Feb. 1, 1955 W. G. PFANN ET AL 2,701,326

SEMICONDUCTOR TRANSLATING DEVICE

Filed Dec. 30, 1949

FIG. 1

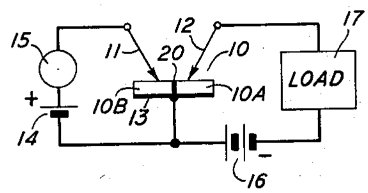



FIG. 2

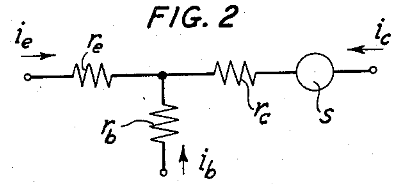



FIG. 3

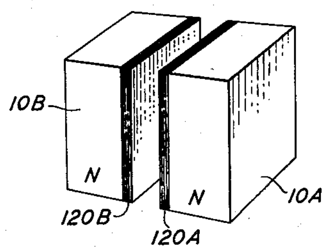



FIG. 4

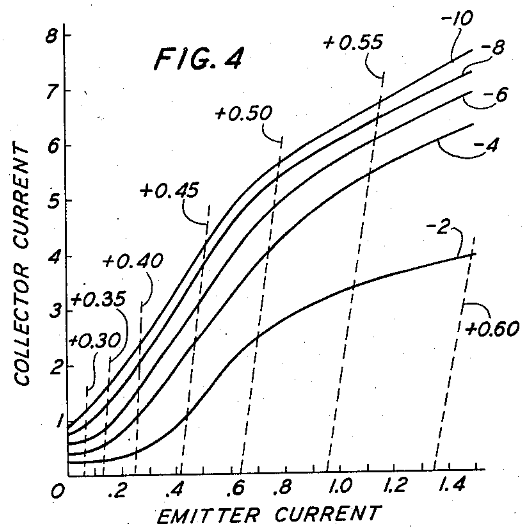



FIG. 6A

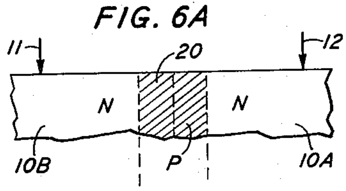



FIG. 6B

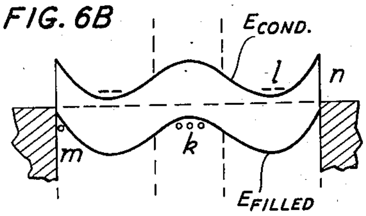



FIG. 5

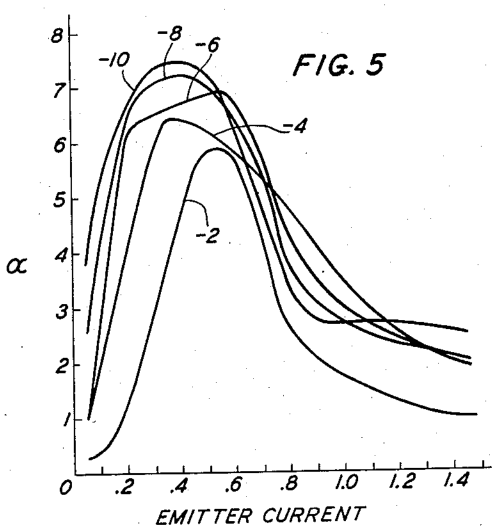



FIG. 6C

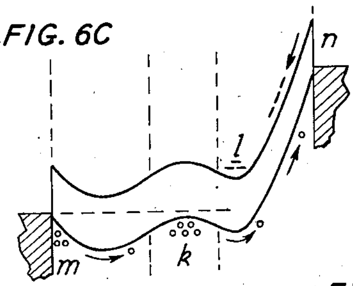



FIG. 7

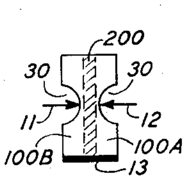
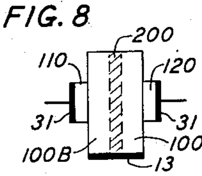



