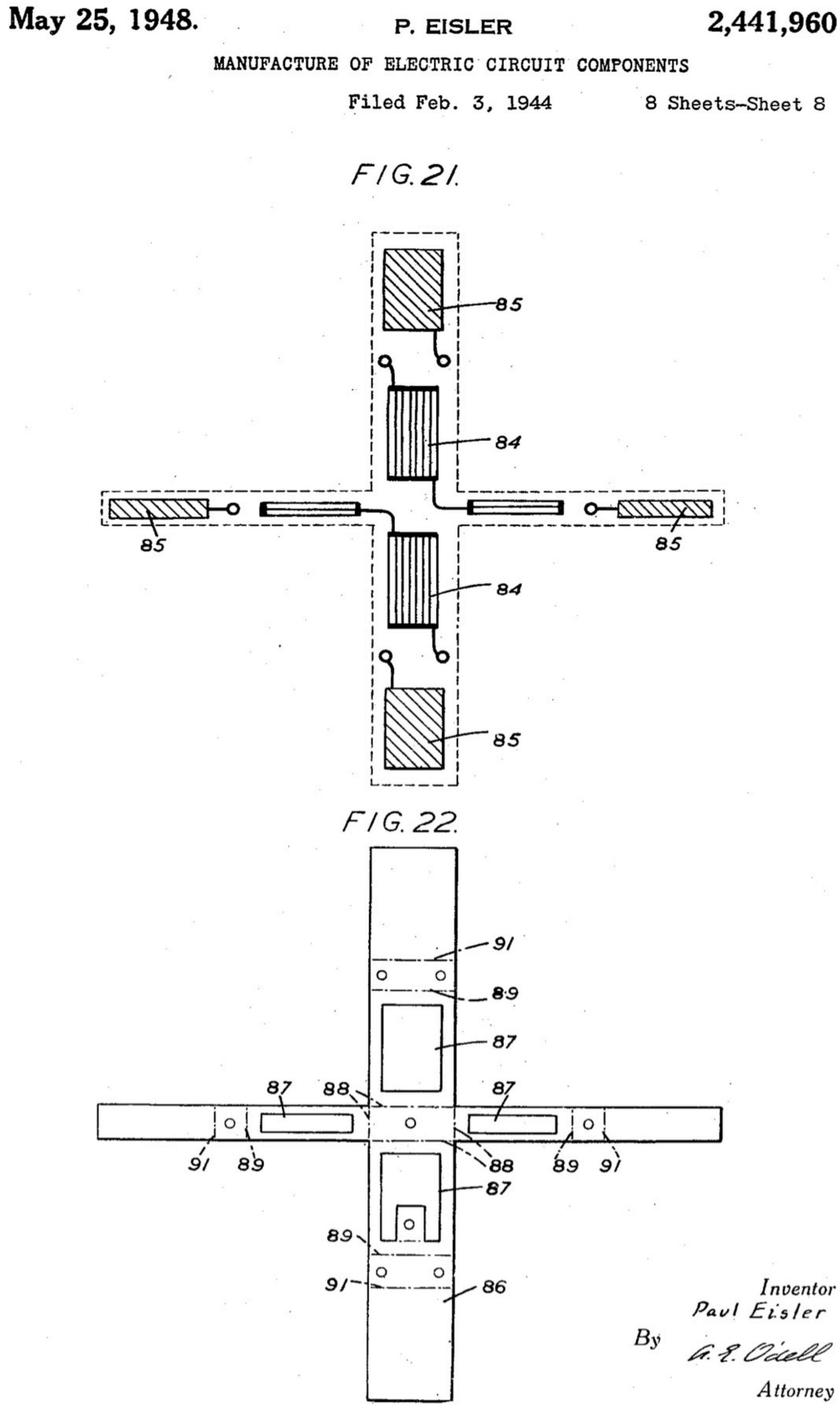


Figure B.115: Paul Eisler produced printed circuits in 1936 and filed a detailed patent application in 1944.

Patented May 25, 1948 **2,441,960**

UNITED STATES PATENT OFFICE

2,441,960

MANUFACTURE OF ELECTRIC CIRCUIT COMPONENTS

Paul Eisler, London, England

Application February 3, 1944, Serial No. 520,991
In Great Britain February 2, 1943

7 Claims. (Cl. 41—43)

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This invention relates to the manufacture of electrical apparatus, and particularly to the production of electric and magnetic circuits and parts thereof.

A principal purpose of the invention is to facilitate and cheapen quantity production of electric circuit components, such as the resistances, inductances, transformers, tubes, and interconnecting networks or circuit connections of radio apparatus, the cores and windings of iron-cored transformers and dynamo electric machines, the connecting networks of switchboards, the conductors of heating appliances, and generally of any electrical circuit component which it may be convenient to manufacture by the methods herein disclosed.

A further purpose of the invention is to facilitate the production of electrical circuit components, even though they be not needed in great quantities, in which a high degree of precision is required in the dimensioning or relative location of conductors such as cannot readily be obtained by known means.

Yet another object of the invention is the production of surface heating elements in which the conductor also constitutes or carries an ornamentation.

Other objects of the invention will appear from the description following.

Most electrical circuit components essentially comprise metal parts, conducting electric current or magnetic flux, supported upon an insulating base, or with interposed insulation upon a metal base.

The invention consists in the production of the metal electric and magnetic conductors in position upon their insulating support by a process based on the printing of a representation of the conductive metal.

The common way of building up an electrical circuit or circuit element is first to draw metal into wire, that is to say make a linear conductor, and afterwards to shape this conductor into coils and networks. By the application of the methods of the printing art the invention brings the metal conductor of the circuit component into existence in its final form, or in a development of that form upon a plane or cylindrical surface.

A typical instance of the invention comprises the steps of preparing by any of the well-known methods of the printing art, a printing plate for printing a representation of the metal electric or magnetic conductors of the circuit component or a part of them; making an imprint

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by the aid of the printing plate upon a surface thereby differentiating on that surface the areas which are required to be conductive from the areas which are required to be non-conductive; and from that imprint producing the conductor by subjecting the printed surface to treatment which operates differently on the areas of the surface differentiated by the printing, thereby changing the differentiation into a differentiation of conductive and non-conductive areas.

The development of the conductor from the imprint is in most cases effected by methods adapted from the printing art or analogous to the methods of the printing art, such as etching, bronzing, electro-deposition and the like.

Where on account of the process of development adopted, or on account of the nature of the fabric which is to form the permanent base of the conductor, it is inconvenient to make the imprint on the permanent base, it may be made on a temporary base, which must be removable, and the development process be followed by a transfer process akin to those known in the printing art.

The invention is explained hereinafter by a description of the production of various circuit components by its aid. This description refers to the accompanying drawings in which—

Figure 1 is a diagram of connections of a radio receiver.

Figure 2 is a diagram showing the approximate lay-out of the components of this receiver.

Figures 3 and 4 show two part schemes of connections prepared for the purpose of applying the invention to the manufacture of the circuit connections of this receiver.

Figure 5 is a cross-section illustrating the making of connections between one part scheme of connections and another and between the circuit leads and a component by means of an eyelet.

Figure 6 is a cross-section illustrating the making of connections between one part scheme of connections and another and between the circuit leads and a component by means of stitching wire.

Figure 7 is a pattern of flat spirals illustrating the making of inductance coils according to the invention by printing with the additional step of folding.

Figure 8 illustrates another way of joining parts of a component.

Figure 9 illustrates a printed pattern of parallel conductors having many useful applications.

Figure B.116: Paul Eisler produced printed circuits in 1936 and filed a detailed patent application in 1944.

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Figure 10 is a pattern of lines on a principal sheet and a connector label illustrating the making of a helical inductance coil according to the invention by printing with the additional steps of winding the principal sheet and attaching a connector label.

Figure 11 illustrates the making of a transformer core according to the invention.

Figure 12 is a section of a helical inductance and its label showing how the label is positioned by embossing.

Figure 13 illustrates a modification of the pattern of parallel lines.

Figures 14 and 15 illustrate the making of an inductance from a pattern of rectangles with the additional steps of twisting and winding on a double core.

Figure 16 is a cross-section of a transformer built by the method of the invention and

Figure 17 illustrates the printing of its core.

Figures 18, 19 and 20 illustrate the application of the invention to the printing of the conductors of dynamo electric machines.

Figures 21 and 22 illustrate the application of the invention to the printing of the conductors of a thermionic tube or valve.

The diagram of connections or hook-up shown in Figure 1 forms no part of the invention, is substantially known, and therefore will not be described further than is necessary to assist the understanding of the later figures. It is seen to consist of valves V_1, V_2 etc., resistances P, R_1, R_2, etc.; inductances such as L′, capacitances C1, C2, etc., an output transformer LS, and a network of conductors by which these other components are connected together. It is the production of the connecting network that will first be studied.

The radio engineer charged with the manufacture of a radio receiver according to Figure 1, must first plan the lay out of the several components, including the connecting network, and produce a lay-out and wiring plan such as is shown in Figure 2. The design of this lay-out is again a matter for the radio engineer with which the present invention is not primarily concerned; though the radio engineer familiar with the present invention will naturally in planning his lay-out have regard to the fact that such and such components of it are to be made by the methods of the present invention. The correspondence between Figures 1 and 2 is sufficiently apparent from the references upon the several parts already mentioned.

It will be noted that the circuit connections shown in Figure 2 involve several instances of crossing conductors; for instance the connection from L. S. to V3 crosses the connection from R3 to V3. In wiring with pre-formed wires such connections are kept separate by suitable disposition in three dimensions; Figure 2 is not intended to represent such disposition; indeed some conductors are displaced to one side merely for the sake of clearness.

For the application of the invention to the manufacture of such a network it is manifestly convenient for the connections to be disposed in one plane; but if they cannot be so disposed without crossings it will be convenient to dispose them in two or three or more planes; so making the network two or more circuit components which are printed separately or side by side and afterwards assembled in superposition or other desired relation and connected together where necessary.

In the present instance the whole of the circuit

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connections can conveniently be set out in two planes, and they are shown so set out in Figures 3 and 4. The general resemblance of Figures 3 and 4 to the lay-out plan of Figure 2 can be seen at a glance, and the location of various components other than the network itself can readily be recognized. For example, V_1, V_2, V_3 and V_4 in Figures 3 and 4 mark the location in the network of the tubes or valves indicated by those references in Figures 1 and 2. It will be seen that if Figure 4 be directly superposed on Figure 2 the valves, or rather valve holders, indicated in the latter figure come in the places to which valve connections converge in Figure 4. Figure 3 will similarly register with Figure 2 and with Figure 4 if turned face downward. If the correspondence of these figures be studied in detail it will be seen that some conductors shown in Figure 2 appear in part in Figure 3 and in part in Figure 4; for example the connection between V_2, C_9 and R_7 in Figure 2 is represented by the connection *a, b* from the position of V_2 in Figure 4, the connection *b, c* in Figure 3, and the connection *c, d* in Figure 4. Provision has to be made for joining these connections into one conductor in the finished articles; for this reason the parts of it are drawn so that their ends overlap when Figures 3 and 4 are superposed back to back; thus the points *b* and *c* of Figure 4 overlap and register with the points *b* and *c* of Figure 3.

To make possible the employment of universal tools, as hereinafter described, in the manufacture of various schemes of connections, of which Figures 1 and 2 are only one example, it is convenient to limit the possible positions of junction points such as *b* and *c*. For this reason it is of advantage to prepare the drawings of the part schemes, Figures 3 and 4, by the aid of squared tracing paper and to arrange that every junction point falls upon an intersection of the lines of the grid. It would only confuse Figures 3 and 4 to superpose such a grid upon them; two lines of the grid are indicated by the chain lines 21 passing through the point *c* in both Figures 3 and 4.

From the drawings, Figures 3 and 4, printing plates are prepared by any of the usual methods of the printing art. These printing plates may, for example, be engravings on metal, or lithographic stones, or they may be prepared by any usual photomechanical process, or they may be photographic plates. The printing plates so produced may be in relief, in intaglio, or planographic, according to the method of production.

From the two printing plates so produced any desired number of identical prints of the circuit component may be made.

In one form of the invention, convenient for the instance under consideration, the prints are made upon a composite material consisting of metal foil upon an insulating backing. The thickness and nature of the foil and of the backing depend upon the particular process chosen for converting the imprint of the circuit component into a circuit component. Metallised or metal-coated paper is one material; it is preferable to impregnate the paper with an acid-resisting varnish made of a suitable plastic. Or metal foil may be coated with varnish or with a layer of plastic of the desired thickness. Or a metal coating may be applied to a pre-formed sheet of insulating material, such as a plastic. Zinc, aluminium, and copper may be named among suitable metals.

For the purpose of the particular example of the invention now under consideration the print

Figure B.117: Paul Eisler produced printed circuits in 1936 and filed a detailed patent application in 1944.

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is made with an acid-resistant ink upon the metal side of such composite material. Except where the pattern to be printed is very fine it is an advantage to impart a grain to the metal surface by use of an etching bath, or by abrasion or otherwise, prior to printing. The print may be made directly from the printing plate or by the off-set method. To ensure a print free from pinholes, the print may be overprinted, or otherwise reinforced. The print is naturally identical with Figures 3 and 4, and those figures equally represent the drawing from which the printing plate was prepared, and the print made from the plate upon the metal surface of a composite sheet.

The part circuit components are next perforated at all the points at which junction has to be made between the conductors of the sheet corresponding with Figure 3 and those on the sheet corresponding with Figure 4, that is to say at all points such as *c*. The restricted location of such junction points as above described enables all the perforations, whether for these particular components or for any other circuit components of like area, to be made by a universal punching tool in which pin punches can be inserted at any of a large number of positions corresponding with the intersections of the grid employed in preparing Figures 3 and 4. If there are large areas of metal to be removed they may be punched out prior to etching, for instance simultaneously with the perforation, so as to even up the extent of etching necessary all over the print.

The sheet is then etched in the well-known manner of the printing art, in a bath suited to the particular metal employed, but with this difference from the usual etching of a printing process that the metal not protected by the resistant ink is wholly etched away. To permit of this complete etching away without undue undercutting of the protected parts it may be convenient, as is commonly done in preparing printing plates, to interrupt the etching and re-coat the surface, for instance with a fatty ground, which can be made to protect the sides of the etched lines as well as the outer surface. When etching is complete the ink may be washed off.

It will be clear that Figures 3 and 4 equally represent the etched print, that is to say they may be regarded as depicting a sheet of insulating material coated with metal over the shaded parts only.

The two part circuit components are now supperposed back to back and metallic junctions are made between them at all the perforations. Such connections may be made in the manner now common in the radio art by means of eyelets. Figure 5, for example, shows a cross-section of a small portion of an insulating sheet **22**, having conductors **23** on each side of it produced by printing methods such as that above described or those described hereinafter, and the conductors on one side are joined to conductors on the other side, and to the terminal tags of other circuit components such as the resistance **24**, by eyelets or hollow rivets **25**. Or such connections may be made by wire stitching, using wire staples, or wires bent twice at right angles into S form as seen at **26** in Figure 6, and the terminal wires **27** of a component such as the fixed capacitance **28** of Figure 6 may be used for such stitching. The eyelets or wires are preferably tinned and solder-painted, so that the joints may subsequently be perfected by soldering. This operation also may be performed by a heated universal tool in which soldering bits are set at the position of the junctions of the circuit component in course of manufacture. If desired the metal may be protected and insulated by a coating of varnish except over points required to be accessible for purposes of testing or the making of further connections.

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The circuit may be tested by a universal testing appliance which permits of contacts being set in desired positions on a surface.

If desired a single printing plate may reproduce the two representations, Figures 3 and 4, side by side, on the same composite sheet. In that case the conductors developed from the print are superposed by folding the sheet back upon itself with the conductors outward.

It will be seen that the essence of the particular method of producing circuit components just described is the preparation of a printing plate, the printing from it of a representation of the conductors of the circuit component, thereby differentiating on the printed surface the areas which are required to be conductive from those which are required to be non-conductive, and the subjecting of the surface to an after treatment which operates differently on the differentiated parts and converts the differentiation into a differentiation of conductive and non-conductive areas. The imprint made is a positive imprint, that is to say the inked part represents the conductors of the component; and the imprint is made on metal; and the component is completed by removal of metal from the unprinted areas. It will be seen below that it is not essential that the imprint be positive, nor that the imprint be made on metal, nor that the component be developed by removal of metal.

In the particular method just described removal of metal was effected by chemical etching; it could equally well be removed by electrolysis, the print being made on metal foil upon a conductive backing, say of another metal, and the printed surface being made the anode in a bath of electrolyte which attacks the foil. This method is appropriate when it is to be followed by transfer of the conductor to a permanent insulating base, after which the conductive backing is dissolved or otherwise removed. In the case of some metal foils, for example aluminium, it may be convenient, instead of removing them wholly, to convert them into non-conductors, a process well-known as "anodising," and which also consists essentially in making the metal an anode in a suitable electrolytic bath.

Instead of producing the circuit component from the imprint by removal of metal it may be produced by adding metal. For example, the printing plate may be prepared to print a negative of the circuit component, that is to say to cover with ink those parts of the surface which are to be non-conductive. A negative imprint can be made in insulating ink upon metal foil, say zinc foil, on a suitable backing, and additional metal of a different kind, say copper, can be added to the parts not inked by electrodeposition, the printed foil being made the cathode in an electrolytic bath. Or the printed foil may be subjected to a galvanising process by coating it with flux and passing it through a bath of molten metal, which must naturally be a metal of low melting point such as Rose metal or a soldering alloy, melting at a temperature which will not harm the insulating backing. These methods, also, appropriately precede trans-

Figure B.118: Paul Eisler produced printed circuits in 1936 and filed a detailed patent application in 1944.

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fer, for the metal foil must subsequently be removed, at least over those areas covered by the ink and therefore not covered by added metal, and this may readily be done after transfer in an acid bath which attacks the metal of the foil but not the added metal.

Other modifications of the method of producing a circuit component by adding metal to the printed surface do not require the print to be made on metal. A positive imprint of the circuit component may be made in sticky ink upon an insulating ground, and the imprint may be metallised in various ways of which the following are examples. Metal leaf may be applied to the printed ground, and so much of it as does not adhere may be removed by dabbing. Or metal powder may be dusted on in the manner usual in the "bronzing" process of the printing art; it will adhere to the imprint and elsewhere may be removed; the adherent powder is not however conductively continuous and must be made so by subsequent consolidation. One method of consolidating a discontinuous powder imprint is to spray metal on the printed and bronzed ground by tools familiar in the art of painting for protection; in the typical case the metal is melted and broken into a fine spray by air under pressure which propels it through a spraying nozzle. The metal spray is molten or at least soft when it impinges on the metal dust of the print, and joins its particles metallically. Alternatively the metal dusted on may include a component of low melting point, such as Rose metal, or a solder, and a flux, as well as a component of less readily fusible metal. These may be mixed as powders or be applied in succession, provided they are intimately mixed in the print. By subsequent heating the low melting point metal is caused to unite the less readily fusible particles. It is not satisfactory to use a low melting point metal alone as it tends to fuse into discrete globules.

Another method of consolidation is to subject the bronzed print to a hot galvanising bath. A third method is to heat the bronzed imprint in the vapour of a metal compound which readily dissolves; for example iron may be thus deposited on the imprint by heating it in the vapour of iron penta-carbonyl; the heating may be effected by a high frequency magnetic field.

If the process of consolidation to be employed involves heating to a temperature at which the ink imprint might soften, something must be done to fix the bronzed imprint in position before consolidation. One means of fixing is to include in the composition of the ink a thermo-settng plastc, which is polymerised and set by heating before the process of consolidation; heating may be effected by a high frequency electro-static field, or by infra-red radiation.

The invention also includes the converse of each of these methods, which consists in preparing a printing plate to print a negative of the circuit component, and making the imprint in ink to which metal will not adhere upon an insulating surface to which it will adhere, and thereafter applying leaf metal or dusting on metal powder and consolidating as above described.

The necessary intimate association of the two metals to be dusted on is better ensured by coating the metal powder of high melting point with a metal of lower melting point, which may be effected in an electrolytic bath, or, particularly in the case of alloys such as Rose metal, by

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stirring the powder of high melting point metal into suspension in the molten low melting point alloy, and grinding to powder the solidified product. The flux may also be a coating on one of the mixed powders or on the metal-coated metal particles made as just described. If the particles are not also coated with flux there may be included in the ink of which the imprint is made ingredients such as rosin oils to serve as flux.

If desired the less readily fusible constituent metal required to produce a consolidated imprint, or both metals, may form the pigment of the printing ink. In the former case the metal particles in the ink may be coated with flux and the second metal ingredient may be added in any of the ways above described, by hot soldering, by spraying, or by deposition from vapour. In the latter case the pigment may consist of particles of less readily fusible metal coated with fusible metal and if desired with flux also, and consolidation will be effected by simple heating of the print, say by a high frequency magnetic field.

The printing plate may be a photographic plate or film, in which case the imprint is made by contact printing or projection upon a sensitised surface. For example a metal plate may be gelatine coated as in zincography, and printed from a negative of the circuit component. The coating is hardened where it is exposed to light and elsewhere may be washed away, and the metal so uncovered can be etched away, preferably in stages. Or the hardened gelatine may be inked, and dusted with metal which is consolidated as above described. The imprint may be transferred to a permanent base prior to consolidation, and this necessary if the gelatine could not withstand the consolidation process chosen.

Any of the processes above described may include or be followed by the step of transferring the imprint from a temporary to a permanent base, provided due regard be paid to the requirements of that step in the selection of materials.

These various methods by which an imprint of a circuit component is converted into a circuit component are to be regarded as illustrative examples only; to those acquainted with the printing art, from which most of the individual steps employed are taken, with some modification, it will be obvious that many other modified operations or modified sequences of operations may be adopted according to the nature of the circuit component that is to be made. A few of these are mentioned below in connection with the making of particular circuit components.

Reverting to the radio receiver of Figures 1 and 2, there has so far been described the production of only one of its circuit components, namely the circuit connections, which can be produced by any of the methods above described. To what extent it is convenient to employ the invention in the making of other components of the radio receiver is a question to be answered on economic grounds. The illustrative examples next described show that other components may readily be made by similar methods, and those examples will assist in indicating how the design of components may usefully be modified with a view to their being manufactured by a printing process.

The inductance L' of the antenna circuit may take the well-known if less usual form of a flat

Figure B.119: Paul Eisler produced printed circuits in 1936 and filed a detailed patent application in 1944.

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spiral, such as one of the spirals 31 of Figure 7. On account of exigencies of drawing the spiral is shown as consisting of a few well spaced turns; the printing methods above described, particularly, for example, the method of printing and etching first above described, permits of the making of a spiral of hundreds of turns spaced apart no more than a few thousandths of an inch. Hence a single spiral will commonly suffice for the inductance L'. The spiral is drawn out carefully, a printing plate is made from the drawing, an imprint is made on metal foil, on an insulating backing, and the metal not protected is etched away; or another of the procedures above described is followed.

If greater inductance is required than can conveniently be obtained in a single spiral—for example if a winding of a great number of turns is required with or without an iron core—the spiral pattern may be repeated as often as desired. A convenient pattern is that shown in Figure 7, which consists of pairs of spirals 31, 32, joined at their outer ends. The free ends of the spirals form junction points 34, and it will be noted that some of these, but not all, have the same angular position as each other; for example no two of the spirals in the second row have their free ends in the same position, but each of them has its free end in the same position as has the spiral beneath it in the third row. This pattern may be printed on metal on an impregnated paper backing which can readily be folded. After the print has been metallised in one of the ways above described and its surface coated (or left coated) with insulation, except at the junction points, the sheet is folded about the line 35—35. The junction points become superposed in register and may be connected by spot-welding by a universal welding tool analogous to the soldering tool above mentioned. Or they may be joined as explained with reference to Figures 5 and 6. After the junctions have been made the print is further folded about the lines 36—36, the line 37, 37 and the lines 38—38. By a small modification in the pattern, junction points may be made to abut upon one another on folding, as shown in Figure 8, which is a cross section of several spirals 41 on insulating sheets 42, the inner or outer end of each spiral being folded to abut on the inner or outer end of its neighbour; the spirals are held together by the bolt 43 which exerts sufficient pressure to make a metallic connection at the points of abutment. If an iron core is to be used the centres of the spirals of Figure 7 are punched out along the dotted lines 39 before folding, and the insulation between spirals may also be punched out as indicated by the dotted circles surrounding the spirals.

Figure 9 may be referred to here as illustrating a pattern of parallel linear conductors 51 upon an insulating ground 52, a pattern which may readily be produced by the method of the invention and which is the foundation of several varieties of circuit components. It will be seen that each end of the pattern all the lines are joined so that electrically they are in parallel. In addition alternate pairs of lines 51 are joined further from the edge of the pattern so that if the extreme edges are sheared off the lines will be electrically in series. Again it is to be noted that exigencies of drawing make Figure 9 highly diagrammatic; in fact the pattern can be of enormously greater length, and be composed of a very great number of closely spaced lines. Figure 9 will be further described below. It is mentioned here as completing the illustration of the circuit component shown in Figure 10. In this figure 55 and 56 show the two ends of a long strip of flexible insulation bearing a pattern of parallel metallic lines, such as is illustrated in Figure 9, but in this case without any end connections between the lines. This pattern is here used as the basis for making a helical winding to serve as an inductance, or as the winding of a transformer or for like purposes. After printing and development of the metallic lines the strip is wound upon a former or upon a core such as that shown in Figure 11. It would ordinarily be a very tedious operation to wind a wire winding upon a closed core such as Figure 11 depicts, perhaps involving threading the bobbin through the core some thousands of times. But when it is remembered that the strip of Figures 9 and 10 may have hundreds of conductors side by side, it will be understood that thousands of turns of wire may be wound about a core by threading such a strip through it only a few times. However, the winding of the strip on the core in this manner only leaves the core winding with, say, a thousand separate conductors each encircling the core a few times. It remains to join these conductors in series, which involves, say, joining the end of the lowermost conductor in the end 55 of the strip to the uppermost in the end 56 and so on. This is conveniently done by the aid of a label 57 of transparent insulating material bearing a pattern of parallel conductors of similar spacing to the conductors of the strip 55, 56 insulated at their middle parts but bare and solder-painted at their ends. In order that this label may be accurately applied to the ends 55, 56, as is necessary considering the close spacing of the conductors, the label is not only printed but embossed, preferably in the printing operation, so that the ends of its conductors lie in grooves. Figure 12 shows a section of the label 57 and of the end 56 upon the lines XII—XII of Figure 10, and shows the end of the label superposed upon the end of the strip. It will be seen that the embossed parts of the label will fit between the conductors of the strip and thereby cause the conductors of strip and label to be accurately superposed. A soldered joint is made by heat and pressure. The flaps 58 of the label may be coated with adhesive and folded around and made adherent to the back of the ends 55, 56.

