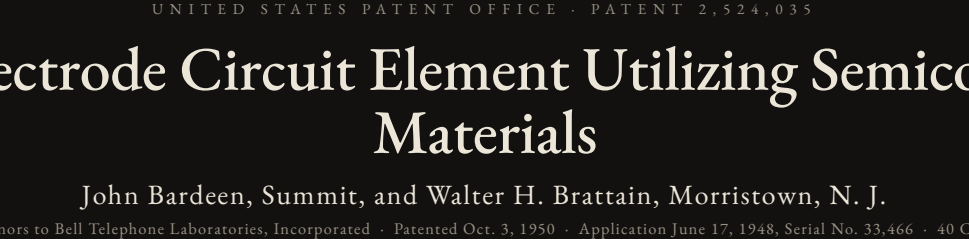
Three-Electrode Circuit Element Utilizing Semiconductive Materials

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The three sheets of drawings (Fig. 1, the germanium block with its emitter, collector and base electrodes in an amplifier circuit; Figs. 2 to 12, the germanium block, the quality of the current, other electrode forms and circuits; Figs. 13 to 16, the germanium distribution in the semiconductor)

This application is a continuation-in-part of application Serial No. 11,165, filed February 26, 1948, and thereafter abandoned.

This invention relates to a novel method of and means for translating electrical variations in the electron emission at a cathode by means of a control electrode, and more particularly to a novel three-electrode circuit element utilizing semiconductive materials, and to a novel method of making the same.

The principal object of the invention is to amplify or otherwise translate electric signals or variations by use of compact, simple, and rugged apparatus of novel type.

Another object is to provide a circuit element for use as an amplifier or the like which does not require a heated thermionic cathode for its operation, and which therefore is immediately operative when turned on. A related object is to provide such a circuit element which requires no evacuated or gas-filled envelope.

Attempts have been made in the past to convert solid rectifiers utilizing selenium, copper sulfide, or other semi-conductive materials into amplifiers by the direct expedient of embedding a grid-like electrode in a dielectric layer disposed between the cathode and the anode of the rectifier. The grid is supposed, by exerting an electric force at the surface of the cathode, to modify its emission and so alter the cathode-anode current. As a practical matter it is impossible to embed a grid in a layer which is so thick as to insulate the grid from the other electrodes and yet so thin as to permit current to flow between them. It has also been proposed to put a current limiting screen of a strip of homogeneous isotropic semiconductive material which by the polarization of a strong transverse electrostatic field, to control the resistance of the strip, and hence the current through it.

So far as is known, all of such past devices are beyond human skill to fabricate with the fineness necessary to produce amplification. In any event they do not appear to have been commercially successful.

It is well known that in semiconductive thesis are two types of carriers of electricity which differ in the signs of the effective mobile charges. The negative carriers are excess electrons which are free to move, and are deterred by the term conduction electrons or simply electrons. The positive carriers are missing electrons or defect "electrons," and are deterred by the term "holes." The conductivity of a semiconductor is called more or defect, or N or P types, depending on whether the mobile charges normally present in excess in the material under equilibrium conditions are electrons (Negative carriers) or holes (Positive carriers).

When a metal electrode is placed in contact with a semiconductor and a potential difference is applied across the junction, the magnitude of the current which flows often depends on the sign as well as on the magnitude of the potential. A junction of this sort is called a rectifying contact. If the contact is made to an N-type semiconductor, the direction of easy current flow is that in which the semiconductor is negative with respect to the electrode. With a P-type semiconductor, the direction of easy flow is that in which the semiconductor is positive. A similar rectifying contact exists at the boundary between two semiconductors of opposite conductivity types.

This boundary may separate two semiconductor materials of different constitutions, or it may separate zones or regions, within a body of semiconductor material which is chemically and microscopically uniform, which exhibit different conductivity characteristics.