FIG. 8

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# United States Patent Office

2,701,326

Patented Feb. 1, 1955



2,701,326

## SEMICONDUCTOR TRANSLATING DEVICE

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Application December 30, 1949, Serial No. 136,038

11 Claims. (Cl. 317—235)

This invention relates to semiconductor signal translating devices and more particularly to such devices of the type disclosed in the applications, Serial No. 33,466 filed June 17, 1948 of J. Bardeen and W. H. Brattain, now Patent 2,524,035 granted October 3, 1950 and Serial No. 98,008 filed June 9, 1949 of R. J. Kircher now Patent 2,623,103 granted December 23, 1952.

Devices of the type disclosed in the above-identified applications comprise, in general, a body of semiconductive material, for example germanium, a pair of rectifying connections to two spaced regions of the body and a third large area or ohmic connection to the body. The rectifying connections, which are designated respectively as the emitter and the collector, may be, in one construction, point contacts bearing against one face of the body and the third connection, termed the base, may be made to the opposite face of the body. Amplified replicas of signals from an input circuit connected, for example, between the emitter and the base, appear in an output circuit connected, for example, between the collector and the base. Both power and current gains are attainable.

The device may be depicted by an equivalent circuit analog of T configuration wherein one series arm is a resistor corresponding to the emitter resistance, the shunt arm is a resistor corresponding to the base resistance, and the other series arm includes a resistor, corresponding to the collector resistance, and a current generator which represents the current multiplication factor, commonly designated as $\alpha$, of the device. The base resistance is in the nature of a positive feedback impedance.

As disclosed in the Kircher application identified hereinabove, improved characteristics, notably a low value of the positive feedback impedance, are realized if the emitter and collector contact the semiconductive body on opposite sides of a grain boundary of particular character therein. One of the requirements of such a boundary, in cases where the body is of N-conductivity type material, is that it exhibit the characteristics of an NPN junction, i. e. that at the boundary regions the conductivities correspond to that of a thin zone of P-type material between two zones of N-type material.

In another form of signal translating devices, such as disclosed in the application Serial No. 35,423, filed June 26, 1948 of W. Shockley, now Patent 2,569,347, granted September 25, 1951, the emitter or collector, or both, are defined by NP junctions or boundaries in the semiconductive body. In still another form of device, such as disclosed in the application Serial No. 130,268, filed November 30, 1949 of W. G. Pfann, now Patent 2,597,028 granted May 20, 1952, concentration of the electrical carriers flowing from emitter toward the collector is effected by provision of a zone of conductivity or conductivity type different from that of the body, extending between the emitter and the collector.

One general object of this invention is to improve the construction and performance of semiconductor signal translating devices of the general type hereinabove described.

Another general object of this invention is to facilitate the production of a zone or layer in a semiconductive body of conductivity or conductivity type different from that of the remainder of the body.

More specifically, objects of this invention are to facilitate the attainment of a small positive feedback impedance in semiconductor signal translating devices, to enable control of this impedance, to attain large current multiplication factors, and to enable the controlled production of NP, NPN, PNP and like junctions in semiconductive bodies.



In one illustrative embodiment of this invention, a signal translating device comprises a body of semiconductive material having two zones of one conductivity type on opposite sides of and contiguous with a thin zone of the opposite conductivity type, emitter and collector connections to one face of the body and on opposite sides of the thin zone aforementioned, and a base connection to the body and contacting the thin zone.

One feature of this invention relates to the production of the thin zone. Specifically, this zone may be formed by coating one face of a body of semiconductive material of one conductivity type with a material capable of altering the conductivity type of the material, placing the coated face against the face of a body of the one conductivity type, and heating the assembly to join the two faces mentioned together. The coating material diffuses into or combines with the semiconductive material to alter the conductivity type of the regions immediately adjacent the coated face, whereby a synthetic grain boundary forming an NPN or PNP junction in a semiconductive body is produced. As an example, bodies of N-type high back voltage germanium and a coating of gold may be used, the gold acting as an acceptor impurity to convert N-type germanium to P-type.