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If it is desired to have parallel conductors upon a strip such as that of Figure 9, or the strip 55, 56 of Figure 10, more closely spaced than lines can reliably be printed, the spacing of the lines may be increased to a little more than the width of the lines, and after printing and metallising the lines may be varnished with plastic. The strip can then be folded about a mid line (59, 59, Figure 10), running lengthwise of it, so that the conductors of one half of the strip come to lie between those of the other half; this is seen in Figure 13 which is a cross-section of such a folded strip, 61 being the insulating backing, 62 the conductors, and 63 their insulating coating.

Where the invention is applied to the making of the magneto-conductive part of an electrical circuit component, such as a transformer core the metal employed for metallisation is naturally iron. The invention is especially of value in the making of cores for radio frequency transformers for in these it is worth while for the avoid-

Figure B.120: Paul Eisler produced printed circuits in 1936 and filed a detailed patent application in 1944.

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ance of eddy current losses to divide the iron of the core, not merely into laminations, but into separate and fine wires. The printing of a pattern of parallel iron conductors as shown in Figure 11 upon a ground of the thinnest insulation that will afford the requisite strength and has the desired electrical properties, and the stamping out of the pattern from the sheet and of the centre from the pattern as indicated by the dotted lines, need no further explanation; nor does the building up of the core by assembling a great number of such patterns in a pile. Obviously any usual form of laminated core may be built of printed line patterns in this way.

Figures 7, 10 and 12 illustrate different ways in which the electro-conductive or magneto-conductive part of a circuit component originally printed on a flat sheet, or maybe on a cylinder, may be deformed into a three dimensional structure; Figures 14 and 15, showing an alternative way of building a cylindrical coil, for instance a relay winding, illustrate a third kind of deformation. In this case the printed pattern consists of a great number of elongated approximately rectangular turns one within the other; the middle part of the figure is broken away to indicate that its length may be large compared with its width. When this is metallised the conductor is continuous from end to end. It is formed into an inductive winding by stamping out its middle as indicated by the dotted line and winding it on the two-part core or former shown in Figure 15, preferably so that its ends become superposed, and then turning one part of the core or former end for end, thereby twisting the ends of the rectangular pattern, and bringing its long sides into juxtaposition with the current travelling around the core in the same direction in all of them.

As already mentioned, where it is intended to use the method of the invention for the production of a circuit component regard may be had to that fact in the electrical design of the component. Figure 16 is a cross-section of a transformer designed to be built by the method of this invention. Its windings **61** may be built of superposed spirals, such as are illustrated in Figure 7, all of the same external diameter but decreasing in radial depth from the middle outwards. Primary and secondary windings may be printed together, closely intermingled to eliminate magnetic leakage. Together the superposed imprints form an annulus of roughly triangular cross-section. Alternatively the winding may be wound of wire upon a former of V-section. The core is built from the printed strip **62** shown in Figure 17; it is a slightly tapering strip (the taper is exaggerated in the figure) on which are formed a large number of parallel closely spaced iron lines. This strip is of very thin insulating material. The middle of the strip is reinforced by a narrower tapered strip **63**. The composite strip is wound around the winding **61** and as it is wound it is folded about the edges of the reinforcing strip, so that the ends of the iron lines come together in the middle of the core as seen in Figure 16. Its insulation breaks and crumples permitting the iron lines to overlap radially. The ends of the lines are brought into good magnetic contact and so held by the end cheeks **64** and the bolt **65**.

The invention is by no means confined to the building of circuit components for radio receivers. The pattern of parallel lines described with reference to Figure 9 is a typical pattern

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for the production of electrical resistances, for example for all kinds of heaters. The pattern of parallel resistant conductors may be wanted upon some article or fabric to be heated on which it is not convenient to print. In that case the resistant pattern is produced by printing upon a temporary ground, for instance printing upon foil of resistant metal upon a backing of waxy paper, and is transferred to its permanent backing by a subsequent operation. The method of printing and etching and subsequent transfer, for example, might well be used to produce a resistant conductor upon cement or plaster of Paris.

A resistant conductor such as indicated in Figure 9 may be formed upon wall-papers, wall and furniture panels, curtains, and other hangings, upholstery fabrics, floor coverings, clothing and bed-clothing, and the like for the purpose of making electric heaters or rather warmers of them. Such a conductor, though of small thickness, will carry a substantial current because its flat form promotes loss of heat by radiation and conduction. The conductor will be insulated and protected by a covering, for instance of a varnish or plastic on which powdered metal oxide may be dusted to increase radiation; in the case of aluminium the conductor is preferably covered by oxidation for the same reasons.

When used on ordinarily ornamental fabrics such as wall-papers the pattern of Figure 9 may be made to provide or contribute to the ornamentation by a double printing process. There is first produced a pattern of parallel lines of say, aluminium, copper, zinc, iron or nickel. Upon this any ornamental design **53** is printed in an insulating ink. The sheet is then made the cathode in an electrolytic bath by which copper is deposited on the metal lines except where covered by ink. The final product is, as before, a sheet with a pattern of parallel lines of which those parts within the design are of higher resistance than the remainder. Alternatively the over-printed sheet may be anodised to bring about reduction in the cross-section of the unprotected parts.

However, the second pattern may be superposed merely for its appearance without any thought of making the pattern rather than the non-patterned part the source of heat, or vice versa. In this case it may be desired to render the pattern of parallel lines inconspicuous to the eye, by suitable dyeing of the base, or of the oxide-coated or otherwise insulated conductor. For such over-printing a pattern of parallel lines of aluminium may be used with advantage, and the sheet subjected to an anodising process and dyeing process by which effects of some beauty may be produced. By the use of dyes which change colour at a temperature above atmospheric and below that which the conductor, or a part of it, reaches when carrying current, a visual indication may be given when the heat is on.

A class of printed patterns deserving mention is the patterns for winding the toothed cores of dynamo-electric machines. In one form shown in Figure 18 the pattern is mainly a star, in which each ray is a group of parallel conductors **71** representing the conductors of one slot; the inner and if desired the outer ends of the rays are prolonged at an angle to their length to form end connections preferably of the form of involutes of a circle; the insulating material between the groups of slot conductors is removed as indicated by the doubled lines, so that the slot conductors

Figure B.121: Paul Eisler produced printed circuits in 1936 and filed a detailed patent application in 1944.

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may be folded through a right angle to enter the slots. Or the slot conductors may appear in the pattern as parallel groups of parallel lines 73 (as seen in Figure 19) upon an insulating sheet which is to be wrapped around the slotted core, openings being punched between the slot conductors, as indicated by the dotted rectangles, for the passage of the teeth. The end connections may be brought into their proper relative position by folding of the insulating sheet. For example the pattern may consist of two rows of groups of parallel lines 73, 74, those of one row being joined to those of the other by other parallel lines 75 at an inclination to the groups, while the outer ends 76 of the group are prolonged at the same inclination. By folding this pattern about a line 77 at right angles to and mid-way between the groups, the latter are superposed in the same slots or made to lie side by side in neighbouring slots, while the inclined lines 75 and 76 become end connections of V form. The rectangular openings punched in the insulating sheet between the groups, as indicated by dotted lines, encircle the teeth when the winding is placed on the core.

The invention is even more readily applicable to dynamo-electric machines employing an armature of disc form or consisting of a plurality of discs, as in some types of multi-pole alternator and inductor alternator. One such disc is shown in Figure 20. The conductor 81 has its radial turns spaced a pole pitch apart, or in the case of the inductor a tooth pitch apart. The ground upon which the print is made and the metal built up may be stamped out as indicated by the dotted line 82.

An example of an electrical circuit component in the production of which a process including the step of transfer is desirable, is the electrodes of a thermionic tube or valve. Figure 21 shows the pattern of the electrodes for a double triode, with the exception of the cathode. There are two grids 84 and two anodes 85. A negative of this pattern may be printed in insulating ink on metal foil, and another metal may be deposited electrolytically on the bare lines of the foil. The imprint is then transferred to a permanent support of glass, which initially is a plane cross 86 as shown in Figure 22 with apertures 87 in it in position corresponding to the position of the elements of the grids in Figure 21. The foil which formed the temporary base is then removed. The support 86 is heated and (the print being on the upper face) its four limbs are folded downward through a right angle about the lines 88; then they are folded outward about the lines 89, and upward about the lines 91. The assembly is mounted on a glass stem around the cathode and connections are made from the grids and anodes to wires sealed through the stem; and the whole is then sealed into a bulb which is evacuated in the usual manner.

I claim:

1. A method of manufacturing a system of electric circuit connections involving crossing connections on a composite sheet formed of insulation backed metal foil, comprising preparing at least two drawings each of a part of the said circuit connections the conductors of which do not cross, said drawings together including all the circuit connections together with overlapping junctions which register when the drawings are superposed, preparing from each drawing a printing plate, printing from each plate upon separate foil surfaces, utilising the differentiation result-

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ing from the imprint to produce a differentation of conductive and non-conductive parts upon the printed surfaces by separating out from the composite sheet the non imprinted portion of said foil surfaces, perforating the said imprints at points where connections are required between one imprint and another, superposing a plurality of thus treated composite sheets with the imprinted foil surfaces thereof disposed in cooperating relationship, spaced from one another by the insulation backing thereof and making metallic connections between the foil imprints through the insulation backing therefor at the points of perforation of the foil imprints.

2. A method of manufacturing a system of electric circuit connections involving crossing connections on a composite sheet formed of insulation backed metal foil comprising preparing at least two drawings each of a part of the said circuit connections the conductors of which do not cross, said drawings together including all the circuit connections together with overlapping junctions which register when the drawings are superposed, preparing a printing plate from each drawing, printing from each plate with acid resist designs upon separate foil surfaces, utilizing the differentiation resulting from the imprint to produce a differentiation of conductive and non-conductive parts upon the printed foil surfaces by etching out from the composite sheet the non-imprinted portions of said foil surfaces, superimposing portions of the thus treated composite sheet with the imprinted foil surfaces thereof disposed in cooperating relationship and spaced from one another by the insulation backing thereof, and making electric connections between the foil imprints through the insulation backing therefor.

3. A method of manufacturing an electric circuit system involving crossing connections from a composite sheet of insulation backed metal foil, which comprises imprinting acid resist designs on separate portions of the foil surface, etching out the non-imprinted portion of the foil surface whereby the imprinted portion of the foil of each composite sheet defines insulation backed electric conductive circuit paths, superimposing portions of a composite sheet with at least one insulation backing interposed between the thus formed electric conductive circuit paths and conductively connecting said conductive circuit paths through said insulation backing.

4. A method of manufacturing an electric circuit system involving crossing connections from a composite sheet of insulation backed metal foil, which comprises imprinting and resist designs on separate portions of the surface of the foil layer thereof, forming connection zones on said foil layer at predetermined portions of said imprinted designs thereon, etching out the non-imprinted portion of the foil layer whereby the imprinted portion of foil layer of the composite sheet defines insulation backed electric conductive circuit paths, superimposing portions of the composite sheet wtih at least one insulation backing layer interposed between the thus formed electric conductive circuit paths, and conductively connecting said electric conductive circuit paths through said insulation backing at such connecting zone.

5. A method of manufacturing an electric circuit system involving crossing connections from a composite sheet of insulation backed metal foil, which comprises imprinting acid resist designs on separate portions of the surface of the foil layer thereof etching out the non-imprinted portion of the foil layer whereby the imprinted foil layer of

Figure B.122: Paul Eisler produced printed circuits in 1936 and filed a detailed patent application in 1944.

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the composite sheet defines insulation backed electric conductive circuit paths extending along one plane, folding the composite sheet to superimpose a plurality of the thus formed electric conductive circuit paths in spaced planes with at least one of the insulation backing layers therefor interposed therebetween and conductively connecting said electric conductive circuit paths through said insulation backing.

6. A method of manufacturing an electric circuit system involving crossing connections from a composite sheet of insulation backed metal foil which comprises coating portions of the foil surface defining predetermined designs with an acid-resistant substance, etching out the non-coated portion of the foil layer, whereby the coating foil layer of the composite sheet defines insulation backed electric conductive circuit paths, removing the coating substance, superimposing portions of said composite sheet to provide a plurality of the thus formed electric conductive circuit paths with the insulation backing layers thereof interposed therebetween, and conductively connecting said electric conductive paths through said insulation backing.

7. A method of manufacturing an electric circuit system involving crossing connections from a composite sheet of insulation backed metal foil which comprises coating portions of the foil surface defining predetermined designs with an acid-resistant substance, etching out the non-coated

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portion of the foil layer, whereby the coated foil layer of the composite sheet defines insulation backed electrical conductive circuit path, removing the coating substance, forming connection zones on the non-etched foil surface at predetermined portions thereof, superimposing portions of said composite sheet to provide a plurality of the thus formed electric conductive circuit paths of the insulation backing layers thereof, interposed therebetween and their connection zones in alinement and conductively connecting said conductive paths through said insulation backing at such connecting zones.

PAUL EISLER.

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Figure B.123: Paul Eisler produced printed circuits in 1936 and filed a detailed patent application in 1944.

Technologica- [illegible] i industrial organization that per-itted the German war machine to maintain nigh output, despite difficulties in communications and transportation and shortages in skilled manpower, offers invaluable clues for improving the mass production methods of American manufacturers, according to Dr. Todos M. Odarenko, of the Office of Technical Services, Department of Commerce.

Dr. Odarenko recently returned from Germany where he headed the overseas Electronics and Communications Unit of OTS Technical Industrial Intelligence Division. He was on leave of absence from his position as a member of the Technical Staff of the International Telephone and Telegraph Company, New York City.

"American industry now has the unparalleled opportunity of mastering German production techniques that has already saved an inestimable amount of time and money in independent research and experimentation and will save more as the exploitation of German practices and their utilization is completed", Dr. Odarenko declared. "American businessmen and manufacturers should send investigators to Germany at once, for as German plants reconvert to peacetime operations, they will become less readily accessible for study by American investigators."

Though the fundamental ideas of many developments in German production methods and processes were not exactly unknown to American engineers, their successful application on a wide scale was novel, Dr. Odarenko stated. Consequently, obtaining exhaustive knowledge of the "know-how" for similar wide scale use in America is of paramount importance, according to Dr. Odarenko.

In Communication and Electronic industries the Germans speeded production by reducing the amount of piece-meal assembly work, by a large scale use of forgings, castings, molds and pre-assembled component units, Dr. Odarenko said. For example, they invented an ingenious machine that casts in one operation complicated radio or radar chassis with precision of such nature that no, or but little, further machining is necessary.

NARA RG 40, Entry UD-75, Box 25, Folder Odarenko, Dr. T. M.

Figure B.124: Printed circuits were in "wide use" in wartime Germany and the technology was transferred to the United States after the war by people such as longtime Bell Telephone Laboratories engineer Todos Odarenko [NARA RG 40, Entry UD-75, Box 25, Folder Odarenko, Dr. T. M., undated press release (probably late 1946)].

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"Previously, the chassis were stamped out of sheet metal, and the partitions and supports -- angle arms and the like -- for each of the many components used in a radio or radar set had to be bolted, screwed or welded separately to the chassis", Dr. Odarenko explained. "The casting machine combines all these separate operations into one, conserving time and labor."

A similar German development for expediting the mounting of electronic assemblies was the wide use of ceramic insulating plates with printed or stamped painted or sprayed, and baked in, electrical connections. These reduced or completely eliminated the need for the conventional, laborious wiring, Dr. Odarenko said.

The need for thoroughly studying German technique is also an essential requirement for successfully manufacturing in the States of many ingenious devices and of useful materials developed or invented in Germany in recent years, Dr. Odarenko declared. Frequently, attempts at manufacture proved that careful reading of the available documents describing the composition of the material and the machinery for its production as well as detailed physical examination of both the material and the machinery revealed insufficient information.

For example, Dr. Odarenko said, American manufacturers ran into difficulty, when they attempted to reproduce the German process for converting powdered polystyrene into a tough plastic film called "styroflex". The film has excellent dielectric and mechanical properties, and the Germans successfully used it in high-frequency cables, in submarine cables and as a substitute for mica sheets in high-precision, electrical fixed condensers. The American manufacturers, however, found that the plastic film they produced lacked the uniformity of thickness, the stability and the flexibility of the German-made product. Thus, quite recently, a special team of experts had to be sent from the States to obtain

NARA RG 40, Entry UD-75, Box 25, Folder Odarenko, Dr. T. M.

Figure B.125: Printed circuits were in "wide use" in wartime Germany and the technology was transferred to the United States after the war by people such as longtime Bell Telephone Laboratories engineer Todos Odarenko [NARA RG 40, Entry UD-75, Box 25, Folder Odarenko, Dr. T. M., undated press release (probably late 1946)].

- 3 -

additional detail information from the North German Submarine Cable plant of Nordenham, the company that perfected the conversion process.

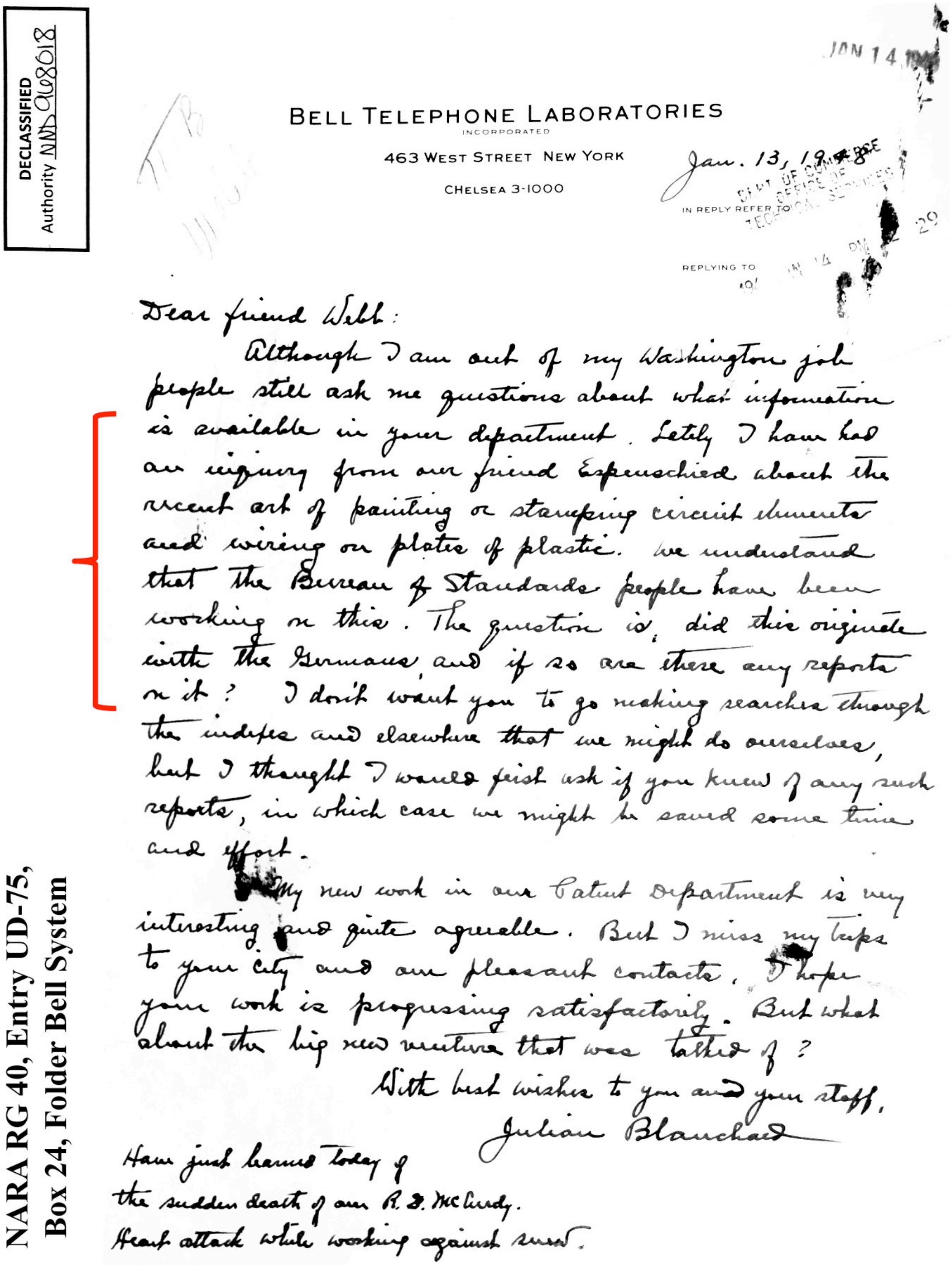
"A little time spent in on-the-spot investigation in Germany before going into production", Dr. Odarenko pointed out, "will more than repay a manufacturer for the expense of sending an investigator to Germany."

Dr. Odaranko spent 4 months in Germany this year and about 6 months last year for the Electronics and Communications Unit of OTS' Technical Industrial Intelligence Division. From 1928 to 1943, he worked as a member of the Technical Staff for the Bell Telephone Laboratories, and prior to joining the staff of the International Telephone and Telegraph Company, he served as a consultant and advisor for the Bureau of Ships of the U.S. Navy and the Radar Division of the War Production Board.

Manufacturers interested in sending investigators to Germany should communicate with John C. Green, Director, Office of Technical Services, Department of Commerce, Washington 25, D. C.

NARA RG 40, Entry UD-75,
Box 25, Folder Odarenko, Dr. T. M.

Figure B.126: Printed circuits were in "wide use" in wartime Germany and the technology was transferred to the United States after the war by people such as longtime Bell Telephone Laboratories engineer Todos Odarenko [NARA RG 40, Entry UD-75, Box 25, Folder Odarenko, Dr. T. M., undated press release (probably late 1946)].



DECLASSIFIED
Authority NND 968018

JAN 14 1948

BELL TELEPHONE LABORATORIES
INCORPORATED
463 WEST STREET NEW YORK
CHELSEA 3-1000

Jan. 13, 1948

DEPT. OF COMMERCE OFFICE OF TECHNICAL SERVICES

IN REPLY REFER TO

REPLYING TO 19

Dear friend Webb:

Although I am out of my Washington job people still ask me questions about what information is available in your department. Lately I have had an inquiry from our friend Espenschied about the recent art of painting or stamping circuit elements and wiring on plates of plastic. We understand that the Bureau of Standards people have been working on this. The question is, did this originate with the Germans and if so are there any reports on it? I don't want you to go making searches through the indexes and elsewhere that we might do ourselves, but I thought I would first ask if you knew of any such reports, in which case we might be saved some time and effort.

My new work in our Patent Department is very interesting and quite agreeable. But I miss my trips to your city and our pleasant contacts. I hope your work is progressing satisfactorily. But what about the big new venture that was talked of?

With best wishes to you and your staff,

Julian Blanchard

Have just learned today of the sudden death of our R. D. McCurdy. Heart attack while working against snow.

NARA RG 40, Entry UD-75, Box 24, Folder Bell System

Figure B.127: Printed circuit technology was transferred from Germany to U.S. companies such as Bell Telephone Laboratories after the war [NARA RG 40, Entry UD-75, Box 24, Folder Bell System].