The present invention in one form utilizes a block of semiconductor material on which three electrodes are placed. One of these, termed the collector, makes rectifier contact with the body of the block. The other, termed the emitter, preferably makes rectifier contact with the body of the block also. The third electrode, which may be designated the base electrode, preferably makes a low resistance contact with the body of the block. When operated as an amplifier, the emitter is normally biased in the direction of easy current flow with respect to the body of the semiconductor block. The current of the emitter electrode and of that portion of the semiconductor which is in the immediate neighborhood of the electrode contact is such as to control the magnitude of the current from this electrode is carried by charges whose signs are opposite to the signs of the mobile charges normally in excess in the body of the semiconductor. The collector is biased in the reverse, or high resistance direction relative to the body of the semiconductor. In the absence of the emitter, the current to the collector flows exclusively from the base electrode and is impeded by the high resistance of this collector contact. The sign of the collector bias potential is such as to attract the carriers which come from the emitter. The collector is so disposed in relation to the emitter that a large fraction of the emitter current enters the collector. The fraction depends in part on the geometrical disposition of the electrodes and in part on the bias potential applied. As the emitter is biased in the direction of easy flow, the emitter current is sensitive to small changes in emitter potential. By virtue of the body of the semiconductor, or between the emitter and the base electrode. Application of a small voltage variation between the base electrode and emitter causes a relatively large change in the current entering the semiconductor from the emitter, and a correspondingly large change in the current to the collector. The effect of the change in emitter current is to modify the total current flowing to the collector, so that the overall change in collector current may be greater than the change in the emitter current. The collector circuit may contain a load of high impedance matched to the internal impedance of the collector, which, because of the high contact resistance of the collector, is high. As a result, voltage amplification, current amplification, and power amplification of the input signal are obtained.

In one form, the device utilizes a block of semiconductor material of which the main body is of one conductivity type while a very thin surface layer or film is of opposite conductivity type. The surface layer is separated from the body by a high resistance rectifying barrier. The emitter and collector electrodes make contact with this surface layer sufficiently close together for mutual influence in the manner described above. The base electrode makes a low resistance contact with the body of the semiconductor. When such a semiconductive device is employed as an amplifier, a current flows from the emitter into the thin layer. Owing to the conductivity of the layer and to the nature of the barrier, this current tends to flow laterally in the thin layer, rather than following the most direct path across the barrier to the base electrode. This current is composed of carriers whose signs are opposite to the signs of the mobile charges normally in excess in the body of the semiconductor. In other words, when there is a thin layer of opposite conductivity type immediately under the emitter electrode, the current flowing into the block in the direction of easy flow contains largely of carriers of opposite sign to those of the mobile charges normally present in excess in the body of the block, and the presence of these carriers increases the conductivity of the block. The bias voltage on the collector which, as stated above, is biased in the reverse or high resistance direction relative to the body, produces a strong electrostatic field in a region surrounding the collector so that the current from the emitter which enters this region is drawn in to the collector. Thus, the collector current, and hence the conductance of the unit as a whole, are increased. The size of the region in which this strong field exists is comparatively insensitive to variations in the collector potential so that the impedance of the collector circuit is high. On the other hand, the current from the emitter to the layer is largely controlled by variations of the emitter potential, so that the impedance of the emitter circuit is low.

It is a feature of the invention that the input and output impedance of the device are controlled by choice and treatment of the semiconductor material body and of its surface, as well as by choice of the bias potentials of the electrodes.

From the standpoint of its external behavior and uses, the device of the invention resembles a vacuum tube triode, and while the electrodes are designated emitter, collector and base electrode, respectively, they may be externally interconnected in the various ways which have become recognized as appropriate for triodes, such as the conventional, the "grounded grid," the "grounded plate" or cathode follower, and the like. Indeed, the discovery on which the invention is based was first made with circuit connections which are extremely similar to the so-called "grounded grid" vacuum tube connections. However, the analogies among the circuits is, of course, no better than the analogy between emitter and cathode, base electrode and grid, collector and anode.

By finding back a portion of the output voltage in proper phase to the input terminals, the device may be caused to oscillate at a frequency determined by its entire circuit elements, and of course, among other tests, power amplification may be confirmed by a feedback connection which caused it to oscillate.

It has been found that the performance of the device is expressed, to a good approximation, by the following functional relations:

$$I_c = f(V_c + R_c I_c) \quad (1)$$

$$I_e = \phi(I_c) + \alpha I_c \quad (1a)$$

where

I_c=emitter current

I_c=collector current

I_{co}=collector current with emitter disconnected

V_c=voltage of emitter electrode measured with respect to the base electrode

V_c=voltage of collector electrode measured with respect to the base electrode

R_c=an equivalent resistance independent of bias, and

α=a numerical factor which depends on the bias voltages

$f(V_c)$=gives the relation between emitter current and emitter voltage with the collector circuit open.