In accordance with another feature of this invention, the applied coating may comprise both a conductivity-type controlling material and a bonding material.

Both of the joined faces may be coated with the conductivity determining material or this together with a bonding agent. The thickness of the junction and the impedance thereof may be controlled by the amount and kind of the coating utilized and by the heat treatment of the assembled unit, whereby semiconductor bodies of prescribed characteristics may be produced.

Translating devices of the type first described hereinabove comprising synthetic boundaries or junctions formed in accordance with features of this invention, have low values of positive feedback impedance of the order of 10 ohms or less. Furthermore, such devices have a large value of the current multiplication factor over a wide range of operating conditions.

This invention and the above-noted and other features thereof will be understood more clearly and fully from the following detailed description with reference to the accompanying drawing in which:

Fig. 1 is a diagram of a semiconductor-type amplifier illustrative of one embodiment of this invention;

Fig. 2 shows an equivalent circuit analog of the semiconductor translating device included in the amplifier of Fig. 1;

Fig. 3 is a perspective view illustrating one way of fabricating a semiconductor body for translating devices in accordance with this invention;

Figs. 4 and 5 are graphs depicting operating characteristics of a typical device constructed in accordance with this invention;

Figs. 6A, 6B and 6C are diagrams which will be referred to hereinafter in a discussion of principles involved in devices illustrative of this invention; and

Figs. 7 and 8 illustrate the construction of other semiconductor devices embodying features of this invention.

In the drawing, in the interest of clarity, dimensions of the semiconductive body have been greatly exaggerated. The extent of the exaggeration will be appreciated from dimensions of typical devices given hereinafter.

Referring now to the drawing, the amplifier shown in Fig. 1 comprises a body **10** of semiconductive material having a pair of point contacts **11** and **12** bearing against one face thereof and having also a large area or ohmic connection **13**, for example, a plating of rhodium, to the other face thereof. The connections **11**, **12** and **13** are commonly designated as the emitter, collector and base, respectively.

An input circuit including a biasing source **14** and a signal source **15** is connected between the emitter and base, the source **14** being of the polarity to bias the emitter **11** in the forward direction. Specifically, when the body **10** is of N-conductivity type, the emitter is biased positive, for example a fraction of a volt with respect to the base. An output circuit comprising a biasing source **16** and a load **17** is connected between the collector **12** and base **13**, the bias upon the collector being in the reverse direction. Specifically, when the body is of N-conductivity type, the bias upon the collector may be of the order of 2 to 100 volts negative with respect to the base **13**. If the body **10** is of P-conductivity type material, the polarities of the biases upon the emitter and collector should be the reverse of that shown in Fig. 1.

Amplified replicas of signals impressed between the emitter and base by the source **15** appear across the load **17**, and both power and current gains are realizable.

The device of Fig. 1 may be represented by the equivalent circuit analog of Fig. 2 wherein the emitter and collector currents $i_e$ and $i_c$, respectively, are shown as flowing in the conventional sense, that is, the directions represent the flow of positive current. In N-type germanium, $i_e$ is usually positive, although sometimes negative, and $i_c$ is negative. In Fig. 2, $r_e$, $r_c$ and $r_b$ represent the emitter, collector and base resistances, respectively, $s$ is a source representing the current multiplication factor $\alpha$ of the device, this factor being defined as:

$$\alpha=\frac{\delta i_c}{\delta i_e}(E_c \text{ constant})$$

It will be noted from Fig. 2 that the base resistance $r_b$ is common to the input and output circuits; thus it represents a path for positive feedback from the output to the input circuits. Such feedback is undesirable in some applications inasmuch as it tends toward instability and further restricts the high frequency range of operation of the device. In typical devices such as shown in the application of Bardeen et al. heretofore identified, the emitter resistance $r_e$ may be of the order of several hundred ohms, the collector resistance $r_c$ may be of the order of 10,000 to 20,000 ohms and the base or feedback resistance may be of the order of several hundred ohms.