Rudolf Strauss (1913–2001) invented wave soldering for printed circuits, or surface mount technology (1951–1955)

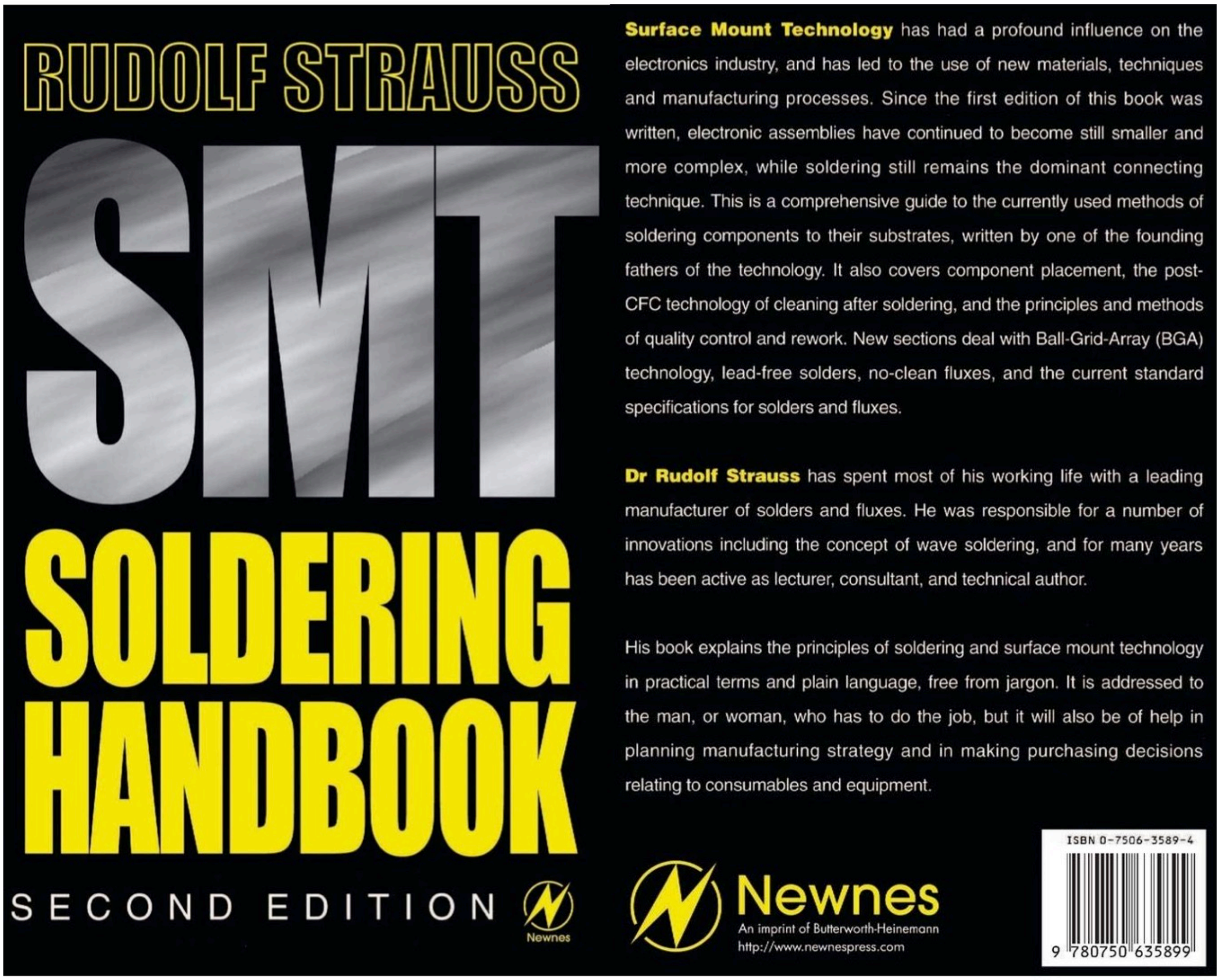
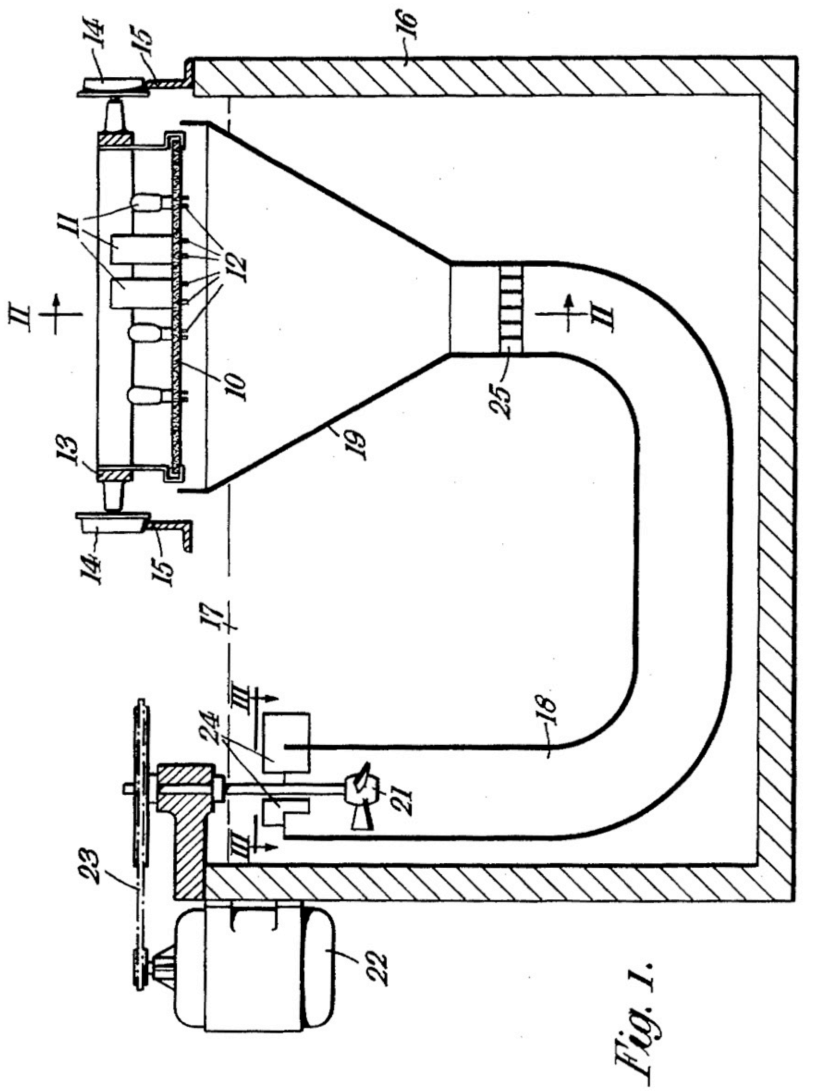


Figure B.128: Rudolf Strauss invented wave soldering for printed circuits, or surface mount technology.

Oct. 2, 1962 **A. F. C. BARNES ET AL** **3,056,370**

APPARATUS FOR SOLDERING

Filed Oct. 9, 1956 2 Sheets-Sheet 1



INVENTORS

ALLAN F.C. BARNES
VICTOR B. ELLIOTT
RUDOLF S. STRAUSS

By
Watson, Cole, Grindle & Watson
ATTORNEYS

Figure B.129: Rudolf Strauss invented wave soldering for printed circuits, or surface mount technology.

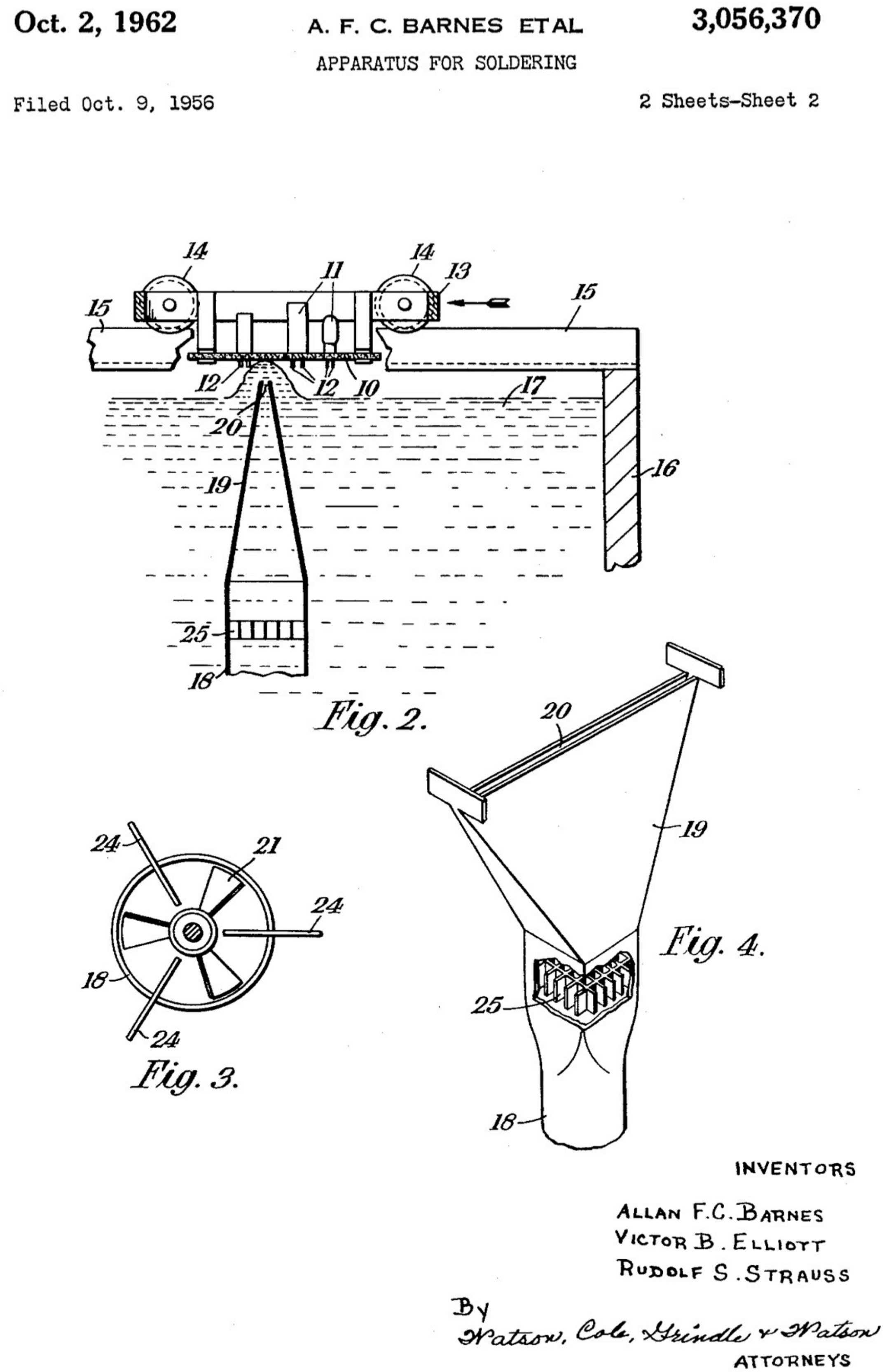


Figure B.130: Rudolf Strauss invented wave soldering for printed circuits, or surface mount technology.

United States Patent Office 3,056,370
Patented Oct. 2, 1962

1

3,056,370
APPARATUS FOR SOLDERING

Allan Francis Charles Barnes, London, Victor Bernard Elliott, Wallington, and Rudolf Siegfried Strauss, London, England, assignors to Fry's Metal Foundries Limited, London, England

Filed Oct. 9, 1956, Ser. No. 614,873
Claims priority, application Great Britain Oct. 14, 1955
3 Claims. (Cl. 113—126)

Components, such as resistors, capacitors, valve sockets and the like are normally assembled on the rear surface of the insulating panel of a printed circuit by inserting pins on the components through suitably placed holes in the circuit panel. It is then necessary to solder the pins to the metal of the printed pattern to secure effective electrical connection of the components to the printed circuit.

The existing practice is to coat the front surface of the panel, i.e. the surface on which the circuit is printed, with a soldering flux, preferably a rosin based flux, and then to dip the flux coated front surface of the panel into a bath of molten solder. This procedure, however, has the disadvantage that the flux may accumulate around the joints to an extent sufficient to deny access to the solder, with the result that an inadequate electrical connection is produced. Another disadvantage is that the surface of the bath is covered with a film of oxide which may prejudice effective soldering. This oxide film has to be removed each time before a panel is dipped which complicates the dipping procedure and in addition, a certain amount of solder is wasted.

The invention provides a method of soldering components to the panel of a printed circuit which consists in effecting relative movement between the panel and a stream of molten solder directed against the flux-coated surface of the panel. The solder will, in this case, be effective to wash out any flux which may have penetrated into the holes in the panel and so ensure effective electrical connection of the pins to the circuit. This method of soldering in effect provides an angled contact between the entire surface to be soldered and the surface of the solder. This permits the flux to be displaced readily by the molten solder, giving the latter complete and unhindered access to the joints to be soldered. In addition, since the panel is in contact with a moving stream of solder, the chilling effect of the panel is negligible, the rate of heat transfer is greatly improved and consequently any part of the panel need be in contact with the molten solder for less time than in the case of flat dipping to produce a satisfactory electrical joint. Another advantage is that since the stream of solder is derived from below the free surface of the bath it is free from oxides or other contaminants.

Preferably the stream of solder is directed vertically upwards against the flux coated front surface of the panel, although it may be directed at any other convenient angle to the surface. Most conveniently, the solder is ejected upwardly against the panel through a rectangular nozzle of a length exceeding the width of the panel, and the panel is moved relatively to the jet until its entire surface has received an application of solder.

The invention includes apparatus for soldering components to the panel of a printed circuit comprising a tank to contain molten solder, a nozzle having a narrow, elongated rectangular mouth disposed horizontally and above the normal level of solder in the tank, a pipe in the tank communicating at one end with the lower end of the nozzle and open at the other end to the solder in the tank, a pump in the pipe which is operative to discharge solder upwardly from the mouth of the nozzle in a wave having a level crest, and horizontal rails adjacent the narrow ends of the mouth of the nozzle for supporting the panel and permitting it to be traversed over the nozzle with its undersurface in contact with the crest of the wave of solder.

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One specific apparatus for carrying the invention into effect will now be described in detail, by way of example, with reference to the accompanying diagrammatic drawing, in which:

FIG. 1 is a vertical section through the apparatus,

FIG. 2 is a section on the line II—II in FIG. 1,

FIG. 3 is a section on a larger scale on the line III—III in FIG. 1, and

FIG. 4 is a perspective view of the nozzle partly in section.

The printed circuit to be soldered is made in any conventional way, e.g. by applying a coating of copper to a panel of insulating material, applying a pattern of acid-resistant ink to the metal coating, etching away the metal unprotected by the ink and removing the ink. Holes are then made in the panel at the points where components are to be connected to it. The components are then assembled on the back of the panel by pushing their contact pins through the holes and flux is applied, e.g. by spraying, to the front surface of the panel.

In the drawing, the panel is indicated at **10**, certain of the components on the panel at **11** and the downwardly projecting pins at **12**. The panel **10** is supported with its flux coated side downwards by a carriage **13**, having wheels **14** by which it can be traversed along horizontal rails **15**.

The rails **15** are located above a tank **16** containing molten solder **17** heated either by an immersion heater or by an external gas heater. Supported in the tank by suitable brackets, not shown, is a pipe **18**, open at one end to the solder in the tank and connected at the other end to a nozzle **19**. The nozzle has a narrow, elongated rectangular mouth **20** extending horizontally above the level of the solder in the tank and with its longer dimension extending transversely to the rails **15**.

In the pipe **18** is a pump constituted by a bladed impeller **21**, driven by a variable speed electric motor **22** through a belt drive **23**. The pump delivers solder, derived from a point below the top level of the solder in the tank, upwardly through the mouth **20** of the nozzle as a wave, the expelled solder being directed against the undersurface of the panel **10** and cascading back into the tank.

It is important that the crest of the wave of solder should be level throughout its length. The nozzle **19** is accordingly designed so that there is no increase in its cross-sectional area from its lower end to its mouth. Consequently no eddies can form in the solder in the nozzle. In the case illustrated the cross-sectional area of the pipe **18** is 9 sq. ins. and the cross-section of the nozzle decreases progressively from its lower end to 4 sq. ins. at its mouth **20**, the mouth being 8 inches long and ½ inch wide. To avoid vortex formation by the pump **21**, vanes **24** are provided at the inlet to the pipe **18**. The nozzle **19** is shaped so that the speed of flow of the solder through it is even throughout its cross section, and the pipe **18** contains a flow straightener **25** of honeycomb form which ensures laminar flow of the solder.

Control of the height of the wave **23** of solder expelled from the mouth of the nozzle is effected by variation of the speed of the motor **22**. The wave of solder must make contact with the undersurface of the panel **10** but must not splash over into contact with the upper surface of the panel. Where the pins **12** project downwardly, as shown from the panel **10** the wave **23** of solder may need to have a height of up to ½ inch. If, however, the pins are turned to lie flat against the undersurface of the panel, the panel may be supported at a lower level and the height of the wave can be considerably reduced.

By suitably dimensioning the pipe **18** and the nozzle **19** and by providing the vortex-preventing vanes **24** and the flow straightener **25**, an overflow from the nozzle is ob-

Figure B.131: Rudolf Strauss invented wave soldering for printed circuits, or surface mount technology.

3,056,370

3

tained which is both level and free from turbulence. The level of the rails **15** is such that the flux-coated surface of the panel **10** is brought into contact with the wave of solder issuing upwards from the nozzle, the pins **12** being clear of the end of the nozzle. The carriage **13** may be pushed along the rails **15** in succession by mechanical means.

The solder effectively joins the pins to the circuit, and remains as a surface coating on the metal portions of the printed circuit. Since it does not wet the insulating backing, the portions of the panel between the printed conductors receive no coating of solder. A non-corrosive electrically insulating flux residue may remain on these portions of the panel.

What we claim as our invention and desire to secure by Letters Patent is:

1. Apparatus for soldering components to panels of a printed circuit comprising a tank to contain molten solder, a nozzle having a narrow, elongated, rectilinear, upwardly opening horizontal mouth disposed above the normal level of the solder in said tank, a pipe in said tank extending upwardly at one end into communication with said nozzle and open at the other end to the solder in said tank, said nozzle decreasing progressively in cross-sectional area from said pipe to said nozzle mouth, a plurality of radially arranged vanes positioned at the entry end of the pipe and before the pump, a honeycomb positioned in the pipe between the pump and the nozzle, and a rotary pump in the pipe for discharging the molten solder upwardly through the mouth of said nozzle in a continuous, smooth, non-turbulent wave overflowing the mouth of the nozzle, while remaining in contact with the nozzle, and having a level rectilinear crest appreciably above said nozzle mouth.

2. Apparatus as defined in claim 1, including means associated with said tank and nozzle for traversing said panels in a continuous rectilinear motion across said overflowing wave of solder and at a predetermined constant level relation to said wave transversely to its said rectilinear crest, with the undersurface of each panel con-

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tacting the said crest but spaced from the mouth of said nozzle.

3. Apparatus for soldering components to panels of a printed circuit comprising a tank to contain molten solder, a nozzle having a narrow, elongated, rectilinear, upwardly opening horizontal mouth disposed above the normal level of the solder in said tank, a pipe in said tank extending upwardly at one end into communication with said nozzle and open at the other end to the solder in said tank, said nozzle decreasing progressively in cross sectional area from said pipe to said nozzle mouth, a honeycomb positioned in the pipe between the pump and the nozzle, and a rotary pump in the pipe for discharging the molten solder upwardly through the mouth of said nozzle in a continuous, smooth, non-turbulent wave overflowing the mouth of the nozzle, while remaining in contact with the nozzle, and having a level rectilinear crest appreciably above said nozzle mouth.

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Figure B.132: Rudolf Strauss invented wave soldering for printed circuits, or surface mount technology.

PATENT SPECIFICATION 715,055

Inventors :—DEREK HAROLD RICHARD BARTON and RUDOLF SIEGFRIED STRAUSS.

Date of filing Complete Specification : Oct. 24, 1952.

*Application Date : Nov. 5, **1951**. No. 25823/**51**.*

*Complete Specification Published : Sept. 8, **1954**.*

Index at Acceptance :—**Class 82(2)**, M.

COMPLETE SPECIFICATION.

Improvements in Soldering Fluxes.

We, FRY'S METAL FOUNDRIES LIMITED, of Tandem Works, Merton Abbey, London, S.W.19, a British Company, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement :—

This invention relates to rosin soldering fluxes. By the term " rosin " we mean the naturally occurring product, known sometimes as colophony, gum rosin, wood rosin or tree rosin, which is obtained from coniferous trees such as the pine tree.

A measure of the activity of a rosin flux is its spreading power on copper as determined by a spreading test. One known type of spreading test consists in placing on a thin sheet of copper a pellet, weighing 0.2 gms., of solder containing 42% by weight of tin and 58% by weight of lead. The pellet is surrounded with a small quantity of the flux under test, and the plate is then heated to 300° C. to melt the solder, and maintained at that temperature until the molten solder spreads no further. The average diameter of the area covered by the solder after the test is then determined.

Various organic activating agents have been proposed for incorporation in rosin fluxes for the purpose of improving their spreading power. Thus it has been proposed to incorporate in the flux from about 0.2—8% of cetyl pyridinium bromide (" Fixanol " C). " Fixanol " is a Registered Trade Mark.

Taking the diameter of the spread of the solder in accordance with the above test, when fluxed with plain rosin, as 1.00, the diameter of spread when the solder was fluxed with rosin activated with 4% by weight of " Fixanol " C was found to be 1.30.

One object of the invention is to effect a further improvement in the spreading power of rosin soldering fluxes.

According to the invention, the spreading power of rosin soldering fluxes is improved by incorporating therein up to 5% by weight, measured on the weight of the rosin, of hydrobromide of morpholine or of a hydrobromide of an N-alkyl substituted derivative of morpholine.

We find that best results are achieved with a flux containing up to 2% by weight of morpholine hydrobromide, the rest rosin, or a flux containing up to 4% by weight of N-methyl or N-ethyl morpholine hydrobromide, the rest rosin.

When such fluxes were tested by the above test the following results were obtained :—

Activating Agent.	*Spreading Factor.*
1% by weight morpholine hydrobromide	1.80
1% by weight N-methyl morpholine hydrobromide ..	2.30
2% by weight N-ethyl morpholine hydrobromide ..	2.27

In the case of fluxes for use when soldering electrical connections and for other applications in which it is of extreme importance that the residue should be substantially non-corrosive, we find it desirable to include in the flux a proportion of cetyl pyridinium bromide (" Fixanol " C) and to restrict the upper limit of the content of the morpholine derivative to 4%. The invention accordingly includes a rosin soldering flux containing up to 5% of " Fixanol " C and 0.5—4% of N-methyl morpholine hydrobromide or N-ethyl morpholine hydrobromide. These fluxes are found to give a residue which is substantially non-corrosive. The following

[*Price*: 2*s*. 8*d*.]

Figure B.133: Rudolf Strauss invented wave soldering for printed circuits, or surface mount technology.

are the results obtained when certain fluxes according to the invention, containing "Fixanol" C, are subjected to the above test :—

Composition of Flux.	*Spreading Factor.*
1% by weight "Fixanol" C, 1% by weight N-methyl morpholine hydrobromide, the balance rosin	1.76
1% by weight "Fixanol" C, 1% by weight N-ethyl morpholine hydrobromide, the balance rosin	1.89

The fluxes according to the invention may be utilised in various forms. Thus they may be used in granulated form or as dry powders. They may be used in solution in ethyl alcohol or other suitable solvent, preferably at a strength of 2—5 lb. of activated rosin per gallon of solution. They may be put up in paste form, the paste consisting of a mixture of 60—80% by weight of activated rosin and 40—20% by weight of ethyl alcohol or other suitable solvent. They may also be put up as solder creams, containing 50—90% by weight of finely powdered solder and 50—10% by weight of the flux paste just referred to. Finally, they may be used in the form of cored solder wire, consisting of a wire of solder having a core or grooves filled with the flux, the weight of flux being from 1—4% of the total weight of the solder wire.

What we claim is :—

1. A soldering flux, consisting of a main body of rosin and, as an activating agent, up to 5% by weight of hydrobromide of morpholine or of a hydrobromide of an N-alkyl substituted derivative of morpholine.
2. A soldering flux according to Claim 1, containing up to 2% by weight of morpholine hydrobromide.
3. A soldering flux according to Claim 1, containing up to 4% by weight of N-methyl morpholine hydrobromide.
4. A soldering flux according to Claim 1, containing up to 4% by weight of N-ethyl morpholine hydrobromide.
5. A soldering flux, consisting of a main body of rosin, up to 5% by weight of cetyl pyridinium bromide and 0.5—4% by weight of the hydrobromide of N-methyl morpholine or of N-ethyl morpholine.
6. A soldering flux according to Claim 5, containing about 1% by weight of cetyl pyridinium bromide and about 1% by weight of N-methyl morpholine hydrobromide.
7. A soldering flux according to Claim 5, containing about 1% by weight of cetyl pyridinium bromide and about 1% by weight of N-ethyl morpholine hydrobromide.

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London, W.C.2.

PROVISIONAL SPECIFICATION.

Improvements in Soldering Fluxes.

We, FRY'S METAL FOUNDRIES LIMITED, of Tandem Works, Merton Abbey, London, S.W.19, a British Company, do hereby declare this invention to be described in the following statement :—

This invention relates to rosin soldering fluxes. Various organic activating agents have been proposed for incorporation in such fluxes for the purpose of improving the fluxing properties of the rosin. Thus, Specification No. 557,816 proposes the incorporation in the flux of from about 0.2—8% of cetyl pyridinium bromide, and more particularly of the commercial form of that substance known as "Fixanol" C. "Fixanol" is a Registered Trade Mark. The object of the present invention is to effect a further improvement in the fluxing properties of rosin soldering flux.

The rosin soldering flux according to the invention contains, as an activating agent, 0.4—5%, measured on the weight of the rosin, of a hydrobromide of morpholine or of an N-alkyl substituted derivative of morpholine, such for example as N-ethyl and N-methyl morpholine. These activating agents materially improve the fluxing properties of the rosin.

We also find that the effectiveness as a flux of resin containing up to 5% by weight of cetyl pyridinium bromide ("Fixanol" C) is substantially increased by the addition of certain of these activating agents. Thus a rosin flux containing 1% of N-ethyl or N-methyl morpholine hydrobromide and 1% of "Fixanol" C has enhanced fluxing properties and is suitable, due to the substantially non-corrosive nature of the residue, for the soldering of electrical connections.

The fluxes according to the invention may be put up as cored solder wire or in solution or paste form, using a conventional vehicle, such as alcohol.

BREWER & SON,
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5–9 Quality Court, Chancery Lane,
London, W.C.2.

Abingdon : Printed for Her Majesty's Stationery Office, by Burgess & Son (Abingdon), Ltd.—1954.
Published at The Patent Office, 25, Southampton Buildings, London, W.C.2,
from which copies may be obtained.

Figure B.134: Rudolf Strauss invented wave soldering for printed circuits, or surface mount technology.