The interpretation of the foregoing Equation 1 is that the collector current lowers the potential of the surface of the block in the vicinity of the emitter relative to the bias electrode by an amount $R_c I_c$, and thus increases the effective bias voltage on the emitter by the same amount. The term $R_c I_c$, thus represents positive feedback.

The invention will be fully apprehended from the following detailed description of one embodiment thereof, taken in connection with the appended drawings, in which:

Fig. 1 is a schematic diagram, partly in perspective, showing a preferred embodiment of the invention;

Fig. 1a is a cross-section of a part of Fig. 1 on a greatly enlarged scale;

Fig. 2 is the equivalent circuit with schematic circuit of Fig. 1;

Fig. 3 is a plan view of the block of Fig. 1, showing the disposition of the electrodes;

Fig. 3a is like Fig. 3 but shows the influence of the collector in modifying the emitter current;

Figs. 4, 5, 6, and 7 show electrode dispositions alternative to those of Fig. 1;

Figs. 8 and 9 show electrode connections to those of Fig. 1;

Fig. 10 shows a modified unit of the invention connected for operation in the circuit of a conventional triode;

Fig. 11 shows another modified unit of the invention connected for operation in a "grounded plate" or cathode follower circuit;

Fig. 12 shows the unit of the invention connected for self-heterodyne operation;

Fig. 13 is a diagram showing the electron potential distribution in the interior of an N-type semiconductive in contact with a metal;

Fig. 14 is a diagram showing the electron potential distribution in the interior of a P-type semiconductive in contact with a metal;

Fig. 15 is a diagram showing the electron potential distribution in the interior of a thin P-type semiconductive layer in contact on one side with a metal and on the other side with a body of N-type semiconducting material, for electrons in the conduction band (upper curves) and in the filled band (lower curves); and

Fig. 16 is a diagram showing the variation of the potential distribution of curve of Fig. 15 as a function of distance from the emitter to the collector.

The materials with which the invention deals are those semiconductors whose electrical characteristics are largely dependent on the inclusion therein of very small amounts of significant impurities. The expression "significant impurities" is here used to denote those impurities which affect the electrical characteristics of the material such as its resistivity, photosensitivity, rectification, and the like, as distinguished from other impurities which have no apparent effect on these characteristics. The term "semiconductive" is intended to include those materials which, as well as any which is or may be included in the finished material as found in nature or as commercially available. Germanium is such a material which, along with some representative impurities, will furnish an illustration of the principles involved in the present invention. Silicon is another such material. In the case of semiconductors which are chemical compounds such as cuprous oxide (Cu_2O) or silicon carbide (SiC), deviations from stoichiometric composition may constitute significant impurities.

Small amounts, i. e., up to 0.1 per cent of impurities, generally of higher valency than the basic semiconductor material, e. g., phosphorus in silicon, antimony and arsenic in germanium, are termed "donor" impurities because they contribute to the conductivity by "donating" electrons in the sense of an unfilled "conduction energy band" in the basic material. In each case the donated negative electrons constitute the carriers of current and the material and its conductivity are said to be of the N type. Similar small amounts of impurities, generally of lower valency than the base material, e.g., boron in silicon or aluminum in germanium, are termed "donor" impurities because they contribute to the conductivity by "accepting" electrons in the atoms of the basic material in the filled band. Such an acceptance leaves a gap or "hole" in the filled band. By interchange of the borrowed electrons from atom to atom, these positive "holes" effectively move about and constitute the carriers of current, and the material and its conductivity are said to be of the P type.

Under equilibrium conditions, the conductivity of an electrically neutral region or zone of such a semiconductive material is directly related to the concentration of significant impurities. Donor impurities which have given up electrons to an unfilled band are positively charged, and react by drought of an equal positive ions. In a region of a semiconductor which has only donor type impurities, the concentration of conduction electrons is equal to the concentration of ionized donors. Similarly, in a region of a semiconductor which has only acceptor impurities, the concentration of holes is equal to the concentration of the negatively charged acceptor ions.