In accordance with one feature of this invention, the positive feedback impedance $r_b$ is substantially minimized. More specifically, in accordance with one feature of this invention, the semiconductive body **10** is constructed to have therein a synthetic boundary of conductivity type opposite to that of the remainder of the body, the boundary being electrically continuous and contacting the base **13**. As shown in Figs. 1 and 3, in one illustrative construction, the body **10** comprises two similar portions **10A** and **10B** of N-conductivity type, these two portions being joined by a portion or section **20** of P-conductivity type, the portion or section **20** extending between the emitter and collector, which may be spaced of the order of 5 mils.

In general, in the fabrication of a body of a construction illustrated in Figs. 1 and 3, the facing surfaces of the two portions **10A** and **10B** are lapped so that they match, for example, are planar, are then etched and a layer **120A** or **120B** of an acceptor impurity is deposited upon the lapped and etched surfaces. The blocks are then pressed together with the coated surfaces in contact, and sintered to bond the two bodies together. The acceptor impurity diffuses into the body portions **10A** and **10B** to convert a layer thereof to P-conductivity type. The resulting unit thus comprises two N-conductivity type zones joined to and separated by a P-conductivity type zone.

N-type germanium may be converted to P-type, and vice versa, by heat treatment. If, in the fabrication of bodies or blocks in the manner above set forth, the temperatures employed are such as to convert some of the N material beyond the bond to P-type, reconversion to N-type may be effected by appropriate heat treatment. If the bonding temperature is below the NP conversion temperature, such heat treatment is not necessary.

A specific and illustrative construction comprises two bodies **10A** and **10B** of high back voltage N-conductivity type germanium produced for example as disclosed in the application Serial No. 638,351 filed December 29, 1945 of J. H. Scaff and H. C. Theuerer now Patent 2,602,211 granted July 8, 1952 and the layers **120A** and **120B** may be of copper. This construction is fabricated in the following manner:

The surfaces to be bonded are lapped, as by grinding



with fine abrasive powder on a lead lap to a highly flat and smooth condition. They are then washed and etched for 30 seconds in a solution containing 40 cc. water, 10 cc.–30% $H_2O_2$ (Superoxol), 10 cc.–48% HF., rinsed in distilled water, and then in absolute ethyl alcohol. A layer of copper, in the order of $10^{-6}$ to $10^{-5}$ inches in thickness, is deposited by electroplating or by evaporation in vacuum. The blocks are pressed together with the treated faces together with a pressure in the order of 90 pounds per square inch, and heated for about 18 hours at about 700 to 900° C. in an atmosphere of dried hydrogen (dew point of about —40° C.). Oxygen is removed from the hydrogen by passing it over palladinized Alundum. The unit then is heated at 500° C. for 24 hours to convert bulk of sample back to N-type.

The bonded blocks have a total thickness of the order of 0.050 inch (.025 inch for each block), which is a convenient size.

The bonded blocks are cut normal to the plane of the synthetic boundary, producing a body substantially .050 inch long, .020 inch thick and .025 inch wide, the boundary bisecting the long dimension.

The base connection may be made by copper or rhodium plating to a face of the block intersected by the zone **20**.

The face or faces to which point contacts are to be made may be ground on 600 wet Alundum on glass, and etched in the above described solution.

Other materials or combinations of materials may be utilized in like manner. The width of the P-type region may be controlled by correlation of the temperature and the period of heating. For example, the following data for gold, which is advantageous for use as both an acceptor and bonding material indicates the control obtainable, the data being for high back voltage N-type germanium:

| Heating Temperature | Heating Time, hours | Width of P Zone, inch |
|---|---|---|
| 700° C | 20 | 0.006 |
| 900° C | 18 | >0.040 |
| 900° C | 2 | 0.014 |

Operating characteristics of a device constructed as above described with copper are illustrated in Figs. 4 and 5. In Fig. 4, collector current is plotted as ordinates against emitter current as abscissa for several values between 2 and 10 volts negative of bias upon the collector, the bias being indicated upon the respective curves. The dotted lines in Fig. 4 indicate the operating characteristics for several values of bias upon the emitter between 0.30 and 0.60 volt, the emitter bias for each line being indicated thereon.