Jean Medawar and David Pyke. 2000. *Hitler's Gift: The True Story of the Scientists Expelled by the Nazi Regime.* New York: Arcade. p. 93.

Rudolf Strauss [...] met and became friends with Paul Eisler, a refugee from Austria, who had invented the printed electrical circuit board, which revolutionized the electronics industry. Strauss invented a technique for soldering thousands of electric connections in one operation. His 'wave soldering' machine, built in 1958, is still being made in a sophisticated form all over the industrial world. [...]

Recognition of Eisler's work took years. In late 1957 Lord Hailsham told the Royal Society that he rated the printed electric circuit as important an invention as penicillin or atomic fission.

Boris Chertok. 2005–2012. *Rockets and People.* 4 vols. Washington, DC: U.S. Government Printing Office. [https://www.nasa.gov/history/history-publications-and-resources/nasa-history-series/rockets-and-people/]

[Vol. 1, pp. 217–218:] We received "directives" and instructions thought up by God knows who, such as: "While inspecting German factories and laboratories, don't get carried away with intellectual achievements, but first and foremost compile a list of the types and number of machine tools, industrial engineering equipment, and instruments. As far as documentation and specialists are concerned, that is a matter of our judgement, and initiative will not be prohibited."

[Vol. 1, pp. 220–222:] DIARY ENTRY. 29–30 April 1945.

We are inspecting DVL [Deutsche Versuchsanstalt für Luftfahrt, or German Aviation Research Institute]. Administrative building. Archives, papers, personal documents—in safes. How do you open a safe? The sergeant and soldier detailed to us from the BAO already have experience. The soldier holds a large chisel against the safe doors. The sergeant, a "non-combatant" well over forty, delivers a precise, powerful blow with a heavy sledgehammer. Usually it opens the first time. Sometimes if the safe is especially "difficult," it takes three or four blows.The safes are full of reports with a red stripe,"Geheim!" (Secret) or "Streng Geheim!" (Top Secret). We leaf through the pages— reports, reports about all kinds of tests.

"DVL"—this is, after all, the equivalent of our TsAGI, LII, and Air Force NII all rolled into one. There is neither the time, nor the physical capability to read and study them.

The general has ordered us to list everything, load it into boxes, and send it by plane to Moscow. But where are we going to get as many boxes as we need? It turns out that the rear services and BAO do have them, and can organize everything! But there isn't even time to make a list of the reports.

Laboratory building. The aeronavigation laboratory is filled with benches for testing onboard instruments. The photochemical laboratory, the laboratory where materials are tested for strength and fatigue, vibration benches. A bombing and firing sights laboratory, accelerometer calibration units. And what magnificent drafting and designing equipment! I am envious of the German designers' workstations. Aside from the nice Kuhlman drafting unit, the swivel chair, and comfortable desk with lots of drawers, it is full of details, and everything has its place. Oh, this German love for details and this exactness, which has engrained such top-notch work into the culture.

The thing that every laboratory needs the most and that is in the shortest supply is the Siemens four-mirror oscillograph. There we found various models: two-, four-, and six-mirror models. Without them, conducting research on rapidly occurring dynamic processes is impossible. This is a new epoch in the technology of measurements and engineering research. In Moscow, at NII-1 we had only one six-mirror oscillograph for the entire institute. And these Germans had so many! No,we no longer felt the hatred or the thirst for vengeance that had boiled in each of us earlier. Now it was even a pity to break open these high quality steel laboratory doors and to entrust these diligent but not very careful soldiers with packing priceless precision instruments into boxes.

But faster, faster—all of Berlin is waiting for us! [...]

The electric instrument laboratory was fantastic! There were so many unique (for us) instruments of all types and ranges from the world-renowned German firms Siemens, Siemens und Halske, Rohde & Schwarz, and the Dutch firms Philips, Hartmann-Braun, and Lorentz! And again— photographic enlargers, slide projectors, movie projectors, chemicals, bulky stationary cameras, cine-theodolites, phototheodolites, and optics of incomprehensible purpose...

We christened a separate building the electrophysics building because of its contents. Electronic low- and high-frequency frequency meters, wave meters, precision noise meters, octave filters, harmonic analyzers, nonlinear distortion factor meters, motor generators and dynamotors for various voltages, even the scarce cathode ray (now called electronic) oscillographs. The richest building of all was the one containing radio and acoustical measurement equipment.

We are writing the addresses of our firms on the boxes:"P.O. Box" so-and-so. But what will really happen to this stuff? Who will meet the airplanes in Moscow?"

[Comments added by Chertok in the 1990s:] After much time had passed, I indeed never found a single report from that mass of secret and top-secret reports that I had sent from Adlershof. They were dispersed over LII, TsAGI, NISO, and other aircraft industry institutions. Only about one-tenth of the instruments that we had sent ended up at NII-1, provoking a justifiable reaction from my immediate chief. At NII-1 in Likhobory, they began preparing the next, independent expedition to Germany. This time, on their own airplane.

[Vol. 1, p. 230:] In the ensuing days, we continued to investigate the Askania facility. The factory had a broad spectrum of interesting items and competed with Siemens for our interest. We discovered another large factory and design bureau in Mariendorf. Here I finally found intact actuators for the V-2, as well as similar actuators for aircraft autopilots. Sets of autopilot equipment intended for delivery were assembled on the test stands. With astonishment, we discovered shops with submarine periscopes, periscope range finders, bombsights, and anti-aircraft fire control equipment (PUAZO). There were special cockpits equipped for crew training and testing where blind flight conditions were simulated. There was a rather large shop that was involved with purely optical production. Optical glass polishing machines stood next to the finished products—virtual mountains of lenses of various diameters up to 50 centimeters! The test laboratories were excellently equipped. They contained pressure chambers, thermal vacuum chambers, vibration stands, and rainfall simulators. Every area was equipped with all-purpose and special-purpose measurement instruments and also with our dream instrument: the Siemens multi-mirror oscillograph!

[Vol. 1, pp. 231–233:] DIARY ENTRY. 9 May 1945.

Our visit to the Telefunken factory in Zehlendorf was very interesting.

Originally it was a radio tube factory, but in the last few years it has switched almost completely to radar. In contrast to many other enterprises here we found almost all of the personnel, including chief engineer Wilki and his immediate staff. Chistyakov and I already spoke German rather briskly. For that reason we did not need an interpreter. Wilki and the production chief showed us the factory and laboratory. Wilki directed research in the field of centimetric waves. His laboratory, which is not located within this factory, has been conducting a thorough study of American and British radar installed on aircraft as well as radar sights for bombing and reconnaissance.

According to the assessments of the German specialists, the Americans and Brits have been very successful in the field of radar—especially in submarine warfare. Their aircraft detect periscopes from tens of kilometers away. In this regard, they have also worked a great deal on instruments to alert submarine crews that they have been illuminated by aircraft radar.

At the factory, they were involved in the series production of aircraft radar using American and British experience. The radar manufacturing shops were well equipped with electronic monitoring instruments.The factory turned out to be relatively new. They finished building it in 1939. In all, counting the Ostarbeiter, some 6,000–7,000 people worked there. Of that number, 3,000 were engineers and technicians. They experienced no shortage of materials or supplies.

The Lorenz and Blaupunkt companies provided large television screens for the radar and receivers."But you didn't study Soviet radar?"

According to information from our military, they did not find radar on a single one of your airplanes. And among the captured materials that they were able to provide us during our troops' offensive, there was also nothing of interest.We decided that the Russians had safeguarded this technology so well that it did not fall into the hands of our military."

I think that he spoke of "safeguarding" to be polite. In actual fact, they had surmised that during the war we had virtually no aircraft radar and radar sights. [...]

We wore them out with questions about other firms and studies. Like all radio and electronics specialists, they were well informed about related firms and developments and told us that Telefunken and Lorentz were involved primarily in radar technology for air defense purposes, while Askania and Siemens were involved in remote control. Over the past six months, many directors along with staff and laboratories had been moved to Thuringia and Westphalia.They knew that the secret weapon, the "vengeance rocket," was being made in Peenemünde. None of them had ever been there—it was very secret. But other divisions of Telefunken were building ground-based radars and stations for the radio control of rockets.

The tube shops were excellently equipped. Here they were making magnetron tubes with a pulse power of up to 100 kilowatts!

That is how we first heard about the Kaiser Wilhelm Institute in Dahlem. Later, while exchanging impressions about everything that we had seen at Telefunken and then at Lorentz, we mused how, in spite of the strictest secrecy, scientific knowledge and its progress are ultimately shared between countries.Thoughts are transmitted between scientists over some sort of telepathic channel. Not only did we all toil separately, but we believed, and quite rightly, that the Germans were our mortal enemies. Our allies, out of consideration for secrecy, hardly shared their work with us. Nevertheless, with the exception of small lapses, parallel developments were taking place in the scientific fields of radar, nuclear energy, and rocket technology.

[Vol. 1, pp. 234–235:] DIARY ENTRY. 10 May 1945.

We barely managed to make our way to the Lorentz company in Tempelhof. [...]

Even before our visit, the factory itself had been taken over by the "trade union" officers of Moscow's radio factories.They had also appropriated from the basement, but did not interfere with our inspection. We talked with the German specialists for about two hours.They showed us transmitters for 3- and 9-centimeter range radars. It was interesting that the laboratory, which specialized in the development of television receivers, was quickly reoriented for instruments with large radar observation cathode ray tubes.

The factory produced ground-based radio stations with large rotating antennas for guiding aircraft to their airfields. We ascertained that in practice these radar stations were also used to control air battles in the direct coverage zone. We were surprised by the number of circular scanning stations with large screens that made it possible to see hostile aircraft and distinguish them from one's own. The Germans claimed that they had already produced around one hundred of these stations. It was hard to believe, considering the exceptional complexity and labor intensity of the system. Development of the Freya radar began as early as 1938. It enabled the detection of an aircraft at a distance of up to 120 kilometers. The Würzburg radar with a spherical antenna was developed to control anti- aircraft fire. Night fighters homed in on the target using the powerful "Würzburg Giant" radar station. At the beginning of the war, all of the German radar technology was in the decimeter range. The German engineers advised us, "Our war with the Brits was fought not only on the battlefield and in the air, but also in laboratories.They had already achieved great success as early as 1942 thanks to their daring switch to the centimeter range. At that time we did not have the same tube technology."

[Vol. 1, p. 235–238] He was Aleksandr Ivanovich Shokin, representing the GKO Council on Radar. At that time I had no way of knowing that I had met with the future deputy minister of the radio engineering industry, who would become the minister of the electronic industry. I would have the occasion to meet with him more than once in the latter period of his hypostases, almost up until his demise in 1986.

At that time in Berlin he said bitterly that, in spite of serious scientific achievements, our radio engineering and electronics industry was undoubtedly poorly developed compared with what we were seeing here. On this visit, as during all of our visits to German factories and laboratories, we were stunned by the abundance of instruments—both universal and special-purpose, especially in comparison to their scarcity at home. Vacuum-tube voltmeters, oscillographs, audio-signal generators, filters of all kinds, standard amplifiers, wave meters, frequency meters, etc., etc.—and all of it was high quality. Instrument models that we had considered precious before the war were continually showing up here. Not one of our institutes, factories, or laboratories could even imagine such abundance.

But indeed the war of the laboratories was not only a war of pure intellects. Each “intellect” had to be armed with the most advanced instruments for scientific research. This required a well-developed instrumentation industry.

Alas, even today, fifty years after the war, we do not fully appreciate the strength of the research scientist’s laboratory weaponry, much less that of the engineer. Incidentally, one of the burning topics for the past ten years, our scandalous lag behind in the field of personal computers, has not only economic but also ideological roots: indifference to the specific needs of the human being as an individual, since, in the opinion of the country’s senior leadership, above all, we had to be ahead of the “entire planet” in the smelting of steel and iron, in coal mining, oil production, and in the number of tractors and machine tools produced.

These garish indicators got through to the dullest bureaucrats at the highest levels of the Party-State hierarchy, but for the longest time they did not comprehend why it was necessary to lead or at least be on the level of an average capitalistic country in terms of providing measurement technology, not to mention expensive computers. And when it suddenly occurred to us,it turned out that we were one of the most backward countries in the world in that field.

Well, these are modern issues, but back then in Berlin and its surrounding areas we continued to collect worthwhile literature and send it to Moscow. I also insisted that we send back a wide variety of measurement technology.

Measurement equipment was my weakness during our collection of “spoils.” I carefully prepared the cases containing instruments that had been retrieved by Red Army soldiers from the aerodrome maintenance battalion, then and waited for “my” airplane to deliver them to “my” institute.

By the middle of May, our *troika*—reinforced by several more specialists from NISO and LII, including Professor Sergey Nikolayevich Losyakov, had already put together a more or less clear picture of the instrument and radio industry in Greater Berlin. Our list contained more than thirty enterprises, each of which surpassed our own in terms of technology and production. The most interesting were the laboratories and factories of Askania, Telefunken, Lorenz, Siemens, AEG, Blaupunkt, and Loewe Radio.

For us it was a novelty that the company List, which specialized only in the development and mass-production of multi-pin plug connectors, existed and flourished among the Germans. They had produced hundreds of thousands of connectors for German aircraft and rockets.The concept was very simple, but the engineering and production involved were fundamentally new to us. This innovation developed in response to the extreme complexity of the electrical circuits used in flying vehicles. The connectors enhanced rapid assembly and allowed electrical components to be connected and disconnected reliably during the repair and testing of individual compartments.

The very term *shteker*, or plug connector, made its way into the Russian language from the Germans after the war. Throughout history much has been transferred to the victors from the vanquished. Only after the war did we come to appreciate what a tremendous technical role such a seemingly simple device as the plug and socket connector was destined to play in aircraft and rocket technology! The Germans spent years developing reliable connectors, and introduced into aircraft and rocket technology the standard List *shteker*, which had from two to thirty pins. We needed three years to reproduce connectors that were as reliable. However, during our first years of mastering rocket technology they gave us a lot of trouble.

Now our industry produces connectors—both tiny and enormous, airtight, onboard and ground-based—to connect and remotely disconnect more than one hundred electric circuits. Despite all of these achievements, the problem of connector technology remains one of the most complex in the entire world. This is why there are booths at every international aerospace exhibition advertising hundreds of modifications of quick and reliable cable connectors. Dozens of powerful companies in many countries produce them by the millions.

We were interested not only in individual factories, but also in the organization and structure of the instrument and radar industry. German companies worked on a lot of technical problems on their own initiative, without waiting for instructions “from the top.” They did not need the decisions of the Gosplan or People’s Commissariats, without which not a single factory of ours could produce anything. Before the war, the electric measuring technology, instrument, and radio industries had developed rapidly to conquer the entire European market, and their products had successfully competed with those of the United States. The companies Hartmann-Braun, Telefunken, Anschütz, Siemens, Lorentz, AEG, Rohde & Schwarz, Askania, and Karl Zeiss enjoyed worldwide fame long before World War II. This created a solid technological base, which we simply did not have in these industries on the required scale at the beginning of the war.

Our general-purpose electrical instrument industry, our aircraft industry, and also our nautical instrumentation industry were all housed in just a few buildings in Moscow and Leningrad (Elektropribor, Teplopribor, and Svetlana in Leningrad; Aviapribor, the Lepse Factory, Elektrozavod, and Manometr in Moscow).

It is revealing that when we began to reproduce technology for the V-2 rocket after the war and develop our own new rockets, we found out that in our country there was only one factory, Krasnaya Zarya in Leningrad, that was able to manufacture such a mundane device as the multi-contact electrical relay. In Germany, Telefunken had three such factories and Siemens had at least two. This is one of the reasons that German weapons production did not drop, but continuously increased until mid-1944, despite the continuous bombing that Allied aviation inflicted on German cities.

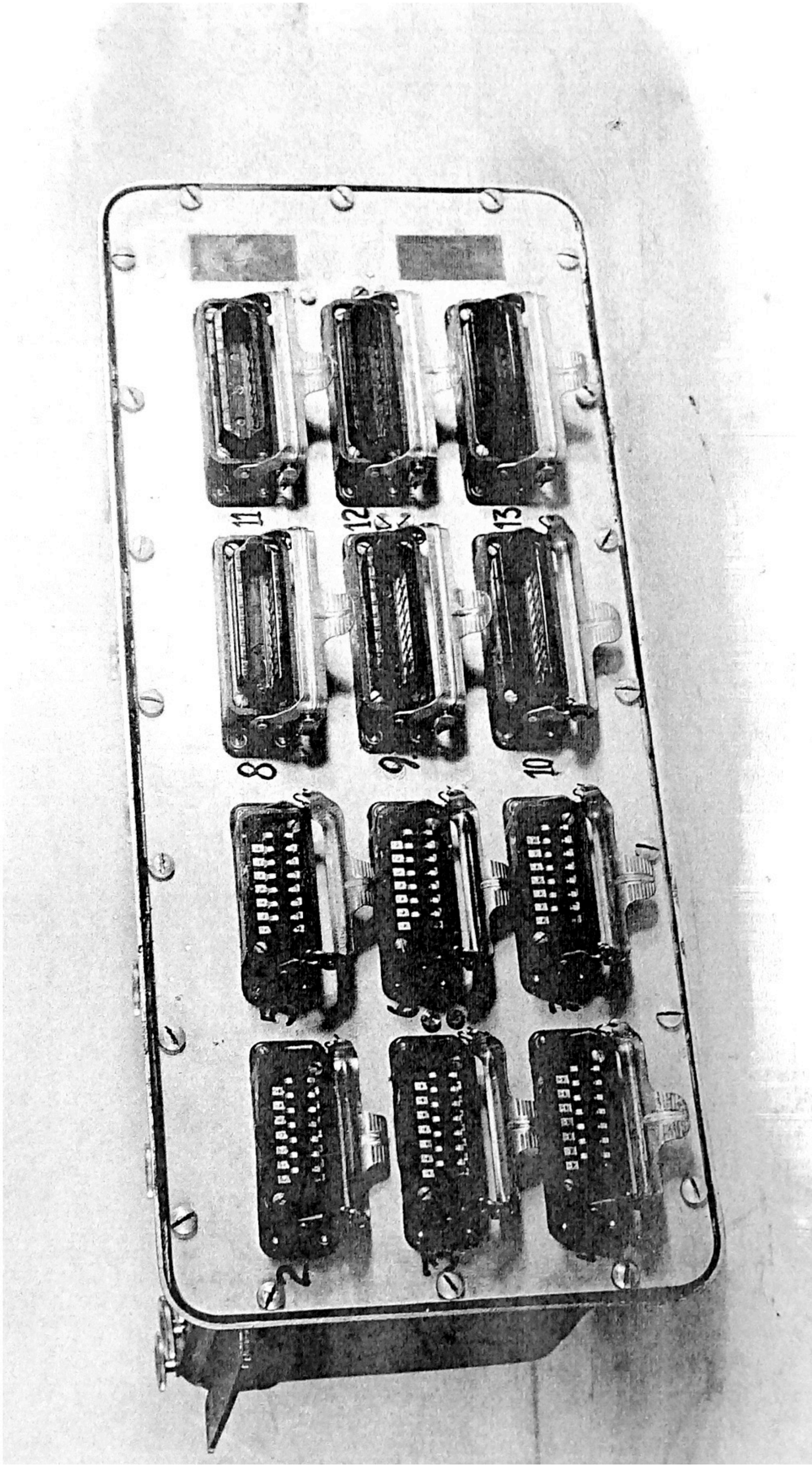

Figure B.135: Panel of multi-pin connectors from an A-4 (V-2) rocket produced during the war [Peenemünde Archive, Folder ARK 41].

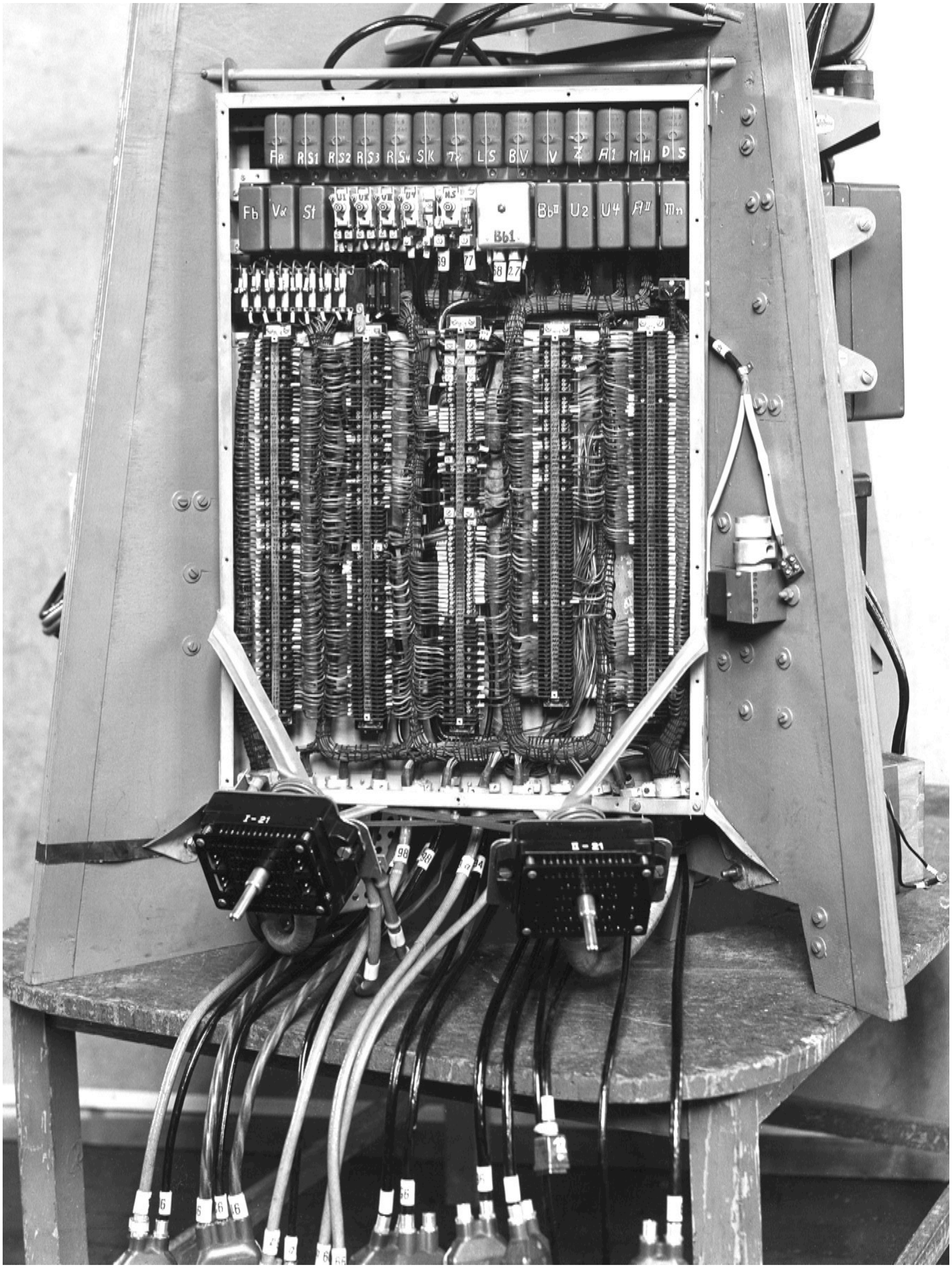

Figure B.136: Part of the guidance system for an A-4 (V-2) rocket (1943) [Deutsches Museum Archive, photo 10890].

B.3 Integrated Circuits

[Even further miniaturization of electronics required moving from individual electronic components to integrated circuit chips that could contain large numbers of components on the same semiconductor substrate.

In 1949, Werner Jacobi (German, 1904–1985) filed a West German patent application on integrated circuits on behalf of Siemens & Halske. Since there were a large number of German inventors who filed patents on their wartime work when the (West) German patent office reopened in 1949, it is quite likely that Jacobi's patent application was based on experimental work that he had conducted at Siemens & Halske during the war (pp. 2816–2817).

Kurt Lehovec (Bohemian/Austrian/Czech, 1918–2012) developed advanced semiconductor devices for Germany in Prague during the war. After the war he was extensively interrogated by the United States and then moved to the United States (as part of Operation Paperclip), where he filed patents on transistors, integrated circuits, and light emitting diodes. See pp. 2757–2763, 2818–2832, and 2895–2910. Lehovec's integrated circuit designs may well have been based on wartime work, but even if they were early postwar ideas, they preceded the claims of American engineers who later worked on integrated circuits.

Other German-speaking scientists developed transistor fabrication methods that made integrated circuits practical:

- Herbert Kroemer (German, 1928–) invented the drift transistor in 1953, the double-heterostructure laser diode in 1963, and III-V semiconductor heterostructures in 1966. (See pp. 1111, 2833–2845, and 2917–2922.) He won the Nobel Prize in Physics in 2000 (p. 1104).

- Jean Hoerni (Swiss, 1924–1997) and Eugene Kleiner (Austrian, 1923–2003) devised methods of manufacturing silicon transistors at Fairchild Semiconductor; see pp. 1101 and 2846–2861. Through Fairchild and their later companies and investments, they also helped to develop Silicon Valley.

- Karl Heinz Zaininger (German, 1929–) developed modern methods for fabricating field effect transistors (pp. 1102 and 2862–2876).

As shown on pp. 2877–2887, Helmut Gröttrup (German, 1916–1981) and Jürgen Dethloff (German, 1924–2002) invented the smart card, or chip card, in 1966. Earlier, Gröttrup developed avionics systems in Germany during the war and led the German-speaking contributions to the postwar Soviet ballistic missile program (pp. 1874–1881).

As with transistors and printed circuits, much more research should be conducted to determine how much work on integrated circuits was conducted in the German-speaking world during the war, and how much impact German-speaking scientists and knowledge had on the postwar development of integrated circuits in other countries.]