If for any reason there is a departure from electrical neutrality in a region, giving a resultant space charge, the magnitude of the conductivity, and even the conductivity type may differ from that indicated by the significant impurities. It was once thought that the high resistance barrier layer in a rectifier differ somehow in chemical constitution or in the nature of the significant impurities from the main body of the semiconductor. W. Schottky, in Zeits. f. Phys., volume 113, page 367 (1939), has shown that this is not necessary. While the concentration of carriers (mobile charges) in the barrier layer is small, the concentration of ionized impurities (fixed charges) may be the same as in the body of the semiconductor. The fixed charges in the barrier layer are in unmeet with induced charges of opposite sign on the metal electrode to produce a potential drop between the electrode and the body of the semiconductor. The concentration of carriers at a point depends on the electrostatic potential at that point, and is small compared with the equilibrium concentration in the body of the semiconductor if the potential differs from that in the body by more than a small fraction of a volt. The mathematical theory has been developed by W. Schottky and E. Spenke in Wiss. Veröff. Siemens Werke, vol. 18, page 225 (1939). These authors show also that if the variation in electrostatic potential with depth below the surface is sufficiently large, the conductivity passes through a minimum for a certain potential and depth and the conductivity is of opposite type for larger values of the potential corresponding to smaller values of depth. They call the region of opposite conductivity type an anomalous region. It is thus possible to have at a rectifier contact a thin layer of one conductivity type next to the metal electrode, separated by a high resistance barrier from the body of opposite conductivity type.

It has been pointed out by J. Bardeen in Phys. Rev., vol. 71, page 717 (1947), that the same sort of barrier layer that Schottky found for rectifying contacts may exist beneath the free surface of a semiconductor, the space charge of the barrier layer being balanced by a charge of opposite sign on the surface atoms. It is possible, for example, to have a thin layer of P-type conductivity at the surface of a block which has a uniform concentration of donor impurities and which, therefore, has N-type conductivity in the body of the block, even though there or no actual acceptor impurities.

To distinguish such a situation from the similar one which depends on the presence of significant chemical impurities of opposite type in a thin surface layer, the terms "physical" and "chemical" are employed. Thus the terms "physical layer" and "physical barrier" refer to the layer of opposite conductivity type next to the surface and the high resistance barrier which separates it from the body of the semiconductor, both of which exist as a result of surface conditions and not as a result of a variation in the chemical concentration of significant impurities. The terms "chemical layer" and "chemical barrier" refer to the corresponding situation which does depend on a variation in significant impurities.

Both physical layers and chemical layers are suitable for the invention.

It is known here, by reason of the distribution of impurities, to fabricate a block of silicon of which the main body is of one conductivity type while a thin surface layer, separated from the main body by a high resistance barrier, is of the other type. In this case the layer is believed to be chemical rather than physical. For methods of preparing such blocks, as well as for certain uses of the same, reference may be made to an application of J. H. Scaff and H. C. Theuerer, filed December 4, 1946, Serial No. 715,744 and to United States Patents 2,402,661 and 2,402,662 to R. S. Ohl. Such materials are suitable for use in connection with the present invention. It is preferred, however, to describe the invention in connection with the material which was employed when the discovery on which it is based was made, namely, N-type germanium which has been so treated as to confirm a thin layer of P-type conductivity at the surface. A field are induced by broken lines 14a. 14b. The two semicircular spots 16, 16', of Fig. 7 are the substantial equivalent of the circle of Fig. 6.

Further increase may be made in the effective resistance of the barrier 4 and therefore in the internal resistance of the emitter-base electrode circuit and of the ratio of the collector current to the emitter current by restricting the area over which the barrier existed in a completely etched region surrounding the emitter 5 and the collector 6. This may be accomplished by restricting the area of the block 1 which is subjected to the anodic oxidation treatment or by machining the block after treatment. In the former case the result is a form of the device as shown in Fig. 9, mounted by a hotel-shaped barrier 4' as shown in Fig. 11, and in the latter case it is a block 1' having the form of a truncated pyramid, with the barrier 4' close to the smallest face, as indicated in Fig. 10.

In the event that the spring-button is not desired for the emitter and collector contact points, various alternative structures may be employed. For example, two sides of a wedge-shaped piece of insulating material may be plated with metal films as in Fig. 8, one 51 to serve as emitter and the other 61 as collector. Or a cone-shaped piece. 17 may be plated over its conical surface and a wire inserted through a central hole as in Fig. 9. The central wire 52 is preferably employed as the emitter and the surrounding plate film 62 as collector. The cone and the wedge serve to hold the rectifier-electrode capacities to a minimum while keeping the contacts close together where they bear against the surface of the semiconductor.