In Fig. 5 the current multiplication factor $\alpha$ is plotted against emitter current for several values of collector bias between 2 and 10 volts, the bias corresponding to each curve being indicated thereon in the figure.

For a typical unit, the characteristics of which are portrayed in Figs. 4 and 5, the positive feedback impedance $r_b$ was 4 ohms which, as will be apparent from comparison with the data heretofore given, represents a very marked improvement over prior art devices. The emitter resistance is of the same order of magnitude as that given hereinabove; the collector resistance is of the order of 2000 ohms. Further, as will be apparent from Fig. 5, large current multiplication factors, greater than 6, are obtained over a substantial range of emitter currents and a moderate range of collector bias; thus, high current gains, large power amplification and highly stable operation are realized.

An explanation of the high values or current multiplication factor realized may be found from consideration of Figs. 6A, 6B and 6C. The first portrays a section of the semiconductive body adjacent the surface against which the emitter and collector bear; the second is an energy level diagram for this section, the curved lines in the diagram representing the bottom of the conduction band and the top of the partially filled band, as designated thereon, with the emitter and collector unbiased. Fig. 6C shows the energy levels when the emitter and collector are biased, the conditions being such that holes, indicated by the small circles at region $k$, are just beginning to be drawn toward the collector.

Assume now that as a result of a signal the positive bias upon the emitter **11** is increased slightly. This will cause holes in the region $m$ to flow to the region $k$ where they will be trapped momentarily because of the shape of the energy contour in the region between the PN barriers or junctions. An accumulation of holes in this region lowers the energy level at $k$ with respect to that at $l$ and, as a result, the height of PN barrier between $k$ and $l$ is decreased. Consequently, some holes will cross this barrier and travel to the collector because of the attracting field of the collector. In the vicinity of the collector, which is electrically formed in ways now known, each arriving hole releases several electrons. A large proportion of these are drawn toward the region $l$ where they accumulate momentarily thereby to further reduce the height of the barrier between the regions $k$ and $l$. As a consequence, more holes are released and flow to the collector. The process is repetitive whereby large values of the current multiplication factor $\alpha$ are realized.

Although in the specific embodiment above described copper was utilized as the agent for producing the P-type region or zone **20**, other materials may be employed. The same material, for example, gold, aluminum or copper, may serve as the acceptor and the bonding agent. Or a bonding agent, such as tin, silver, gold, copper or platinum, may be used in conjunction with one or more acceptors, such as gallium, indium, thallium, gold, aluminum or boron. Or several acceptors may be used together, such as gold and aluminum.

Particularly advantageous agents are those which lead to the formation of a low-melting eutectic mixture with germanium which melts and tends to braze the two bodies or portions **10A** and **10B** together, examples are gold, aluminum, tin, platinum and combinations of these.

Mixtures of elements may be deposited on the blocks prior to treatment in several ways:

1. By evaporation in discreet layers.
2. By simultaneous evaporation to form an alloy layer.
3. By electrodeposition in discreet layers, or simultaneously where feasible.

Further control of the extent of the P-zone in each block can be had by means of a diffusion heat treatment used before the final sintering process. Thus, each P-zone may be essentially completely formed before sintering. This permits individual control of the extent and character of the PN boundary region in each block. The sintering may then be done by means of a bonding agent which is not necessarily an acceptor.

In all cases, it is desirable that the intermediate agent material be diffused essentially completely into the semiconductor as its presence in metallic form would tend to create imperfections in the NPN boundary region.

The invention may be embodied also in translating devices of the type disclosed in the applications Serial No. 44,241 filed August 14, 1948 of J. N. Shive and Serial No. 45,023 filed August 19, 1948 of W. E. Kock and R. L. Wallace, now Patent 2,560,579, granted July 17, 1951, wherein the emitter and collector bear against opposite faces of a semiconductive body. Two illustrative constructions are shown in Figs. 7 and 8.