Werner Jacobi (1904–1985)
filed a patent application on
integrated circuits in 1949
(based on wartime work?)

Erteilt auf Grund des Ersten Überleitungsgesetzes vom 8. Juli 1949
(WiGBl. S. 175)

BUNDESREPUBLIK DEUTSCHLAND

AUSGEGEBEN AM
30. JUNI 1952

DEUTSCHES PATENTAMT

PATENTSCHRIFT

Nr. 833 366

KLASSE **21a²** GRUPPE 18 08

p 2589 VIII a / 21 a² B

Dr. phil. Werner Jacobi, Erlangen
ist als Erfinder genannt worden

Siemens & Halske A. G., Berlin und München

Halbleiterverstärker

Patentiert im Gebiet der Bundesrepublik Deutschland vom 15. April 1949 an
Patenterteilung bekanntgemacht am 15. Mai 1952

Figure B.137: Werner Jacobi filed a patent application on integrated circuits in 1949, which was quite likely based on experimental work that he had conducted during the war.

Wenn der Halbleiter in der zur Zeit bekannten Form vielleicht auch nicht geeignet ist, in allen Fällen von Verstärkeranordnungen an die Stelle einer Elektronenröhre zu treten, so scheint seine Anwendung jedoch für bestimmte Zwecke vorteilhaft zu sein. So dürfte er sich u. a. besonders für Schwerhörigengeräte eignen. Aus dieser Zweckbestimmung heraus entsteht die Aufgabe, deren Lösung selbstverständlich auch für jegliche andere Anwendung des Halbleiterverstärkers grundsätzliche Bedeutung z. B. aus preislichen Gründen hat, einen solchen Halbleiterverstärker nicht nur billig, sondern auch raum-, gegebenenfalls auch gewichtssparend aufzubauen. Zur Lösung dieser Aufgabe wird erfindungsgemäß vorgeschlagen, auf den Halbleiter mehrere in verschiedenen Schalt- bzw. Verstärkerstufen wirkende Elektrodensysteme aufzusetzen.

Nimmt man z. B. an, daß der in der Figur als geschnittene Halbkugel gezeigte Halbleiter *K* einen Durchmesser von 2 mm hat, so können je nach der konstruktiven Gestaltung und Anordnung der einzelnen Elektroden mehrere Elektrodensysteme in je einem Abstand von 0,2 mm bei bekanntem Elektrodenabstand von 0,05 mm aufgesetzt werden, ohne daß eine gegenseitige Beeinflussung der einzelnen Systeme eintritt. Diese Elektrodensysteme können dann in bekannter Weise durch Kopplungsglieder zu einem mehrstufigen Halbleiterverstärker zusammengeschaltet werden.

Hierbei können die Kopplungsglieder gegebenenfalls aus einer Halbleiteranordnung bestehen, welche zusätzlich aufgewendet oder durch Einsatz von auf den Halbleiter schon aufgesetzten Elektrodensystemen gebildet werden. Zu diesem Zweck wird die sonst als Eingang dienende Elektrode als Ausgang des Kopplungsgliedes benutzt und umgekehrt, da der Halbleiterverstärker einen niederohmigen Eingang und einen hochohmigen Ausgang benötigt. Man erspart also auf Grund der vorliegenden Erkenntnis, den Halbleiter mit vertauschtem Eingang und Ausgang als Transformator zu benutzen, mit Rücksicht auf diese Eingangs- und Ausgangsverhältnisse besonders auszubildende Kopplungsglieder. In der Figur sind fünf solcher Systeme mit den beispielsweise einzuhaltenden Maßen schematisch angedeutet.

PATENTANSPRÜCHE:

1. Halbleiterverstärker, dadurch gekennzeichnet, daß auf den Halbleiter mehrere in verschiedenen Schalt- bzw. Verstärkerstufen wirkende Elektrodensysteme aufgesetzt werden.

2. Halbleiterverstärker, insbesondere nach Anspruch 1, dadurch gekennzeichnet, daß bestimmte Elektrodensysteme nach Vertauschung von Eingangs- in Ausgangselektrode und umgekehrt als Kopplungsglieder zwischen anderen Elektrodensystemen dienen.

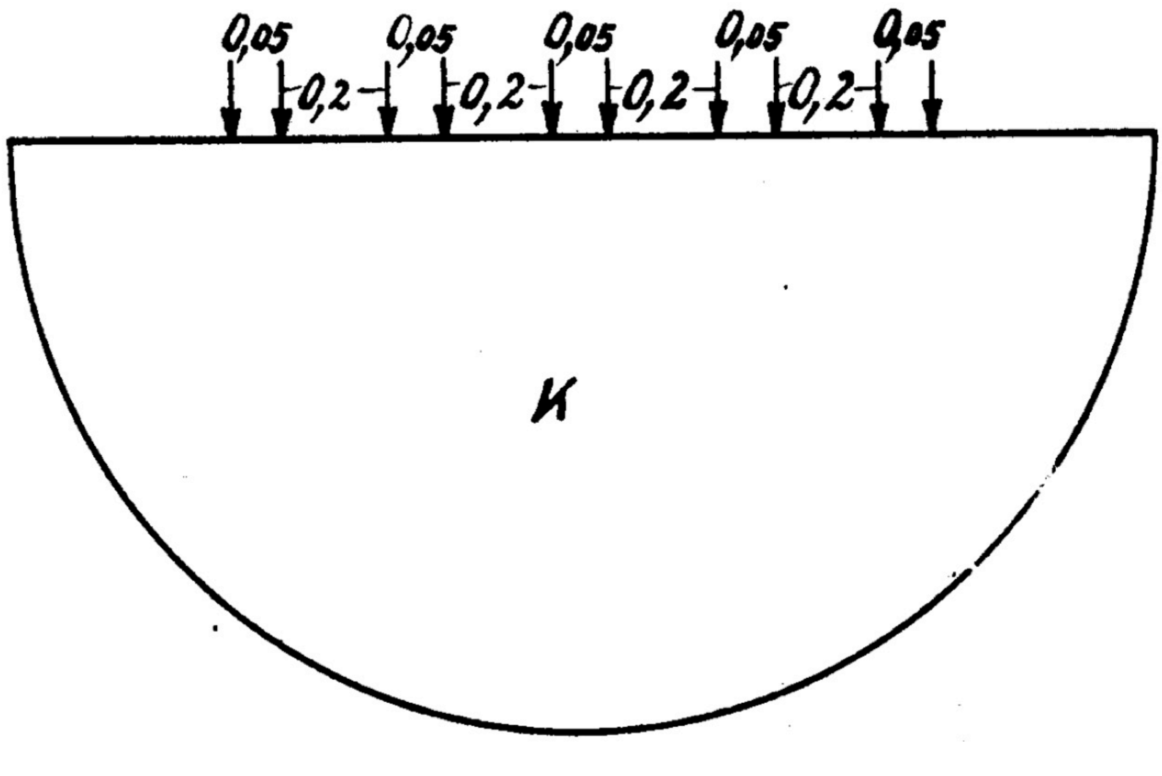

Figure B.138: Werner Jacobi filed a patent application on integrated circuits in 1949, which was quite likely based on experimental work that he had conducted during the war.

DECLASSIFIED
Authority NND968018

**NARA RG 40, Entry UD-75,
Box 28, Folder Edwin Y. Webb, Jr.**

(1) Developments on Heat Image Tubes.

(2) Developments on Mosaics (conglomerations of sensitive elements).

(3) Developments on Lead Selenide and Lead Telluride photocells.

(4) Developments on sensitive high speed bolometers and thermocouples

(5) "Concentrated-arc" lamps - gas filled. Gas having closely spaced electrodes, giving essentially a point source of light.*

(6) Any new or improved gaseous discharge lamps.*

(7) Carbon arc lamps especially rich in infrared, if any.

(8) Tungsten lamps suitable for key-operated signalling, having extremely short time lag for incandescence and nigrescence.

*Information desired on design, operation, spectra, especially infrared spectra; and modulation characteristics, if applicable.

/s/
Harry Dauber
Electronics Engineer.

Penciled note:
Interrogate Dpl. Phys. Kurt Frank and Dr. K. Raithel on heat image tube (both were assistants of Prof. Gudden). ?
Dr. Martin Tren, Nurnberg (Arnim in strasse 5) knows their address (check on Tren in FIAT files, his present address should be available there.

Kurt Lehovec, formerly Prof. Gudden's assistant in charge of rectifier research, should be interrogated and requested to expand on the information provided in FIAT FINAL REPORT No. 706. Lehovae was last known to work at the Weissenberg Laboratory of the SAF near Nuernberg. Documents pertaining to his work are at FIAT.

HD

Dr. Ing. H. Gaertner should be requested to write volume III and IV of his series on the "importance of infrared radiation for military applications."

Figure B.139: Kurt Lehovec developed semiconductor devices for Germany during the war. After the war he was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits [NARA RG 40, Entry UD-75, Box 28, Folder Edwin Y. Webb, Jr.].

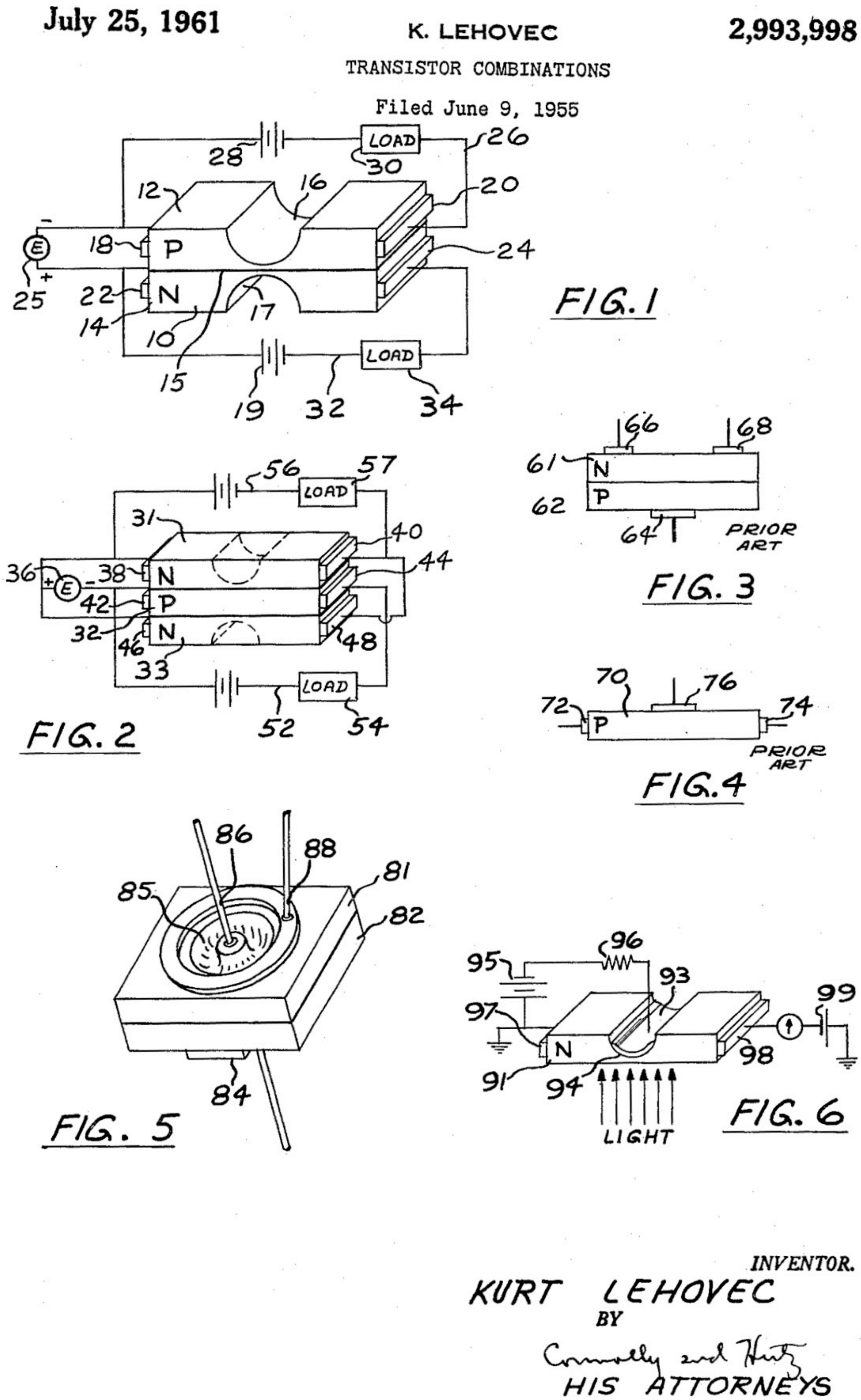

Figure B.140: Kurt Lehovec developed semiconductor devices for Germany during the war. After the war he was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits.

United States Patent Office

2,993,998
Patented July 25, 1961

1

2,993,998

TRANSISTOR COMBINATIONS

Kurt Lehovec, Williamstown, Mass., assignor to Sprague Electric Company, North Adams, Mass., a corporation of Massachusetts

Filed June 9, 1955, Ser. No. 514,220
5 Claims. (Cl. 250—211)

This invention relates to transistor combinations, more particularly to combinations by which signals can be amplified.

Among the objects of the present invention is the provision of novel transistor combinations which have improved amplification characteristics as compared to prior art combinations.

The above as well as additional objects of the present invention will be more clearly understood from the following description of several of its exemplifications, reference being made to the accompanying drawings wherein:

FIG. 1 is a representative showing, partly in schematic form, of one embodiment of a unipolar transistor;

FIG. 2 is a schematic showing of a modified unipolar transistor combination according to the present invention;

FIGS. 3 and 4 are diagrammatic views of prior art forms of unipolar transistors; and

FIGS. 5 and 6 are pictorial representations of modified unipolar semiconductor devices according to the invention.

A unipolar transistor was fully described by W. Shockley in an article, entitled "A Unipolar Field Effect Transistor," which appeared in the November 1952 issue of the Proceedings of the IRE, Volume 40, No. 11, pages 1365–1376. Briefly the device consists essentially of a semiconductor having a conducting channel with an adjacent equipotential layer or gate electrode and a space charged region in the semiconductor between the channel and the equipotential layer. By varying the potential between the channel and the equipotential layer, the effective channel width can be varied and the channel current which is being carried therein is similarly varied. When the current flows along the channel the potential thus varies along the channel, which in turn results in a potential variation between the channel and the equipotential layer. As a result, the width of the space charged region varies along the channel and with sufficiently high potentials imposed on opposite ends of the channel, the space charged region may extend completely over the channel rendering it insulating or may even cause breakdown if maintained. This limits the usefulness of the device. It is thus the intent of this invention to render these unipolar field effect transistors less susceptible to breakdown or alternatively, susceptible to much higher current gain, as well as reliability of operation when used with signal voltages of substantial amplitudes.

It has been found possible to improve the operating curve of the unipolar transistor so as to handle larger signal voltages as well as to produce much higher power gains, through provision of two parallel current flows in a unipolar transistor so as to maintain the width of the charged layer at a uniform dimension. This is readily accomplished as indicated by providing a potential drop along the gate electrode which is the same or similar to the voltage drop along the channel.

For better understanding of this invention refer to FIG. 1, wherein the combination here illustrated has a semiconductor body **10** with two portions **12**, **14** of opposite types of conductivity. Portion **12**, for example, is indicated as having p-conductivity and portion **14** n-conductivity. Between them there is a p–n junction **15** that is relatively elongated. Intermediate of the ends of the rectangular crystal **10** are two depressions **16** and **17**, the

2

former extending down into the p-region of conductivity and the latter extending into the n-region of conductivity. These grooved areas extend fully across the face of the crystal and are readily produced by magnetostrictive cutting followed by a jet electrochemical etch, both techniques of which are well-known to the art. The thickness of the web formed in the crystal between the points of maximum depth of depressions **16** and **17** is preferably very thin, not over 20 mils thick, and preferably much thinner, in the order of 2 mils thickness. Of course, it is to be realized that this lower limit of distance between the two depressions is dictated by the structural strength requirements which the device must exhibit. However, for optimum operational characteristics the thin region separation is desirable although the crystal can readily be supported by outside insulators, such as plastic holders, etc.

At opposite ends of each portion **12**, **14** are positioned electrodes represented at **18**, **20**, **22**, **24**. A bias supply **25** is connected between a correspondingly located pair of electrodes **18**, **22**, on the respective semiconductor portions, to bias the portions in the direction that blocks the passage of current from one body to the other. In the construction of FIG. 1 the bias supply also impresses varying signals "E" between the same electrodes **18**, **22**.

Electrodes **18**, **20** are shown as connected to an output circuit **26** including a source of potential **28** and an output load **30**. Another output circuit **32** is similarly connected between electrodes **22** and **24** and similarly polarized. For purposes of discussion the n-conductivity having electrodes **22** and **24** is designated the "channel" while the p-region with its electrodes **18** and **20** is designated the "gate."

The entire combination of FIG. 1 makes a so-called unipolar transistor amplifier in which the junction **15** provides a space charge effect that is substantially uniform along its length. For the greatest uniformity the semiconductor portions **12**, **14** should have corresponding electrical resistivities, e.g. of the order of 5 ohm-centimeters, and the output circuits should be arranged to apply corresponding potentials so that there are corresponding potential gradations along the effective length of the junction in both the channel and gate portions. The resistivities are controlled by the concentration of doping ingredients added to the respective semiconductor bodies either by diffusion into the solid body, surface melting or by alloying with a liquefied mass from which the bodies are formed.

A feature of the construction of FIG. 1 is that two different amplified output signals are provided so that one can be used independently of the other as a monitor, for example. In addition, where maximum power output is desired, both output signals can be combined as by transformer coupling. This is made possible by the use of the two depressions **16** and **17** so that the dimension of the space charge region could materially effect the current flow in the channel. Herein, in FIG. 1, for one part of the circuit including load **30** the n-region is the channel and the p-region the gate, and for the other part of the circuit including load **34**, vice versa.

FIG. 2 shows a modified construction of the unipolar transistor type in which one region of conductivity is sandwiched between regions of opposite conductivity. The three regions are illustrated as **31**, **32**, **33**, being produced by techniques well-known in the art. Blocking bias, as well as incoming signals, are supplied by source **36** between the intermediate body **32** on the one hand, and the outer two which can be connected together. Electrodes **38**, **40**, **42**, **44**, **46** and **48** are provided on the individual bodies as in the construction of FIG. 1.

The junction construction of FIG. 2 also has two output circuits **52**, **56**. One of these is connected to inter-

Figure B.141: Kurt Lehovec developed semiconductor devices for Germany during the war. After the war he was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits.

mediate body **32** as in the construction of FIG. 1. The second output circuit **56** is connected to both outer bodies **31, 33** in parallel. As a result of this construction, signals in the sandwiched body are subjected to what corresponds to two space charge effects, one at each junction. The voltage amplification of this body will therefore be larger than that of the others. Moreover, signal currents in the outer bodies can be added together by the parallel output connection.

With the construction of FIG. 2 the amplified output is taken from load **54** while load **57** serves merely to maintain the space charge region relatively constant along the junction. For taking a useful output from both loads **54** and **57** depressions similar to those of FIG. 1 must be imposed in the n-regions **31** and **33** completely across the opposing faces of the crystal.

FIGS. 3 and 4 are cross-sectional representations of known prior art devices of the unipolar field effect type. In FIG. 3 the n-region designated as **61** has two electrodes **66, 68** between which an output circuit can be connected. Bias, as well as incoming signals, are supplied between electrode **64** and one of the electrodes **66, 68** using the p-region to produce the gate and the n-region as the channel. In this construction, as well as the construction shown in FIGS. 1 and 2, all of the electrodes are of a non-rectifying nature.

In FIG. 4, however, an area metal contact which extends fully across the width of the crystal is utilized to produce a space charged region which can thus serve as the modulating means for the current flow in the channel. A semiconductor body **70** designated for the purposes of this discussion as having a conductivity of the p-type has spaced output electrodes **72** and **74** of the non-rectifying kind and an intermediate electrode **76** of the rectifying metal type. Thus a space charge effect similar to that described above appears to be provided by the metal electrode **76** when it is electrically biased in the current blocking direction. The bias and the incoming signals are impressed between the metal electrodes **76** and one of the other electrodes. Amplified output signals can be taken thus from between electrodes **72** and **74**. The construction of FIG. 3 is susceptible to breakdown at pinch-off because here, as well as in the Shockley discussion, the space charged region is non-uniform with the junction area. Breakdown additionally may occur rendering the device conducting so that the FIG. 4 construction is limited both in current level, as well as amplification characteristics.

In FIG. 5 is shown an embodiment of the invention constituting an improvement of the unipolar transistor construction shown in FIG. 3. This construction somewhat similar to that of FIG. 3 has a first semiconductive region **81** and a second semiconductive region **82**, the regions having opposite types of conductivity so that a junction exists between them. Output electrodes are illustrated in the form of a central non-rectifying electrode **86** engaging body **81**, and a circular non-rectifying electrode **88** surrounding electrode **86**. Between the two electrodes **86, 88** is produced an annular depression **85** extending into body **81** in order to increase the amplification effect of the device. The depth of the depression should be such as to approach the junction region, e.g. less than 5 mils therefrom. The use of a rotating etch jet as described in the above-identified patent application, Serial No. 460,835 (abandoned), makes a very convenient technique for the annular cutting operation. A suitable biasing electrode of the non-rectifying type can be provided as indicated, for example, at **84**. Using this technique allows close control of the distance between the junction and bottom of cut.

Of course, it is to be understood that where even higher amplification is desired or where it is desired to increase the useful current ranges of the device, thus requiring complete avoidance of the breakdown in the pinch-off region resulting from the non-uniformity of the space

charged region, the construction of FIG. 5 is modified to conform to the concept of FIG. 1. This is readily accomplished by imposing a second annular groove on the opposite surface of the crystal of FIG. 5, namely that surface whereon electrode **84** is shown to be imposed.

Instead of applying the bias to the same electrodes by which the input signals are impressed, other electrodes can be used. In the construction of FIG. 1, for example, bias can be provided between electrodes **18** and **22**, whereas the input signals can be applied between electrodes **20** and **24**. A similar arrangement can be used in the construction of FIG. 2. Furthermore, the bias need not be applied between correspondingly located electrodes, and can be impressed between electrodes **18** and **24**, for example. The incoming signals can also be applied in this manner.

FIG. 6 shows a further form of unipolar transistor construction most useful as a photosensitive device in which the bulk of the crystal **91** is of one conductivity, e.g. n-type, however a diffused junction exists at the region of the depression. In the depression there is an electrode **93**, and at opposite edges of the crystal are non-rectifying electrodes **97, 98**. The electrode **93** and one of the other non-rectifying electrodes **97** are connected to a high impedance bias source shown as a resistive impedance **96** and a voltage source or battery **95**. When the body **91** of such material is exposed to incident light, current flows across the web between electrode **93** adjacent the irradiation site and the crystal **91**. This current flow reduces the bias imposed by the battery **95** through resistor **96**. Thus the space charge in body **91** adjacent to electrode **93** is reduced allowing greater flow of current in the channel between non-rectifying electrodes **97, 98**.

The voltage source **95** biases the electrode **97** in the current-blocking direction. With the impedance **96** relatively low as compared to the blocking impedance of the un-illuminated junction, the potential of source **95** is essentially entirely impressed across this junction **94**. When irradiation takes place, the impedance of the junction is sharply diminished so that the potential across the junction **94** is greatly lowered. The lowering of the potential across the blocking junction causes a corresponding amplified change in the current passed between output electrodes **97, 98** as a result of the decrease of the space charge region. The photoelectric output of the construction of FIG. 6 will accordingly be much higher than that conventionally obtained from present devices, and has a sensitivity to radiation which is remarkable.

Although it is to be fully understood that the following specific examples are representative of the best constructions known to us, they should not in any way limit the scope of the instant invention. Reference should now be made to the drawing of FIG. 1 wherein in its preparation one would take a rectangular slab of p-n junction crystal produced by surface melting techniques or other techniques known to the art, and properly dimension the crystal as follows: The crystal could be a cube of 100 mils in each dimension with the junction region substantially in the center of the plane of the cube. Such a crystal would be of germanium and have for the p-impurity indium and for the n-impurity antimony, with each region of conductivity having a resistivity in the order of 5 ohm-centimeters. As indicated above, such a crystal could be produced by any of the known techniques including the surface melting technique fully disclosed in the copending application of Lehovec et al., Serial No. 364,138, filed June 25, 1953 (abandoned). The depressions **16, 17** should be then imposed across the opposing faces of the crystal first by magnetostrictive cutting with an appropriate tool, which technique is fully disclosed in United States Patent No. 2,580,716. The width of this cut would be approximately 15 mils and extend with vertical sides down to the region adjacent to the junction. After the magnetostrictive cutting has produced a depression of

Figure B.142: Kurt Lehovec developed semiconductor devices for Germany during the war. After the war he was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits.

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approximately 40 mils depth or within 10 mils of the junction area, the final cutting should be accomplished by jet-etching techniques in the manner described in the Tiley et al. article in the December 1953 issue of the Proceedings of the I.R.E., pages 1706–1708, or as described in the co-pending Lehovec et al. application, Serial No. 460,835, filed October 7, 1954 (abandoned). Etching would then continue with the jet-electrochemical etching technique until the depth of the cut is within about 1 mil of the junction or alternatively, until the opposing cuts have a crystal web thickness approximating two mils separating them. Non-rectifying electrodes **18, 20, 22** and **24** would then be imposed upon the crystal after it has been thoroughly etched so as to exhibit rectifying characteristics. This etch would be of the conventional hydrofluoric acid type etch. Copper leads can be imposed as the non-rectifying electrodes by means of using a lead-tin solder containing indium for the p-region, that is electrodes **18** and **20** and antimony for the n-region of conductivity, that is electrodes **22** and **24**. The bias voltage **E25** should, for suitable operation, be 100 v., while potential sources **28, 19** should be 30 v. For the load resistors **30, 34** a suitable value would be about 5000 ohms.

Now referring to FIG. 6, the crystal **91** could be made of n-type germanium, e.g. germanium doped with antimony to a resistivity of approximately 5 ohm-centimeters. A typical dimension for the crystal would be 100 mils by 100 mils rectangular surface area and a thickness of from 10 to 20 mils. A depression would be created fully across the face of the crystal using magnetostrictive cutting techniques followed by electrochemical etching until the depth of the cut approaches within 2 mils of the opposite surface of the electrode. Thereafter the crystal would be thoroughly etched, washed and dried prior to imposition of the area of opposite or rectifying conductivity **94** at the depression or web of the crystal. This fabrication of area **94** would be accomplished by placing a wire of indium on the bottom of the groove and thereafter heating the crystal in a hydrogen atmosphere at 500° C. for 5 minutes. This should result in the penetration of the indium into the germanium web of substantially 1 mil so that a junction is therein produced. The non-rectifying electrodes **97, 98** are readily attached by using lead-tin solder having a minor amount of antimony so as to produce a non-rectifying junction. To attach the electrode **93** a nickel wire is placed adjacent to the indium deposit and fused therein to that region by heating the wire by radiation from a wire loop. The potential of the bias **95** should be in the order of 100 v. so as to effectively cut off current flow and the resistive impedance **96** of about 100,000 ohms. The potential of the battery **99** to induce current flow between electrodes **97, 98** to the n-region **91** should be in the order of 30 v.

A thin semiconductor body or zone can also be made from a semiconductor mass having a p-n junction by causing the junction to shift toward a boundary surface. By having one of the semiconductor portions on one side of the junction doped to a greater degree than the other, a high temperature diffusion treatment will cause the more highly doped section to become larger so that the junction will be effectively shifted. Annealing for from 15 minutes to an hour or more at temperatures of 40 to 50° C. below the melting point of the semiconductor mass will be suitable for the above type of operation. In general a temperature below and within 100° C. of the melting point can be used. The same type of shifting can be provided with the sandwich construction of FIG. 2, for example. In this case both end bodies **31** and **33** will be more heavily doped than the intermediate body **32** so that the diffusing operation will have the desired result. One can also alter the junction width by suitable selection of donor and acceptor materials. To narrow the p-region of a multiple symmetrical n-p-n crystal an n-impurity of higher diffusion constant than that of the p-type impurity would be used; to widen the p-region, an n-impurity of lower diffusion constant would be used, the crystal being subjected to the annealing conditions above.

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Another desirable feature of the annealing treatment is that it increases the breakdown voltage of the junction. Among other benefits is the fact that the higher bias potentials can be used, larger input signals can be handled, etc. By way of example, a one-hour treatment at 900° C. increases the breakdown voltage from 120 to 170 volts.

As many apparently widely different embodiments of this invention may be made without departing from the spirit and scope hereof, it is understood the invention is not limited to the specific embodiments hereof except as defined in the appended claims.

What is claimed is:

1. A transistor combination having a p-conductive semiconductor portion, an n-conductive semiconductor portion, an elongated p-n junction between the portions, a pair of non-rectifying electrodes at corresponding spaced locations on each portion, bias means connected for biasing the junction in the current blocking direction, an input connection for impressing incoming signals between two of the electrodes at corresponding locations on the respective portions, and a pair of output circuits each connected to pass current corresponding to amplifications of said incoming signals through the respective portions from one electrode to the other and cause corresponding electrical variations along the length of the junction.

2. The combination of claim 1 in which there is a third semiconductor portion providing another elongated p-n junction generally parallel with and spaced equally from the first junction, and a third pair of electrodes is located on the third portion at locations corresponding to the other pairs.

3. The combination of claim 1 in which at least one of the semiconductor portions has at least part of its inter-electrode section shallower than the remainder, and the shallow region is not more than about 1 mil thick.

4. A unipolar transistor combination comprising a semiconducting body of one conductivity type, two spaced ohmic contacts on said body, a narrow web section in said body between said two ohmic contacts, a region of opposite conductivity type at one surface of the said narrow web section whereby a P-N junction is formed adjacent said one surface, means to bias said P-N junction in the blocking direction such that the space charge layer at said P-N junction extends over a substantial part of the narrow web section having said one conductivity type, whereby the resistance between said ohmic contacts is governed by the potential applied at said P-N junction.

5. A photoamplifier comprising a semiconducting body of one conductivity type, a portion of said body exposed for receiving light rays, a narrow web formed in said body at said portion, two spaced ohmic electrodes on said body in a geometrical arrangement such that current passed therebetween is forced to flow through said narrow web, means to induce a space charge layer in said narrow web including a rectifying contact at the face of said narrow web opposite said portion, means to apply a bias voltage in the blocking direction to said rectifying contact of such magnitude that said space charge layer extends substantially across the entire narrow web thereby blocking the current path between said two ohmic electrodes in absence of illumination, a resistance in series with said rectifying contact of such a magnitude that the voltage drop across said series resistance due to the photocurrent flowing through said rectifying contact when the narrow web is illuminated reduces the bias voltage at said rectifying contact thus decreasing the width of said space charge layer thereby releasing a part of said narrow web for current flow between said two ohmic electrodes, the resistance between said two ohmic electrodes thus decreasing with increasing light intensity incident on said narrow web.

(References on following page)

Figure B.143: Kurt Lehovec developed semiconductor devices for Germany during the war. After the war he was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits.

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Figure B.144: Kurt Lehovec developed semiconductor devices for Germany during the war. After the war he was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits.

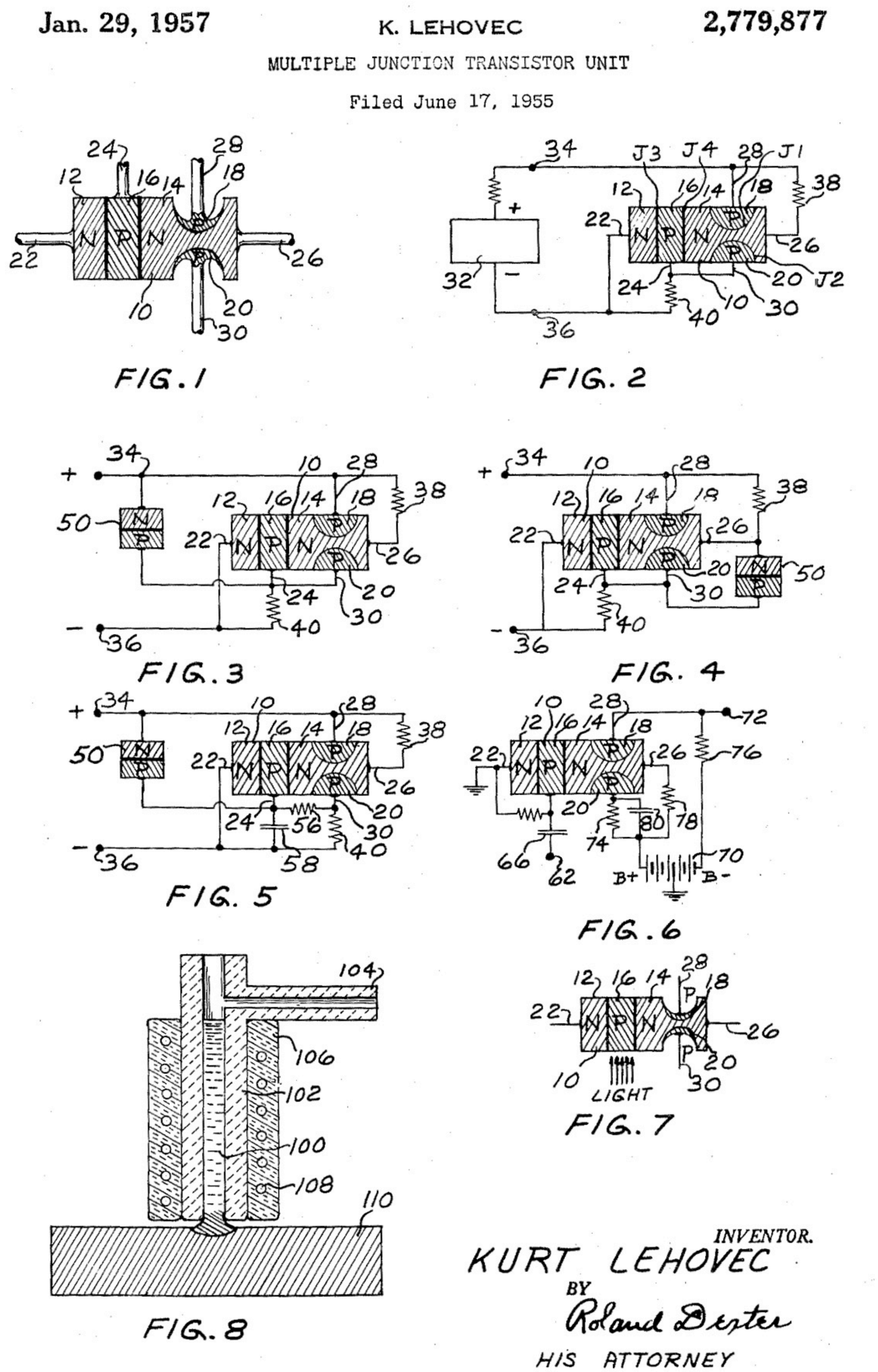

Figure B.145: Kurt Lehovec developed semiconductor devices for Germany during the war. After the war he was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits.

United States Patent Office

2,779,877
Patented Jan. 29, 1957

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2,779,877

MULTIPLE JUNCTION TRANSISTOR UNIT

Kurt Lehovec, Williamstown, Mass., assignor to Sprague Electric Company, North Adams, Mass., a corporation of Massachusetts

Application June 17, 1955, Serial No. 516,180

4 Claims. (Cl. 250—211)

This invention relates to semiconductor signal translating devices and more particularly to bi-stable circuits which include a novel semiconductive device.

Bi-stable circuits that include transistors of the junction type form the subject matter of United States Patent No. 2,655,609, issued October 13, 1953. This patent is concerned with the use of a pair of symmetrical multiple junction transistors associated so as to constitute a composite circuit element having novel advantageous characteristics as a switching structure readily transferable from the open circuit to the closed state upon application of a voltage of prescribed amplitude between the input terminals. The individual transistors used have to be protected carefully against the influence of the operational enviroment by hermetic sealing. This requirement of hermetic sealing necessitates a housing requiring a substantially greater volume than that volume demanded by the physical configuration of the transistor itself. Further, to be satisfactory, the operational characteristics of the two transistors must be carefully matched for incorporation into the circuit.

One general object of this invention is therefore to produce multiple junction semiconductor crystals suitable for bi-stable circuits. A more specific object of this invention is production of a fused junction by a novel process. Other objects will be apparent from the following paragraphs and appended drawings.

Briefly, the objects of this invention have been achieved by the production of a semiconductive crystal of the symmetrical multiple grown junction type which further has at least two fused junction regions integrated into one conductivity region of the multiple junction.

In a more limited sense, the objects of this invention have been achieved by the production of a signal translating device which comprises a semiconductive crystal of the symmetrical multiple grown junction type having at least two fused junctions with electrodes secured respectively to the intermediate section of said multiple grown junction, the two said fused junctions and the end regions of said multiple grown junction.

The invention and the other features noted above will be understood more clearly and fully from the detailed description with reference to the accompanying drawings in which:

Fig. 1 is a cross-sectional view of the grown and fused junction semiconductor element of the invention;

Fig. 2 is a diagram representing a circuit embodiment of utilizing the device of the invention;

Figs. 3, 4 and 5 depict other circuitry including both Zener diodes and the device of the invention;

Fig. 6 illustrates an amplifier circuit using the single transistor of the invention;

Fig. 7 pictures a cross-sectional view of a light responsive signal translating device; and

Fig. 8 is a cross-sectional view of an apparatus for imposing the fused junction regions onto the surface of the multiple grown junction crystal.

Referring now to the drawings, Fig. 1 shows a cross-

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section of a semiconductive structure which replaces two of the transistors previously required for bi-stable circuits. The crystal 10 is monocrystalline and of germanium or silicon appropriately doped with impurities so as to effect symmetrical multiple junctions of the n-p-n or p-n-p types. Herein is shown a grown n-p-n crystal having the n-regions designated 12 and 14 and the p intermediate region as 16. At one end of the crystal there are imposed two regions 18 and 20 of p conductivity produced as fused junctions. It is thus seen that there is in one crystal an n-p-n body which in turn finds one of the regions of n conductivity serving as the intermediate conductivity region for a p-n-p junction crystal. Appropriate non-rectifying electrodes 22, 24, 26, 28 and 30 are attached to the crystal shown in Fig. 1. For best operation the crystal 10 has surface depressions in which the fused junctions are produced so as to limit the thickness of the intermediate n region. For certain applications it is not necessary to have the non-rectifying electrode 26 present.

In Fig. 2 which shows an elementary circuit application of the device of the invention the source 32, poled as shown in the drawing, is connected between the terminals 34 and 36 of the composite crystalline body. The terminals 34 and 36 may be, for example, the cross points in telephone switching systems. The polarity of the source 32 is such that at least one reversed biased junction is included in every current path that can be traced between the terminals 34 and 36 through the composite multiple junction crystal 10. Thus, as shown, the junctions J–2 and J–4 are biased in the reverse or high resistance direction, at least one of which junctions is included in any current path through the combination. The operating state with such a polarity is thus the high impedance or low current condition. Upon increase of the voltage between the terminals 34 and 36 the currents passed by the reversely biased junctions J–2 and J–4 will increase changing the bias across J–1 and J–3 which is a function of the current flow through resistors 38 and 40. At a certain potential the circuit will change to a high current or conduction condition which state obtains when the resistances of the crystal approach those of resistors 38 and 40. Thus the circuit may be triggered from a substantially open circuit (low current) state to a closed circuit (high current) state by the application of voltage of a necessary magnitude between the terminals 34 and 36.

In certain applications it is desirable to determine the point at which the circuit will trigger at a present value. This is readily accomplished by modification of the circuit of Fig. 2 to that of Figs. 3, 4 and 5 by the utilization of a semiconductor junction diode 50, for example, germanium or silicon, which is connected in series with resistor 40 between the terminals 34 and 36. Therefore in Fig. 3, when the voltage between the terminals 34 and 36 rises to such a level as to establish the Zener voltage across the diode, the resulting large current which flows through both resistors 38 and 40 produces such biases on the respective emitters of the composite transistor element to transfer the condition from a low current to a high current level. The preparation of such Zener diodes is readily accomplished by surface melting of a crystal of given impurity, doping the melt with an impurity which produces a body of opposite conductivity and solidifying. The Zener voltage is a function of the conductivity of the crystal and can thus be fabricated for a given voltage of up to 100 volts or greater. In both Figs. 2 and 3, after the device is triggered to the high current or closed circuit conditions, it remains in that condition until the voltage between the terminals 34 and 36 is reduced to substantially 0. For ease of discussion the designation of the elements is common for Figs. 2, 3, 4 and 5. In

Figure B.146: Kurt Lehovec developed semiconductor devices for Germany during the war. After the war he was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits.

Fig. 4 the Zener diode is in series with the resistors **38** and **40** so that when the voltage between **34** and **36** reaches the Zener voltage the circuit shifts to the conduction state.

Now looking a Fig. 5, it may be particularly advantageous in the utilization of a switching system to effect changes of the conduction state with small exciting currents of very short duration. Herein the Zener diode **50** is in series with resistor **40** and a second resistor **56** which resistor combination **56** and **40** is paralleled by a capacitor **58**. The resistor **40** is made relatively small in comparison to the resistors **38** and **56**, with the resistor **38** being quite large. As the Zener voltage is obtained across the diode **50** from the terminals **34** and **36**, substantial current flow occurs through resistor **40** changing the system to a conducting state. When the voltage between terminals **34** and **36** falls to a low value before the transition to the high current condition has been completed, this change will continue as the resistor **40** discharges capacitor **58** slowly because of the relatively high value of resistor **56**. The voltage drop in the high current condition will be small since a low resistance path is provided through resistor **40**.

As it is apparent, the device of the invention can be used wherever it is desired to have a direct connection from the emitter or collector region of a transistor element to the base region of a second transistor element. In Fig. 6 the structure is used as an integral part of a direct coupled pulse amplifier. The input voltage **62** is imposed through a coupling capacitor **66** to the base region **16** of p-type conductivity. The emitter **12** is grounded while the n-region **14** serves both as the collector for the n-p-n segment and the base for the n-p-n portion of the composite crystal **10**. A center grounded battery **70** produces both the positive voltage for the emitter region **20** and the negative bias for the collector region **18**. Upon application of a positive pulse to **62** the n-p-n segment conducts to amplify the pulse which in turn is amplified by the p-n-p segment producing an output at **72**. Resistors **74, 76** and **78** and capacitor **80** determine the output level of the amplified pulse.

In Fig. 7 is shown a light sensitive device produced according to this invention. The electrode connected in the foregoing drawings to the base region of the grown multiple junction crystal has been replaced by a light beam. Such embodiment would thus act as a photo transistor of considerable sensitivity.

The rectifying electrode contacts which are actually of the fused type and previously indicated as **18** and **20** can be applied in the manner shown in Fig. 8. A quantity of molten electrode material **100** is held in a capillary tube **102** of carbon, glass or quartz, for example. An internal tube diameter of about 5 mils or less is particularly suitable. The molten electrode material, which can be an indium-germanium alloy in equal parts by weight, is readily drawn up in such a capillary as by applying suction through a conveniently connected side tube **104** near the upper end of the capillary. The top of the capillary can be covered by a plug, not shown, or can be sealed shut if desired. In order to keep the electrode material from solidifying in the capillary, it can be surrounded by a jacket of insulation **106** and in addition an electric heating coil **108**, either of the resistive or inductive type, can be provided to generate heat.

The capillary containing the molten electrode material is used by placing its lower end against or within about 10 mils of the surface of the body **110** to which the electrode is to be applied. Pressure then applied as by way of the side tube **104** will cause the lower end of the molten column of conductive material to be forced out and into contact with the surface of the body **110.** By keeping the conductive material at a relatively low temperature, as for example 100 to 500° C. below the freezing point of the molten electrode material, the contacting end will solidify and be firmly affixed to the surface of the body **110** with limited diffusion of the impurity so that the rectifying junction is immediately below the crystal surface. Although wider differences in temperature can be used, the best adhesion, which closely approximates a welded joint, will be formed when a small temperature difference is present. After the end of the molten stem has solidified, the capillary can be slowly withdrawn from the solidified joint with or without the continued application of pressure to the side tube **104**, and the molten electrode material will be pulled out, gradually solidifying against the adhered end to provide an elongated filament.

By using the above technique, an electrode contact having a contact area two mils wide or even less, is readily provided on bodies of germanium, silicon or even on the surface of other materials such as indium wafers or the like. The contacted surface of body **110** can have a melting point above or below that of the electrode material **100**.

To produce the device of the invention, a germanium crystal is pulled from a germanium melt which is doped repeatedly during the pulling in order to create an n-p-n symmetrical multiple junction structure. The p-region should be of a width of about ½ mil. A wafer of about 100 mils by 20 mils surface area is cut from the grown crystal and reduced to a thickness of about 2 mils by known lapping and etching techniques. Two indium electrodes are fused on opposite sides of one n-region and into the crystal to a depth each of about 0.5 mil or a 1 mil separation. This is accomplished by disposing indium pellets of from 15 to 30 mils diameter on the opposing surfaces and heating in a hydrogen atmosphere to about 500° C. for five minutes. Thereafter etch the crystal in a mixture of hydrofluoric and nitric acids, wash with water and dry. The electrode to the n-region not containing the fused junction is soldered with a solder containing antimony for a non-rectifying contact. The electrode to the intermediate p-region of the grown junction can be a fused gold wire containing 2% of indium for a non-rectifying contact. The fused regions have electrodes of platinum wire attached to the indium deposits. A modification of these latter contacts are the rectifying electrodes by the process of Fig. 8. Further, the crystal need not be lapped to a thickness of 2 mils but can be upwards of 10 mils with indentations in the surface where the fused p-regions are created, said indentations each about 4 mils deep.

The junctions **18** and **20** shown as a fused type need only be of a rectifying nature so that they include numerous configurations such as surface barrier rectifying metal contacts, rectifying pressure contacts of the point contact wire type, mercury type and fused wire type; electrically formed rectifying pressure contacts; grown junctions produced by local surface melting and recrystallizing after introduction of impurities; and rectifying contacts produced by diffusion of impurities into the semiconductor, forming a p-n junction and application of non-rectifying electrodes to the diffused region.

As many apparently widely different embodiments of this invention may be made without departing from the spirit and scope hereof, it is to be understood that the invention is not limited to the specific embodiments hereof except as defined in the appended claims.

What is claimed is:

1. A semiconductor crystal of a grown symmetrical multiple junction structure having two fused junctions disposed inwardly from opposed surfaces of said crystal, said fused junctions present in an end region of conductivity of said multiple junction structure.

2. A signal translating device comprising a semiconductor crystal of a grown symmetrical multiple junction structure having at least two fused junctions present in an end conductivity region of said structure, electrodes secured respectively to the intermediate conductivity region of said structure, the end conductivity regions of said structure and to the surfaces of said crystal defined

Figure B.147: Kurt Lehovec developed semiconductor devices for Germany during the war. After the war he was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits.

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by said fused junctions and bi-stable circuit means integrated with said electrodes.

3. A light responsive signal translating device comprising a semiconductor crystal of a grown symmetrical multiple junction structure having disposed in opposed relationship in a terminal conductivity region of said structure two fused junctions, non-rectifying electrodes secured respectively to the terminal conductivity regions of said structure and to the surface regions of said crystal defined by the fused junctions, a means for photo-illumination of the intermediate conductivity region of said structure.

4. A circuit controlling element comprising an n-p-n grown multiple junction semiconductor crystal having two fused junctions, resistor means connecting the first n-region of said grown junction to said p-region of said

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grown junction, a second resistor means connecting the other of said n-regions of said grown junction to one of said fused junctions, said fused junction further connected both to the n-region of a semiconductor diode and the signal source, the other of said fused junctions connected to the intermediate p-region of said grown junction and to the p-region of said diode, said first n-region of said grown junction connected to the signal source, said diode having a pre-assigned Zener voltage.

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Figure B.148: Kurt Lehovec developed semiconductor devices for Germany during the war. After the war he was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits.

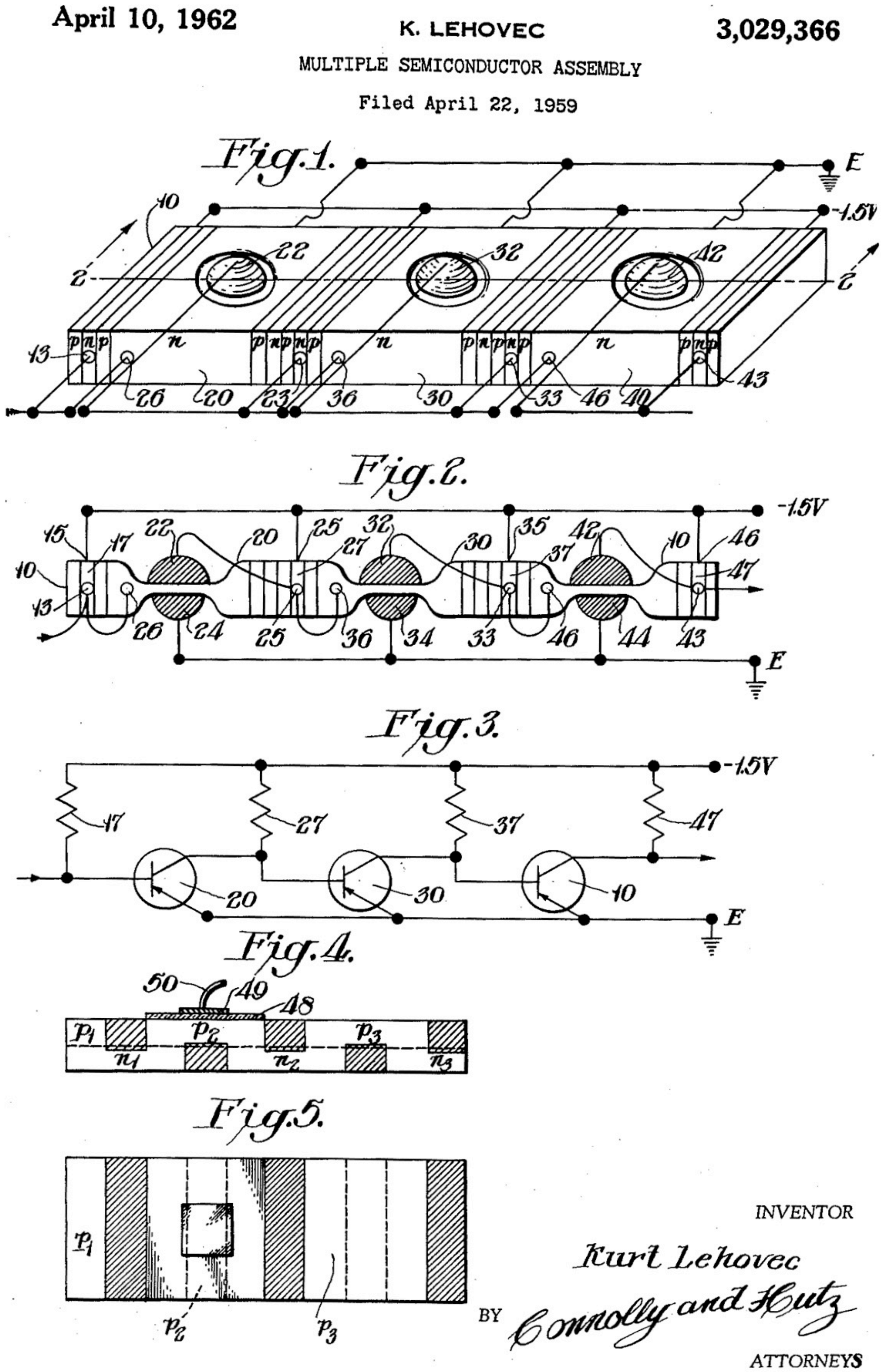

Figure B.149: Kurt Lehovec developed semiconductor devices for Germany during the war. After the war he was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits.