In the device shown in Fig. 7, the zones or bodies **100A** and **100B** of one conductivity-type semiconductive material have therein aligned semispherical recesses **30** and the axially aligned emitter and collector **11** and **12**, respectively, are located centrally in these recesses. The intermediate zone **200** is of the opposite conductivity-type or of the same type as the zones **100A** and **100B** but of lower conductivity; it may be produced in the same ways as the zone **20** in the construction illustrated in Figs. 1 and 3 and described hereinabove. The base connection **13** is made to the periphery of the semiconductive body.

In the construction illustrated in Fig. 8, the emitter and collector **110** and **120**, respectively, are bodies of semiconductive material of conductivity type opposite that of the zones **100A** and **100B** and form rectifying junctions therewith. Connection to the emitter and collector is made by way of ohmic coatings **31**, for example of rhodium, to which suitable leading-in conductors are affixed.

Although the invention has been described thus far with particular reference to the formation of a P zone between two N-type regions, it will be understood that it may be utilized to produce an N zone between two P regions. In this case, blocks **10** of P material are used and a donor impurity, such as phosphorus, arsenic, antimony or bismuth, with or without a bonding material, is employed, the donor diffusing into the P blocks to form thin layers of N material therein.

The invention thus may be utilized to produce a zone or layer of one conductivity type in a body of the opposite conductivity type, e. g., a P zone in an N body or an N zone in a P body. Furthermore, the invention is of use in the formation of a zone or layer in a body of conductivity different from that of the body. For example, by use of appropriate acceptor materials, a low conductivity N zone or layer may be formed in a high conductivity N body, or by use of appropriate donor materials a low conductivity P zone or layer may be produced in a high conductivity P body.

Also, in accordance with this invention, PN layers may be formed between two bodies of the same or different conductivity types. For example, a PN layer or zone between two N bodies may be formed in the following manner: acceptors are diffused into one face of one low conductivity N block to produce a P layer, and donors are diffused into one face of another low conductivity N block to form a high conductivity N zone or layer. Then the two blocks with the layers or zones in juxtaposition are bonded together. In similar manner, a body having an NPNP configuration may be produced by starting with an N and a P block.

The invention may be practiced also in the forming of PN boundaries or junctions between blocks of opposite conductivity types. This may be accomplished in any one of several ways. For example, a P block and an N block may be joined by use of a bonding material applied to one or both of the juxtaposed faces of the blocks and sintering the two blocks together. In this case, the PN boundary will coincide with the synthetic grain boundary. Also, for example, an acceptor material may be used as or with the bonding material. Diffusion of the acceptor into the N block will cause the PN boundary to be displaced into this block from the grain boundary. In a third case, a donor is used as or with the bonding material, and diffuses into the P block, whereby the PN boundary is displaced into this block. A particular advantage of the use of a donor or acceptor is that the transition region of the NP boundary is substantially free of defects or faults, such as may be present at the synthetic grain or body boundary.

Also, several superposed layers of different conductivity or conductivity type can be produced on a body or block of a given conductivity and type. For example, gold may be deposited upon a block of low conductivity N-type germanium and the unit heated at 900° C. to diffuse all of the gold into the block, thereby to form a P-type layer, for example of from about 0.001 inch to about 0.010 inch thick upon the block. Then a donor material, such as phosphorus or antimony is deposited upon the P layer and diffused inward to form a high or low conductivity N layer on the P layer. The thickness of the layers will be dependent, of course, upon the amount of the conductivity determining agent, the diffusion constant, nature of the agent, and time and temperature of heating. In general, the thickness increases with heating time and heating temperature.

Further, both donors and acceptors can be deposited simultaneously and the development of the layers determined by correlation of the factors above mentioned and by subsequent treatments.

Although specific embodiments of the invention have been shown and described, it will be understood that they are but illustrative and that various modifications may be made therein without departing from the scope and spirit of this invention.

What is claimed is:

1. The method of forming a synthetic grain boundary in a body of semiconductive material for signal translating devices, which comprises forming mating surfaces upon two bodies of the semiconductive material, applying a coating of a material capable of alloying with the semiconductor material upon one of said surfaces, pressing the two surfaces against each other, and heating said bodies to sintering temperature.

2. The method of forming a synthetic grain boundary in a body of semiconductive material for signal trans-

lating devices, which comprises forming mating surfaces upon two bodies of semiconductive material of like conductivity type, applying upon one of said surfaces a coating of a conductivity controlling material, pressing said surfaces against each other, and heating the assembly to sintering temperature.

3. The method of forming a synthetic grain boundary in a body of semiconductive material for signal translating devices, which comprises forming mating surfaces upon two bodies of semiconductive material of N-conductivity type, applying a coating of acceptor material to one of said surfaces, pressing said surfaces against each other, and heating the assembly to sintering temperature.

4. The method of forming a synthetic grain boundary in a semiconductive element for signal translating devices, which comprises forming mating surfaces upon two bodies of N-conductivity type germanium, applying a coating of acceptor material to one of said surfaces, pressing said surfaces against each other, and heating the assembly to bond said bodies together.

5. The method of forming a synthetic grain boundary in a body of semiconductive material for signal translating devices, which comprises forming mating surfaces upon two bodies of the semiconductive material, applying to one of said surfaces a mixture of a bonding material and a conductivity controlling material, pressing said surfaces against each other, and heating the assembly to bond said bodies together.

6. The method of making a semiconductive element for signal translating devices, which comprises forming mating surfaces on two bodies of N-type germanium, applying to one of said surfaces a coating of a mixture of an acceptor material and a bonding material, pressing said surfaces against each other, and heating the assembly to bond said bodies together.

7. The method of making a semiconductive element for signal translating devices which comprises forming on a face of each of two bodies of N-type germanium a layer including a P-type addition agent and a bonding metal, pressing the two bodies together with the two layers in face to face relation, and heating the unit thus formed in a protective atmosphere to bond the two bodies together.

8. The method of forming a semi-conductive element for signal translating devices, which comprises forming mating surfaces upon two bodies of N-conductivity type germanium, applying a coating of copper to one of said surfaces, pressing said surfaces against each other with a pressure of the order of 90 pounds per square inch, and heating the assembly at a temperature of about 700 to 900° C. for about 18 hours in an oxygen-free atmosphere.



9. The method of forming a semiconductive element for signal translating devices, which comprises forming mating surfaces upon two bodies of N-conductivity type germanium, applying a coating of gold to one of said surfaces, pressing said surfaces against each other, and heating the assembly at a temperature of about 700 to 900° C. for between about 2 and 20 hours.

10. A signal translating device comprising a body of germanium having therein a synthetic grain boundary extending between opposite faces of said body, a pair of rectifying connections to said body on opposite sides of said boundary, and a substantially ohmic connection to said body and contacting said boundary.

11. A signal translating device comprising a body of N-conductivity type germanium having a synthetic grain boundary of P-conductivity type extending between opposite faces of said body, a pair of rectifying connections to said body on opposite sides of said boundary, and a substantially ohmic connection to said boundary.


**References Cited in the file of this patent**

UNITED STATES PATENTS

| | | |
|---|---|---|
| 1,881,064 | Sayles et al. | Oct. 4, 1932 |
| 2,410,268 | Carlson | Oct. 29, 1946 |
| 2,415,841 | Ohl | Feb. 18, 1947 |
| 2,437,269 | Ohl | Mar. 9, 1948 |
| 2,438,110 | Brattain | Mar. 23, 1948 |
| 2,438,944 | Ransley | Apr. 6, 1948 |
| 2,449,484 | Jaffe | Sept. 14, 1948 |
| 2,450,851 | Colbert et al. | Oct. 5, 1948 |
| 2,496,432 | Blackburn | Feb. 7, 1950 |
| 2,514,879 | Lark-Horovitz et al. | July 11, 1950 |
| 2,555,001 | Ohl | May 29, 1951 |
| 2,556,991 | Teal | June 12, 1951 |
| 2,560,792 | Gibney | July 17, 1951 |

FOREIGN PATENTS

| | | |
|---|---|---|
| 541,739 | Great Britain | 1941 |

OTHER REFERENCES

Purdue University, Preparation of High Voltage Germanium Crystals, November 1, 1944, abstract page and Figure 6, 75–Ge.