United States Patent Office

3,029,366
Patented Apr. 10, 1962

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3,029,366
MULTIPLE SEMICONDUCTOR ASSEMBLY

Kurt Lehovec, Williamstown, Mass., assignor to Sprague Electric Company, North Adams, Mass., a corporation of Massachusetts

Filed Apr. 22, 1959, Ser. No. 808,249
7 Claims. (Cl. 317—101)

This invention relates to a multiple semiconductor assembly, and more particularly to a plurality of semiconductive devices produced on a single semiconductor slice. Still more particularly, this invention relates to the micro-miniaturization of semiconductor assemblies by the preparation of several transistors and related devices on a single semiconductor slice, and the utilization of the resistive and capacitive properties of regions in that slice.

The present day miniaturization of electronic components has reached a state of art that may now be termed "micro-miniaturization," which may be defined as the assembly of a plurality of complementary components in an extremely small volume. Considerable activity has been expended in micro-miniaturizing circuits in which a plurality of transistors is employed. This micro-miniaturization activity has included the concept of direct coupling between stages of some particular types of transistors; e.g., surface-barrier and alloy-junction transistors have properties that permit their use in so-called common-emitter configurations in which the voltage at the collector of one transistor may be high enough to cause saturation at the base of the next transistor in the circuit. An article entitled, "Directly Coupled Transistor Circuits" by R. H. Beter, W. E. Bradley, R. B. Brown and M. Rubinoff, which was published in Electronics for June 1955, discloses the concept of employing a common-emitter transistor amplifier having more than one base connected to a single collector. Others in the art have suggested processes for producing a plurality of p-n junctions in a single semiconductor body; e.g., G. K. Teal U.S. Patent 2,727,840 and R. N. Hall U.S. Patent 2,822,308. However, great difficulty has been experienced in reaching the objective of a generally acceptable multi-transistor assembly on a single semiconductor body, because transistors so-produced have been electrically connected through the semiconductor slice. For example, in transistors of the alloy-junction type wherein the semiconductor slice of homogeneous impurity concentration represents the base of the transistor, all transistors in a multi-transistor assembly are connected to a common base, which is not a desirable configuration for many circuit applications.

A further example of the restricted nature of prior art multi-transistor assemblies is found in my U. S. Patent 2,779,877 issued January 29, 1957, which discloses and claims a signal translating device comprising a semiconductive crystal of the symmetrical grown junction type having two fused junctions disposed inwardly from opposed surfaces of the crystal.

It is an object of this invention to overcome these and other deficiencies of the prior art.

It is a further object of this invention to produce an assembly having a plurality of semiconductive components on a single semiconductor slice, and to provide a sufficient degree of electrical insulation between these semiconductive components through the semiconductor slice so as to permit a circuit designer to have substantial freedom in the interconnection of the components.

It is a still further object of this invention to produce an assembly having a plurality of transistors together with other components such as capacitors, resistors and diodes on a single semiconductor slice.

These and other objects of this invention will become more apparent upon consideration of the following de-

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tailed description when read in conjunction with the accompanying drawing, wherein:

FIGURE 1 is a diagrammatic perspective view of a multiple semiconductor assembly constructed in accordance with this invention, with electrical circuit wiring attached thereto to accomplish the circuit shown in FIGURE 3;

FIGURE 2 is a diagrammatic cross-section of the multiple semiconductor assembly taken along line **2—2** in FIGURE 1; in order to establish a clearer picture of the electrical interconnection of the various semiconductive components, FIGURE 2 is not a true cross-section of FIGURE 1, in that the contacts at the front surface of the assembly of FIGURE 1 have been shown again on the diagrammatic cross-section of FIGURE 2, although it should be understood that these contacts are not in the plane **2—2** of FIGURE 1;

FIGURE 3 is a schematic diagram of a chain of direct coupled amplifiers which may be assembled on a single semiconductor slice of the configuration shown in FIGURE 1 in accordance with this invention;

FIGURE 4 is a diagrammatic cross-sectional view through a multiple region semiconducting slice such as may be used in the construction of another embodiment of the multiple semiconductor assemblies according to this invention; and

FIGURE 5 is a diagrammatic plan view of the multiple region semiconductor slice of FIGURE 4.

In general, the objects of this invention are attained by a multiple semiconductor assembly in which a plurality of semiconductor components are prepared on the same semiconductor slice in such a manner as to ensure electrical separation of the terminals of the individual semiconducting components. Since these semiconducting components will be transistors in many cases, the following description will be directed specifically to transistors although the concept of the invention applies also to other components, such as capacitors, resistors and diodes.

More particularly the objects of this invention are attained by utilizing a semiconductor slice having a series of p-n junctions that are so constructed and arranged that a transistor may be produced on each of a plurality of regions that are separated from one another by at least one additional p-n junction.

It is well known that a p-n junction has a high impedance to electric current, particularly if biased in the so-called "blocking direction," or with no bias applied. Therefore, any desired degree of electric insulation between two components assembled on the same slice can be achieved by having a sufficiently large number of p-n junctions in series between the two semiconducting regions on which said components are assembled. For most circuits, one to three p-n junctions will be sufficient to achieve the desired degree of insulation. These p-n junctions may be placed quite closely to each other. However, it is often required that they are placed sufficiently far apart from each other that the multiple p-n junction structure used for electric insulation should not act as an active semiconducting element such as a transistor or a four-layer npnp diode. In order to assure this condition, it is required that the region between two junctions is wider than a small multiple of the diffusion length of the minority carriers in said region. The diffusion length is the square root of the diffusion constant multiplied by the lifetime of these minority carriers. For instance, assuming a diffusion constant of 40 cm.^{2} per second and a lifetime of 1 microsecond, a diffusion length of 60×10^{-4} cm. or approximately 2 mils results, and a separation of 4 mils between the two junctions will be sufficient to avoid any appreciable interaction by carrier injection between the two junctions delineating said region.

In a restricted form of this invention, the objects are attained by a multiple transistor assembly comprising a

Figure B.150: Kurt Lehovec developed semiconductor devices for Germany during the war. After the war he was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits.

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semiconductor slice that is provided with a plurality of transistors that are separated by a plurality of regions of alernating p and n type conductivity, with one of said plurality of regions serving as a resistor element in said transistor in a circuit assembly.

FIGURES 1 and 2 of the drawing show a semiconductor slice **10** having recurring series of p-n junctions throughout its length. A plurality of narrow regions of alternating conductivity types are shown as being separated by relatively wide regions **20, 30,** and **40.** That is, there are three regions of greater width than the rest of the regions, and between any two of these wider regions there are a plurality of the regions of narrow width. Each of the n-type regions **20, 30** and **40** is separated from the other two wide regions by a plurality of the narrow width regions of alternating conductivity types, which are exemplified by n-type regions **17, 27, 37** and **47.** The narrow width regions shown in the drawing are of substantially equal width. However, it is desirable in providing devices for some circuit configurations to utilize regions of varying widths. Therefore, it should be understood that the term "narrow regions" as employed in this specification includes regions of both equal and unequal widths.

Semiconductor slice **10** is preferably obtained by cutting a slice from a crystal that has been produced according to the presently well-known "rate-growing" process. A detailed description of the process and apparatus employed in rate-growing semiconductor crystals is found in the above noted U.S. Patent 2,822,308 to R. N. Hall, and is succinctly described in a paper by Hall entitled "P-N Junctions Produced by Growth Rate Variation" that appeared in Physical Review 88, 139 (1952). For the purposes of describing this invention, rate-growing may be summarized by noting that the impurity concentration in a germanium crystal pulled from a melt containing antimony is related to the impurity concentration in the melt by the so-called segregation factor k. It is recognized in the art that this segregation factor is a function of the growth rate of the crystal from the melt in the case of some impurities (e.g., antimony) but not in the case of most other impurities, including indium and gallium. From these facts, it has been found that an ingot grown from a germanium melt doped with the proper amount of antimony and indium (or gallium) will be p-type (excess of indium) when grown slowly, and n-type (excess of antimony) when grown rapidly. The substantially uniform width alternating p and n regions shown in FIGURES 1 and 2 between the wider n-type regions **20, 30** and **40** are produced by cycling the growth rate of the ingot, whereas wider regions **20, 30** and **40** are produced by timing the growth rate in the manner taught in the Hall patent.

To obtain results of the highest order of predictability and reproducibility, semiconductor slice **10** is cut from the crystal so as to be oriented in the direction of crystal growth in the ingot. This oriented cutting produces a slice that exhibits alternate regions of p-type and n-type resistivities that uniformly extend across the complete width of the slice.

The wide n-type regions **20, 30,** and **40** are converted into transistors by the utilization of conventional processes such as the alloy-junction transistor technique or the electrochemical transistor technique. Alloy-junction transistor techniques are described in the chapter entitled, "Uniform Planar Alloy Junctions for Germanium Transistors" by C. W. Mueller and N. H. Ditrick in Transistors I, pp. 121–131, RCA Labs (1956). Electrochemical transistor techniques are described in a series of five papers by members of the technical staff of the Philco Research Division that were published in Proceedings of the I.R.E. 41, (12) 1702–1720 (1953).

As shown more clearly in FIGURE 2, collectors **22, 32** and **42** are fabricated respectively on one face of slice **10** within regions **20, 30** and **40.** On the opposite face of

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slice **10,** emitter electrodes **24, 34** and **44** are fabricated so as to produce the typical narrow web between collector and emitter that characterizes the electrochemical and alloy-junction transistors. While the method and materials utilized in producing these junctions are not an essential part of this invention, it should be noted that for the n-type germanium regions **20, 30** and **40** shown in FIGURES 1 and 2, than an indium-gallium alloy of 98% indium and 2% gallium provides a preferred rectifying emitter junction, and a pure indium alloy provides a preferred collector junction. Ohmic base contacts **26, 36** and **46** are produced to complete the transistors in each of the regions **20, 30** and **40.** These ohmic contacts are preferably produced by utilizing an alloy of 97% tin and 3% arsenic.

The schematic diagram shown in FIGURE 3 of the drawing is the circuit shown in FIGURE 2(A) in the above identified Beter et al. publication in Electronics. This circuit is a chain of direct coupled amplifiers that employs a resistor between each transistorized stage. These resistors are fabricated on semiconductor slice **10** by making ohmic contact to the opposed edges of one of the n-type regions that separates the wide n-regions from one another. These resistor contacts shown in FIGURES 1 and 2 are ohmic contacts produced by the tin-arsenic alloy mentioned above. The area of the alloy contacts for these resistors, for example contacts **13** and **15** to n-region **17,** may overlap onto the adjacent p-type regions without affecting the resistance value, since the tin-arsenic alloy employed has a high impedance to p-type zones, forming a rectifying junction thereto. While the method of producing resistors on semiconductor slice **10** has been described in terms of contacts **13** and **15** to region **17,** it should be understood that regions **27, 37** and **47** are provided similarly with pairs of contacts **23, 25** and **33, 35** and **43, 45,** respectively.

When capacitors of low capacitance are required in a circuit, it is necessary only that ohmic contacts be made to the face of adjacent regions across a p-n junction, or alternatively that an ohmic and a rectifying contact be made to opposite edges of a single region. The capacities that can be best provided by this use of narrow regions on the semiconductor slice are in the 1 to 100 micromicrofarad range. When circuit configurations require capacities that are outside the limits set by the geometrical dimensions and resistivities of the p and n regions of the semiconductor slice, the lead-wires used to interconnect the various regions of the slice are employed to connect "lumped" or discrete external components in the circuit. Alternatively, the external components can be provided on portions of the semiconductor slice by utilizing an insulating film coating as a substrate on the desired portions, and then depositing the components by known techniques; e.g., printing or vaporizing in the case of resistors, and multi-layer build-ups of alternating layers of metal and ceramic in the case of capacitors. Simple and effective processes for producing the insulating substrate include high temperature air-oxidation, and anodization, e.g., a quartz layer in the case of silicon. This quartz layer may also serve as a dielectric of a capacitor whose electrodes are the underlying semiconducting region and a metal film deposited on the quartz layer.

The electrical connections may be made to the various alloy contacts on semiconductor slice **10** by a number of generally conventional techniques. It should be understood that the electrical connections to the various alloy contacts on semiconductor slice **10** need not be made in accordance with the illustrative connections shown in FIGURES 1 and 2. For instance, wire contacts may be attached to the emitter or collector electrodes and thereafter circuit wires may be secured to the wire contacts to make connection to the emitter, collector or base regions of another transistor. An alternate system of electrical contacts utilizes hemispherical metal alloy base contacts for each transistor and then connects emitters, collectors

Figure B.151: Kurt Lehovec developed semiconductor devices for Germany during the war. After the war he was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits.

and base contacts of various transistors by means of a printed circuit board that is placed in contact with the hemispherical contacts. Still another system of electrical connections utilizes the "deposited" or printed circuit techniques described above, which includes coating the semiconductor slice with an inert insulating material such as evaporated quartz, then removing the quartz layer from the actual contact areas, and then by use of suitable conductive inks the connection desired between the emitter, collector and base contacts may be printed on the quartz.

The extreme micro-miniaturization afforded by this invention is apparent from consideration of the fact that the construction shown in FIGURES 1 and 2 of the drawing was produced on a germanium semiconductor slice having a thickness of 4 mils, a width of 20 mils, and a length of 90 mils. The narrow width regions are of from 1 to 5 mils, with substantially uniform regions of 2 mils as the preferred construction; the large n-type regions on which the transistors are fabricated are preferably of 20 mils width. The resistivity of the n-type regions to which the electrical contacts are made is approximately 1 ohm centimeter.

Another method for making multiple p and n junctions on the same slice of semiconducting material is illustrated for the case of silicon. A silicon crystal is pulled containing arsenic as an impurity to give the crystal n-type conductivity. A slice is cut from this crystal and is subjected to surface melting, i.e. the slice is positioned under a heat source which melts the surface layer of the slice. A detailed description of surface melting is given by K. Lehovec and E. Belmont in an article entitled "Preparation of p-n Junctions by Surface Melting" in Journal of Applied Physics 24 (12), 1482–1484 (1953). Aluminum is introduced into the melted portion at a sufficient concentration such that upon recrystallization, the melted portion exhibits p-type conductivity. This provides a slice with a p-n junction through its middle as indicated in FIGURE 4. By cutting and lapping techniques, a slice with parallel surfaces is produced with a total thickness of approximately 6 mils, the junction being through the center of the slice and parallel to its large surfaces. FIGURE 4 indicates a blown-up drawing of the cross section of the slice and indicates means by which this slice can be transformed in a series of p and n regions. In FIGURES 4 and 5 the series of p and n regions are numbered in subscripts. The transforming means consists of machining grooves into the slice, whereby these grooves protrude alternately from the p-type side and the n-type side and cut through the p-n junction. The material removed by the grooves is indicated by the dashed regions in FIGURE 4. FIGURE 5 gives a top view of the slice indicating the grooves which protrude from the p-type surface. It is clear that in order to proceed from the region P_1 to the region P_2 through the slice, one has to cross two p-n junctions, while in order to proceed from the region P_1 to P_3, one has to cross four p-n junctions. Thus, one may separate two p regions by any desired number of junctions depending on the closeness of the grooves. Two additional layers atop region P_2 illustrate an insulating substrate covering a portion of the slice and an electrical component on the substrate in circuit with the semiconductor device. A substrate **48** is provided on the region P_2 by suitable means and an electrical component **49** is positioned on the substrate **48** by suitable means such as metallization. A lead **50** is connected to the electrical component **49**.

In the preparation of the grooves there are several well-known techniques which may be employed, e.g., the grooves may be produced by ultrasonic cutting, or by masking techniques with photoresists and chemical etching, or by electrochemical jet etching. Multiple p-n regions on the same slice as illustrated in FIGURES 4 and 5 can be used in the same manner as the multiple p-n

junctions in the rate-grown slice illustrated in FIGURES 1 and 2.

Other circuit constructions and configurations are attained on a single semiconductor slice in accordance with this invention by shorting out one or more of the p-n junctions by depositing metal films completely across the junctions. Others of the p-n junctions fabricated in a single semiconductor slice in accordance with this invention may be utilized as circuit elements such as capacitors or diodes. Furthermore, other regions in the semiconductor slice may be used for discrete resistance purposes either as a substrate for printed resistors or as the resistor material proper; e.g., by providing non-rectifying alloy contacts at the two ends of a narrow region of homogeneous conductivity separated by p-n junctions from the rest of the semiconductor slice.

Although the two specific examples of this invention have been described in terms of germanium and silicon, respectively, it should be understood that this invention is capable of utilizing other semiconductive materials; e.g., silicon carbide, and intermetallic compounds of group III–V elements.

It should be understood that although the invention has been described in terms of the construction wherein the transistors are fabricated on n-type regions, it is within the concept of the invention to utilize p-type regions. Similarly the resistors, capacitors and diodes constructed or fabricated on the narrow regions may employ either p or n type conductivity regions.

It will be understood that the above identified embodiments of this invention are for purpose of illustration only, and that modifications may be made without departure from the spirit of the invention. It is intended that this invention be limited only by the scope of the appended claims.

What is claimed is:

1. A multiple semiconductor assembly comprising a semiconductor slice having a plurality of regions of alternating p and n conductivity types to thereby provide a plurality of p-n junctions, at least two semiconducting components assembled each on one of said regions of said slice, said components being separated by a plurality of said regions so as to provide therebetween at least two p-n junctions thereby achieving electric insulation of said components through said slice by the impedance of said p-n junctions.

2. A multiple semiconductor assembly comprising a semiconductor slice having a plurality of regions of alternating p and n conductivity types to thereby provide a plurality of p-n junctions, two of said regions being separated by at least two of said p-n junctions, and semiconductor devices fabricated on said separated regions, whereby said semiconductor devices are electrically isolated from one another by said at least two p-n junctions.

3. A multiple semiconductor assembly as defined in claim 2 wherein at least one of said semiconductor devices is a transistor.

4. A multiple semiconductor assembly as defined in claim 3 wherein said transistor has emitter and collector contacts on opposite faces of said slice.

5. A multiple semiconductor assembly as defined in claim 2 wherein electrical circuit contacts are made on opposite sides of one of said separating p-n junctions to thereby provide a semiconductive component in circuit with said semiconductor devices.

6. A multiple semiconductor assembly as defined in claim 2 wherein spaced electrical circuit contacts are made to one of said plurality of regions to thereby provide a semiconductive component in circuit with said semiconductor devices.

7. A multiple semiconductor assembly as defined in claim 2 wherein portions of said slice are covered by an insulating substrate, and electrical components are provided on said substrate in circuit with said semiconductor devices.

(References on following page)

Figure B.152: Kurt Lehovec developed semiconductor devices for Germany during the war. After the war he was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits.

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Figure B.153: Kurt Lehovec developed semiconductor devices for Germany during the war. After the war he was extensively interrogated by the United States and then moved to the United States, where he filed patents on light emitting diodes, transistors, and integrated circuits.

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(72) Als Erfinder benannt: Krömer, Dr. Herbert, Princeton, N. J. (V. St. A.)

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Figure B.154: Herbert Kroemer invented the drift transistor in 1953.

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Die Störstellenkonzentration ist in der Basiszone eines üblichen Flächentransistors praktisch konstant, so daß dort kein elektrisches Feld herrscht. Die vom Emitter herkommenden Minoritätsladungsträger können also nur durch reine Diffusion zum Kollektor gelangen. Dieser Flächentransistor ist also ein »Diffusions-Transistor«. Die Anwendung desselben ist gegenüber derjenigen des Spitzentransistors durch die wesentlich niedriger liegende Frequenzgrenze beschränkt.

In der Patentanmeldung P 13 01 862.7-33 (deutsche Auslegeschrift 1 301 862) ist bereits ein Verfahren zum Herstellen eines Drifttransistors angegeben, das darin besteht, daß eine oder mehrere Störstellenarten in die Basiszone von der Emitterseite so eindiffundiert werden, daß die Störstellenkonzentration an der Emitterseite der Basiszone mindestens zehnmal größer als an der Kollektorseite der Basiszone ist. Es ist dort auch bereits hervorgehoben, daß es bei einem solchen Drifttransistor besonders vorteilhaft ist, die Störstellenkonzentration vom Emitter zum Kollektor monoton abklingend verlaufen zu lassen, wobei die Abnahme an der Emitterseite stärker ist als an der Kollektorseite, so daß der 2. Differentialquotient der Kurve der Störstellenkonzentration überwiegend positiv ist. Beispielsweise kann die Störstellenkonzentration etwa rein exponentiell abfallen. In der Baziszone herrscht dann wegen der räumlichen Konstanz der Fermischen Grenzenergie ein ungefähr konstantes elektrisches Feld, welches die Minderheitsträger zwangläufig zum Kollektor hintreibt. Dies hat zur Folge, daß die oberste Grenzfrequenz des Transistors ansteigt.

Die Erfindung betrifft einen Drifttransistor, bei dem das elektrische Feld in der Basiszone des Transistors erfindungsgemäß dadurch erzeugt wird, daß die Halbleitergrundsubstanz selbst ein nichtstöchiometrischer Mischkristall verschiedener Halbleitermaterialien mit verschiedenen Bandabständen ist, wobei sich die Zusammensetzung des Mischkristalls innerhalb der Basis derart ändert, daß die Bandbreite von der Emitter- zur Kollektorseite monoton abnimmt, während der Leitfähigkeitstyp unveränderlich bleibt. Auf diese Weise läßt sich ein noch höheres Driftgefälle und damit eine noch stärkere Verbesserung der Frequenzgrenze erzielen.

Gegebenenfalls kann zusätzlich zu der Bandbreitenvariation die Störstellenkonzentration des Halbleitermaterials vom Emitter zum Kollektor monoton abnehmen. Dabei ist zweckmäßig die Feldstärke, die durch das Zusammenwirken von Störstellen- und Bandbreitenvariation entsteht, möglichst homogen zu machen. Diese Maßnahmen können zu einer weiteren Steigerung des Driftgefälles und damit zu einer weiteren Verbesserung der Frequenzgrenze führen. Vorzugsweise verläuft die Variation der Bandbreite linear, während der Störstellengehalt konstant ist oder exponentiell verläuft.

Als miteinander zu kombinierende Halbleitersubstanzen kommen für die Erfindung alle die Halbleitermaterialien in Frage, die auch sonst für die Transistorherstellung geeignet sind, vorausgesetzt, daß die Symmetrie ihrer Kristallgitter dieselbe ist. Dies sind insbesondere die Halbleitersubstanzen der IV. Gruppe des periodischen Systems der Elemente, wie Germanium und Silizium, sowie die gemischten Halbleiter vom Typ $A_{III}B_V$. Und zwar kann man sowohl Halbleitermaterialien der IV. Gruppe untereinander, als auch einen oder mehrere Halbleitermaterialien der IV. Gruppe mit einem oder mehreren

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$A_{III}B_V$-Halbleitern, als auch mehrere $A_{III}B_V$-Halbleiter untereinander kombinieren.

Die Herstellung der erforderlichen dünnen Basisschichten mit inhomogener Zusammensetzung geschieht zweckmäßigerweise so, daß man eine geeignete Menge einer geeigneten flüssigen Mischung der Komponenten langsam von einer Seite her erstarren läßt. Dabei ändert sich die Zusammensetzung des erstarrten Kristalls stetig, beginnend mit der Halbleitersubstanz des höchsten Schmelzpunktes, die im ersten und im dritten Falle der obigen Kombinationsmöglichkeiten gleichzeitig die Halbleitersubstanz mit dem höchsten Bandabstand ist.

Vorzugsweise kann man diesen Schmelzprozeß so durchführen, daß man die niedrigschmelzende(n) Komponente(n) auf ein festes Kristallstück der höchstschmelzenden Komponente aufbringt und das Ganze so hoch erhitzt, daß erstere schmilzt bzw. schmelzen und eine geeignete Menge der letzteren auflöst bzw. auflösen, woraufhin man die Erstarrung wie oben beschrieben durchführt.

Der hochschmelzende Kristall und die niedrigschmelzende(n) Komponente(n) werden dabei zweckmäßigerweise in einander entgegengesetzter Richtung so vordotiert, so daß sich beim Erstarren sogleich der eine der beiden die Basiszone begrenzenden pn-Übergänge bildet.

Wir betrachten jetzt einmal näher den Fall eines nur zweikomponentigen Mischkristalls, wo die höchstschmelzende Komponente auch den höheren Bandabstand hat. Dann bildet der nach dem beschriebenen Verfahren zuerst entstehende pn-Übergang später den Emitter. Es ist dann zweckmäßig, zur Vordotierung des festen Kristalls einen Stoff mit sehr kleinem Verteilungskoeffizienten zu wählen, d. h. einen Stoff, der beim Erstarren bevorzugt in die flüssige Phase geht, während man die niedrigschmelzende Komponente zweckmäßigerweise mit einem Stoff mit einem möglichst großen Verteilungskoeffizienten, vorzugsweise einem Verteilungskoeffizienten > 1, vordotiert. Man erhält dann nämlich gleichzeitig beim Erstarren der Schmelze den gewünschten monotonen Abfall der (Netto-)Störstellenkonzentration. Wenn die Verteilungskoeffizienten der beiden Dotierungsstoffe sich hinreichend stark unterscheiden, überwiegt schließlich gegen Ende des Erstarrungsprozesses wieder die Störstellenart des Emitterkristalls, so daß auch der zweite die Basiszone begrenzende pn-Übergang, der Kollektorübergang, in demselben Vorgang entsteht. Durch Variation der Menge der zweiten Halbleiterkomponente und Variation der Fremdstoffgehalte lassen sich die physikalischen Parameter der so entstehenden Transistoren in weitem Bereich beeinflussen.

Im Falle einer Silizium-Germanium-Kombination eignen sich zur Dotierung des Emitterkristalls vorwiegend die Elemente der III. Gruppe des Periodensystems der Elemente wie Arsen oder Antimon, zur Dotierung des Germanium vorwiegend Bor und Aluminium. Dabei entstehen npn-Transistoren.

Ganz analoge Überlegungen gelten für mehrkomponentige Systeme für andere Halbleiterarten sowie für den Fall, daß die höherschmelzenden Komponenten den niedrigeren Bandabstand haben.

Patentansprüche:

1. Drifttransistor, dadurch gekennzeichnet, daß ein elektrisches Feld in der

Figure B.155: Herbert Kroemer invented the drift transistor in 1953.

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Basiszone des Transistors dadurch erzeugt wird, daß die Halbleitergrundsubstanz ein nichtstöchiometrischer Mischkristall verschiedener Halbleitermaterialien mit verschiedenen Bandabständen ist, wobei sich die Zusammensetzung des Mischkristalls innerhalb der Basis derart ändert, daß die Bandbreite von der Emitter- zur Kollektorseite monoton abnimmt und der Leitfähigkeitstyp unverändert bleibt.

2. Drifttransistor nach Anspruch 1, dadurch gekennzeichnet, daß zusätzlich zu der Bandbreiten-

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variation die Störstellenkonzentration des Halbleitermaterials vom Emitter zum Kollektor monoton abnimmt.

3. Drifttransistor nach Anspruch 2, dadurch gekennzeichnet, daß die Feldstärke, die durch das Zusammenwirken von Störstellen- und Bandbreitenvariation entsteht, möglichst homogen ist.

4. Drifttransistor nach Anspruch 3, dadurch gekennzeichnet, daß die Bandbreitenvariation linear verläuft und der Störstellengehalt konstant ist oder exponentiell verläuft.

Figure B.156: Herbert Kroemer invented the drift transistor in 1953.

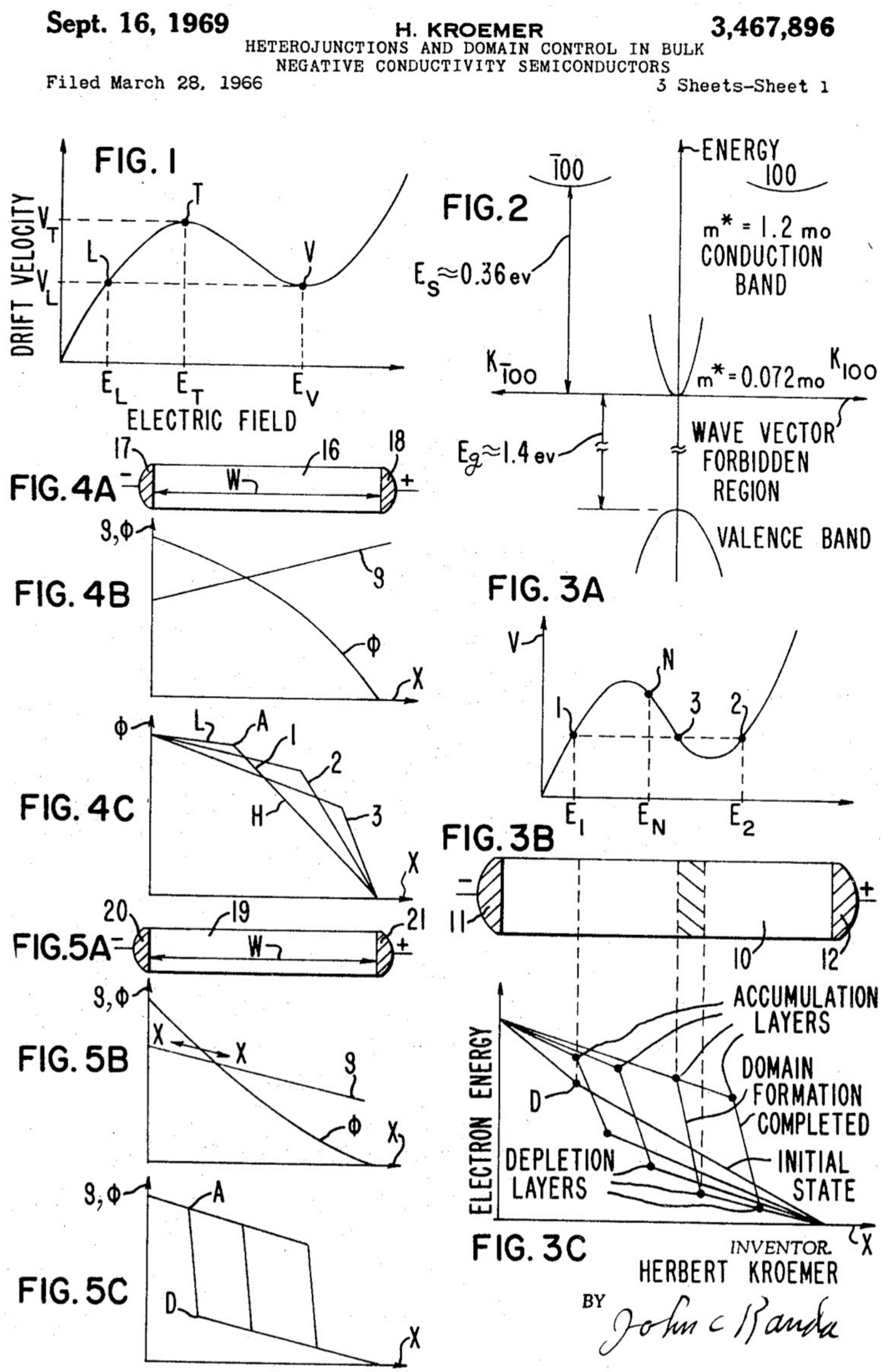

Figure B.157: Herbert Kroemer invented III-V semiconductor heterostructures in 1966.

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HETEROJUNCTIONS AND DOMAIN CONTROL IN BULK NEGATIVE CONDUCTIVITY SEMICONDUCTORS
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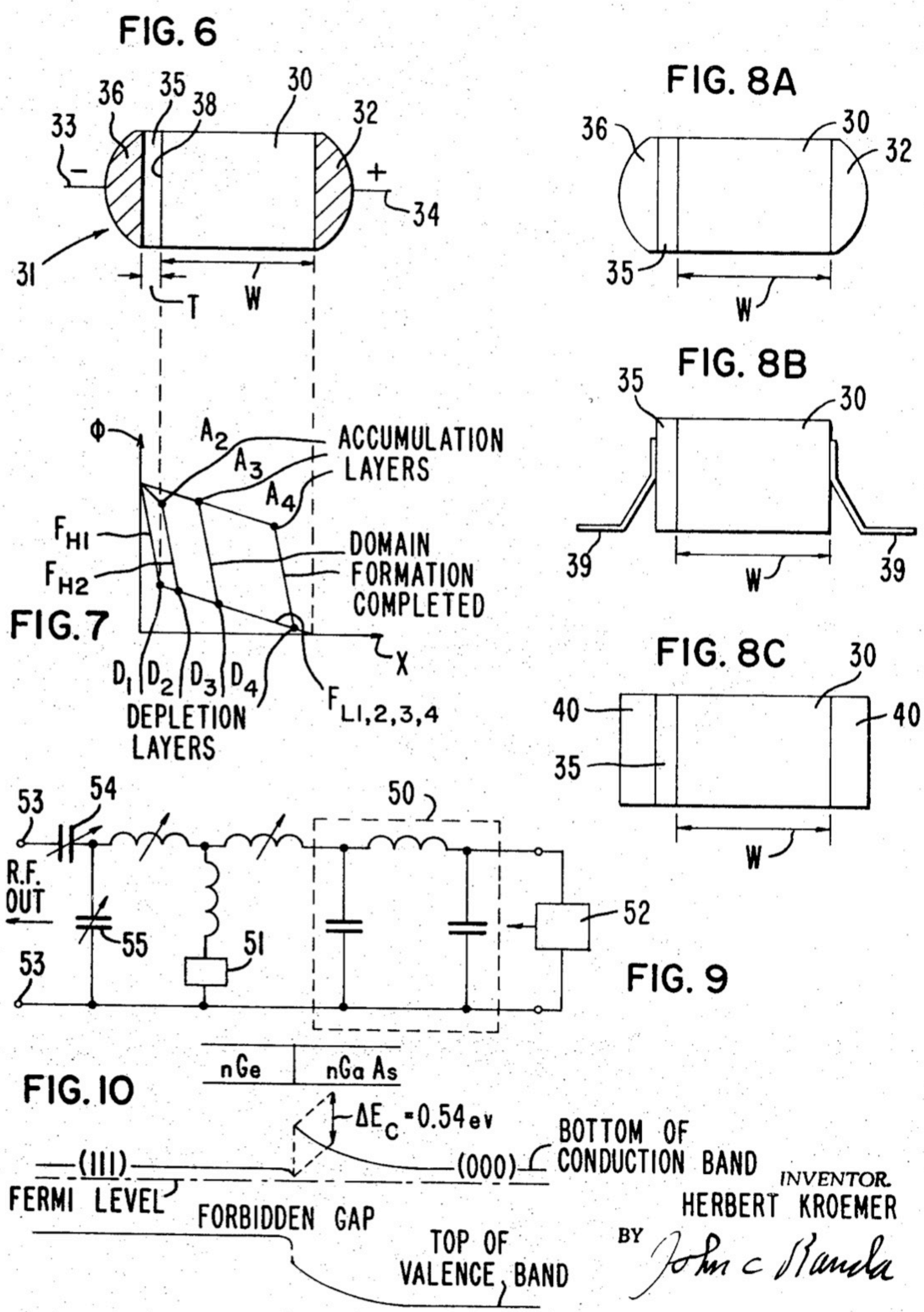

Figure B.158: Herbert Kroemer invented III-V semiconductor heterostructures in 1966.

Sept. 16, 1969 H. KROEMER **3,467,896**

HETEROJUNCTIONS AND DOMAIN CONTROL IN BULK NEGATIVE CONDUCTIVITY SEMICONDUCTORS

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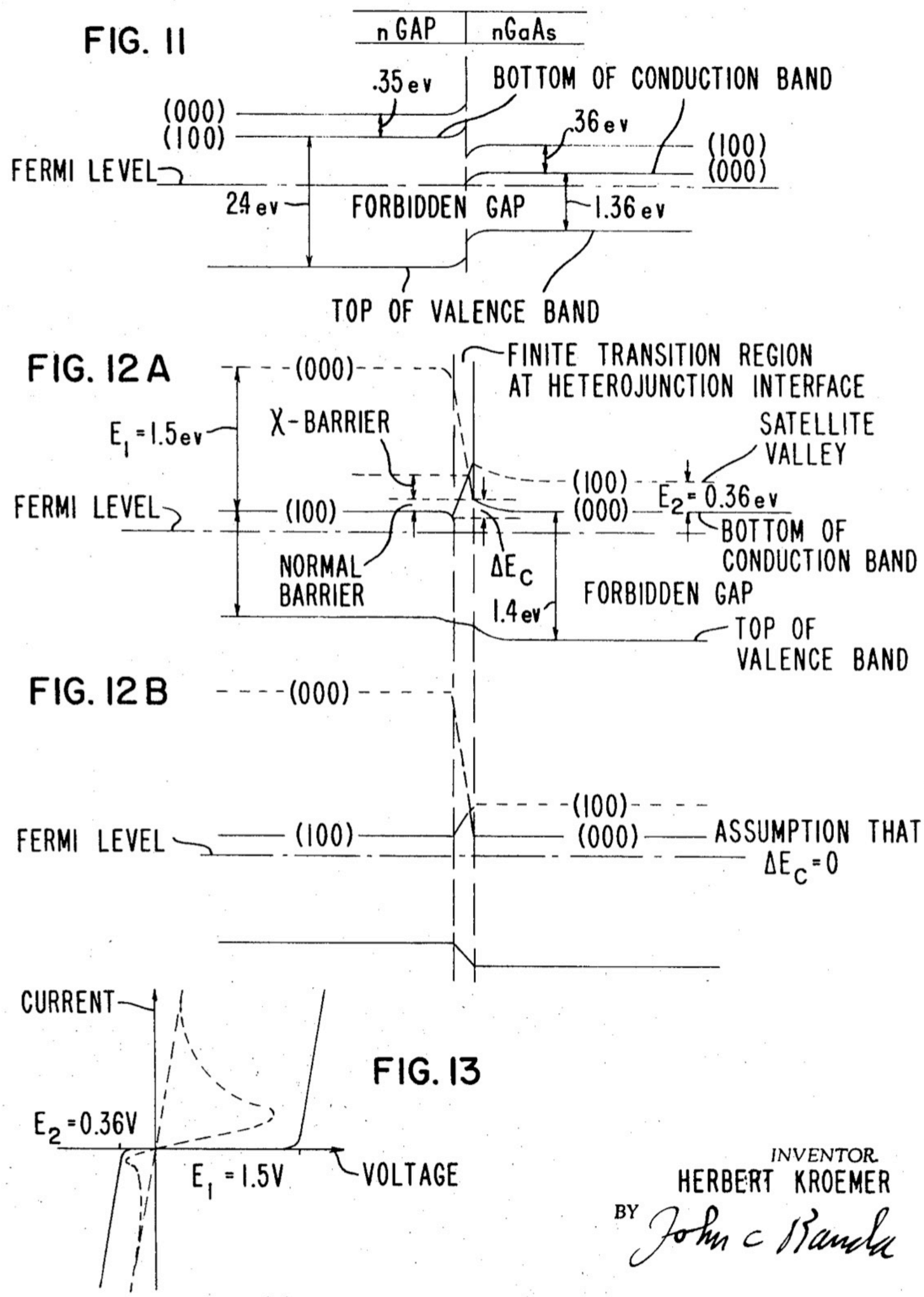

Figure B.159: Herbert Kroemer invented III-V semiconductor heterostructures in 1966.

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HETEROJUNCTIONS AND DOMAIN CONTROL IN BULK NEGATIVE CONDUCTIVITY SEMICONDUCTORS

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U.S. Cl. 317—234 7 Claims

ABSTRACT OF THE DISCLOSURE

A means for controlling the oscillation mode in bulk negative conductivity semiconductor oscillators. By doping the semiconductor so that a resistivity gradient exists between the positive and negative electrodes with a higher resistivity at the positive electrode, the oscillator can be made to reliably function in the pure accumulation mode. If the resistivity gradient is in the opposite direction, operation will be in the dipole space charge mode. Alternatively the operating mode can be controlled by utilizing a negative electrode formed of a semiconductor material having a higher resistivity than the semiconductor material of the main body and having a positive mobility over the operating range of the oscillator device.

This invention relates in general to microwave oscillators utilizing semiconductors which exhibit bulk negative conductivity and more particularly to the use of resistivity gradients and heterojunction electrodes in bulk negative conductivity semiconductors for the purpose of mode control.

The phenomena of bulk negative conductivity (BNC) in semiconductors having a particular type of band structure which results in the semiconductor having a drift velocity v vs. electric field E dependence which contains a region of negative differential mobility $\mu=dv/dE<0$ or a bulk negative conductivity has finally been achieved. The utilization of BNC semiconductors as oscillators, frequency generators at microwave frequencies up to 100 and perhaps 1000 gc., which is an ultimate limit, is clearly forseeable. The present invention is concerned with basic improvements in such BNC semiconductors with a resultant improvement in efficiency and spectral purity of the microwave oscillations generated by a BNC semiconductor.

The following background information should help in clarifying the terminology involved in the phenomena of a BNC semiconductor and lead to a better understanding of the basic improvements taught by the present invention.

An illustrative graphical portrayal of a typical BNC semiconductor drift velocity v vs. applied electric field E dependence containing a region of bulk negative differential conductivity is shown in FIG. 1. The region between T and V where $\mu=dv/dE<0$ where μ=electron mobility typifies a BNC semiconductor. The negative differential mobility region occurs at applied electric fields above E_T and extends to E_V. The exact values of E_T and E_V will of course depend on the particular BNC semiconductor under consideration.

The rationale for the negative differential mobility region of the FIG. 1 plot can be seen from an examination of the generic energy band diagram of FIG. 2. This K-space diagram is particularly directed to n-type GaAs but is representative of the generic class of semiconductors falling within the teachings of the present invention. In brief, the conduction band structure of a BNC semiconductor will be a many valley type characterized in the following manner:

The semiconductor will be an n-type semiconductor body having a conduction band structure characterized by having satellite valleys which lie energetically higher than a central main valley, with the satellite valleys further characterized by a lower mobility (higher effective mass) than the mobility (lower effective mass) associated with the central main valley, and wherein the energy differential between the bottom of the satellite valleys and the bottom of the central main valley portions of the conduction band is smaller than the energy differential between the top of the valence band and the bottom of the central main valley of the conduction band and wherein the energy differential between the bottom of the satellite valleys and the bottom of the central main valley portion of the conduction band is greater than $2kT$ at the operating temperature where k=Boltzmann's constant and T=absolute temperature in degrees Kelvin of the semiconductor body or crystal temperature at the operating temperature.

It is to be noted that the generic band structure is obviously not to be restricted to any particular crystallographic axis such as the (100) axis which was chosen only to illustrate a particular example of the general case.

This type of semiconductor will, upon application of a D.C. bias voltage such that $V/w>E_T$ for any portion of the body where

V=bias voltage
w=semiconductor body width between source and drain electrodes and
E_T=threshold field;

generate traveling space charge domains which originate at the negative or source electrode and exit at the drain electrode. The exact natural frequency of any given BNC semiconductor will of course vary with the bias, load, material, etc., parameters. The generation of traveling space charge domains can be shown to occur for BNC semiconductor diodes characterized by the following relationship:

$$nw \gtrsim 10^{12}/\text{cm.}^2$$

where n=conduction electron number density and
w=semiconductor body width or thickness in cm. between source and drain electrodes.

The generated frequency will in any case be approximately $f \approx 10^7/\text{w.}$ in Hz. or cycles/sec. with an upper limit around v_T/w and a lower limit around v_L/w at fields above E_T.

The spectral purity, coherence etc. of any given BNC semiconductor oscillator is dependent upon the particular type of traveling space charge domain being generated and the initial starting conditions. The observed rather erratic performance of BNC semiconductors with regard to poor coherence and spectral purity is fundamentally due to microscopic spatial fluctuations in the impurity distribution of the donor ions which results in instabilities in the nature of the initial starting conditions of the traveling space charge domains. By the utilization of resistivity gradients in the main body of the semiconductor between the source and drain electrodes it is possible not only to better control the point of origin of a given space charge domain but also to predetermine the particular type of domain which will be propagated. The resistivity gradients can be positive or negative between the source and drain electrodes and the particular shapes are preferably linear although stepped, non-linear and curved gradients would suffice.

By introducing a positive resistivity gradient between the source and drain electrodes of a BNC semiconductor, higher resistivities at positive or drain electrode, the curve of potential energy of the conduction electrons ϕ along the direction of applied field, just prior to the onset of

Figure B.160: Herbert Kroemer invented III-V semiconductor heterostructures in 1966.

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oscillations will be convex upward. When the applied voltage is increased beyond threshold such that $V/w>E_T$ the convex shape of the potential energy distribution of the conduction electrons between source and drain electrodes will cause a pure accumulation mode to form.

A pure accumulation mode will then be propagated as a traveling space charge domain towards the exit region or drain eletrode. The accumulation mode will be characterized by the presence of an accumulation layer bounded on the upstream side by a low field region and bounded on the downstream side by a high field region. The accumulation layer itself is a narrow region of excess or negative space charge populated by electrons of both high and low mobilities as referenced to the generic many valley conduction band structure depicted in FIG. 2.

By introducing a negative resistivity gradient between the source and drain electrodes of a BNC semiconductor, lower resistivities at positive or drain electrode, the curve of the potential energy of the conduction electrons ϕ along the direction of applied field, just prior to the onset of oscillations will be concave upward. When the applied voltage is increased beyond threshold such that $V/w>E_T$ the concave shape of the potential energy distribution of the conduction electrons between source and drain electrodes will cause a depletion layer to form in addition to the accumulation layer formed by the negative electrode itself.

A dipole space charge mode will then be propagated as a traveling space charge domain toward the exit region or drain electrode. The dipole space charge mode will be characterized by the presence of a pair of low field regions bounding an upstream accumulation layer separated from a downstream depletion layer by a high field region. The accumulation layer is the same as in the pure accumulation mode case and the depletion layer is a region of positive space charge characterized by the absence of conduction electrons. The high and low field regions will have values dependent on the particular semiconductor material.

The design criterion for the resistivity gradients (in both the positive and negative cases) is the limitation of the gradient to values which are no stronger than is necessary to just override the random nucleation processes in order to assure that all portions of diode main body width w do indeed oscillate. Good results can be obtained using resistivity gradients between 1% and 20% of the average resistivity.

Furthermore, in the case of the negative gradient, the region of high resistivity can be concentrated in the area near the source electrode.

I have also determined that the spectral purity, stability and coherency of BNC diodes can be improved by utilizing a heterojunction source electrode in conjunction with a BNC diode body with the heterojunction electrode (a heterojunction being a junction between two dissimilar semiconductors as opposed to a homojunction which is a union of similar semiconductors) being characterized as follows: (a) higher resistivity than the BNC diode body portion; and (b) not exhibiting a negative mobility at the fields reached during oscillation of the oscillating semiconductor.

In other words, the source electrode making contact to the BNC semiconductor body is not a simple metal contact or a more heavily doped or degenerate region of the same semiconductor. In other words, by selecting the source electrode parameters such as indicated above, it is possible to control the original nucleation point of each dipole domain as well as the initial starting conditions for dipole domain formation in a manner which results in a depletion layer being nucleated directly at the heterojunction interface and developing into a mature dipole domain from this point rather than being left to chance as heretofore occurred. The rationale for the previous instabilities in dipole domain formation and operating frequency were due, in my opinion reached through theoretical analysis, to microscopic spatial fluctuations of the donor distribution in n-type BNC semiconductors which result in a high degree of uncertainty as to what the initial starting conditions and starting point of any given dipole domain will be. By restricting the inital starting condition of each dipole domain to the formation of a depletion layer with the starting point located at the heterojunction interface good improvement in the stability and coherence of the operating frequency will result.

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Other types of heterojunction source electrodes which are taught by the present invention are the simple narrow to wide gap case wherein a particularly useful case involves nGe-nGaAs wherein the depletion layer, positive space charge region, created by the $\Delta\epsilon_c$ is useful for forming an initial high field region. The use of a wide to narrow gap heterojunction such as nGaP-nGaAs is taught by the present invention as a technique for obtaining direct injection of electrons from the GaP into the satellite (100) valleys of the nGaAs. A particularly useful junction called the CHI-junction (χ-junction) is also taught by the present invention for obtaining direct electron injection into the satellite valleys of the BNC semiconducor. This χ-type of heterojunction has other uses as will be developed hereinafter.

It is therefore an object of the present invention to provide a novel bulk negative conductivity semiconductor.

A feature of the present invention is the provision of a BNC semiconductor with mode control means.

Another feature of the present invention is the provision of a BNC semiconductor with a positive resistivity gradient for controlling the nucleation of a traveling pure accumulation mode.

Another feature of the present invention is the provision of a BNC semiconductor with a negative resistivity gradient for controlling the nucleation of a traveling dipole space charge mode of propagation.

Another feature of the present invention is the provision of a BNC semiconductor with a heterojunction source electrode for nucleation and mode control.

Another feature of the present invention is the provision of a novel χ-junction type of heterojunction.

Another feature of the present invention is the provision of a narrow to wide forbidden band gap heterojunction control electrode for BNC semiconductors.

Another feature of the present invention is the provision of a wide to narrow forbidden band gap heterojunction source control electrode for BNC semiconductors which can produce direct electron injection into the satellite valleys of the BNC semiconductor.

These and other features and advantages of the present invention will become more apparent upon a perusal of the following specification taken in conjunction with the accompanying drawings wherein:

FIG. 1 is an illustrative graphical portrayal of the drift velocity v vs. applied electrical field E dependence of a BNC semiconductor having a region of negative differential mobility.

FIG. 2 is an illustrative K-space diagram of the generic band structure associated with a BNC semiconductor particularly directed to n-type GaAs.

FIGS. 3A, 3B, and 3C depict the formation of a dipole space charge mode in a BNC semiconductor without a resistivity gradient.

FIGS. 4A, 4B, and 4C depict the formation of a traveling pure accumulation mode in a BNC semiconductor having a positive resistivity gradient.

FIGS. 5A, 5B, and 5C depict the formation of a traveling dipole space charge mode in a BNC semiconductor having a negative resistivity gradient.

FIG. 6 is a cross-sectional view of a typical BNC semiconductor incorporating a heterojunction source electrode for mode control.

FIG. 7 is an illustrative graphical portrayal of controlled formation of a traveling dipole space charge

Figure B.161: Herbert Kroemer invented III-V semiconductor heterostructures in 1966.