Further understanding of the considerations which govern the thickness of the P-type surface layer may be had from the following considerations, which apply specifically to a chemical layer. Fig. 13 is a plot of the electrostatic potential within the body of an N-type semiconductor in contact with a metal. As shown stand, the N-type material of the semiconductor contains fixed or bound positive charges. They are believed to be distributed with fair uniformity to depth to a certain distance, beyond which the material is electrically neutral because the bound positive charges are balanced by equal negative (electron) charges. In accordance with Poisson's equation:

$$\frac{dV}{dx} = \frac{4\pi\rho}{\epsilon} \quad (2)$$

where

V is the potential

ρ is the distance, measured from the metal into the semiconductor

ρ is the charge density, and

ϵ is the dielectric constant of the material.

Assuming the charge density ρ_0 to be uniform, two integrations give the potential as a function of depth. When plotted, it is a parabola. In the figure, negative potential has been plotted upward. The vertical axis E_0 from the Fermi level in the interior of the crystal, i. e., to its impurity with the potential axis, represents the energy which must be imparted to an electron to cause it to move from the metal to the semiconductor. These matters are fully explained in the literature, for example, in "Schottky's Theories of Dry Solid Rectifiers," by J. Scaff, published in "Electrical Communication," vol. 22 (1944–1945) at page 217.

Similarly Fig. 14 shows the potential distribution, for positive holes, within a P-type semiconductor in contact with a metal. In this case the height E_0 of the terminus of the curve from the Fermi level represents the energy which must be given to a positive hole to cause it to leave the metal and enter the semiconductor.

Fig. 15 is a composite diagram showing, in the upper curves, the electron energy and in the lower curves the hole energy, within a semiconductive which comprises a thin layer of P-type material separated from a body of N-type material by a barrier layer. The final charges are negative in the P-type material and positive in the N-type, and for simplicity are assumed to be distributed uniformly in each zone. Integration of the charge density, twice, in accordance with Poisson's equation gives the lowermost curve, a of the two groups, which represent equilibrium conditions and which, late for an additive constant V_0 are alike. The constant E_0 represents the energy difference between the filled band and the conduction band for the particular material.

The middle curves a_1, b_1, of each group represent the conditions when a small negative bias is applied to the semiconductor block 1 with respect to the emitter 5, and the upper curves a_2, b_2, of each group represent the conditions when a signal applied between the emitter and the control electrode further reduces the potential peak of the block. Evidently the alteration of the block potential with respect to the emitter operates in such case to increase the effective thickness of the P-type layer and so the density of holes and the layer conductivity. Such an increase in conductivity with increase in the forward bias has been observed in connection with the potential probe measurements referred to above.

The potential peak of the block is shown below the Fermi level. The exact value the thickness of the P-type layer, the more the terminus of this curve falls below the fermi level, i. e., the greater the magnitude of E_0, and the greater the difficulty for holes to leave the metal of the emitter and enter the semiconductor. Similarly, the thinner the P-type layer, the less is the magnitude of E_0, and the greater the ease with which holes move from the metal of the emitter to the interior of the collector electrode, to modify the impedance of its contact to current flowing from the low resistance contact electrode to the collector electrode, whereby the current drawn from the collector electrode contains a component which is an amplified version of the signal voltage, and charges acting, by reason of their accumulation in the block in the vicinity of the collector electrode, to modify the impedance of its contact to current flowing from the low resistance contact electrode to the collector electrode, whereby the current drawn from the collector electrode contains a component which is an amplified version of the signal current.

Fig. 16 is a three-dimensional representation of the conditions which the holes encounter in the course of their travel in the layer from the emitter to the collector—it the figure, positive holes are shown as circles. As in Fig. 15, the main current density is assumed to be uniform in the direction of easy flow, but to approximately logarithmic scale, represents negative potential. As the holes approach the collector the peak of the potential curve becomes less and less pronounced until finally, at the collector, the potential curve falls off to the value which exists in the body of the base, which is the collector itself, where they are withdrawn.

Of that part of the emitter current which crosses the barrier, a certain fraction crosses it again in the vicinity of the collector and is collected, thus forming a part of the collector current. The foregoing hypothesis as to the mechanism by which amplification is obtained applies to this fraction of the current as well as to the fraction which proceeds entirely within the layer.

The collector current contains still another component, which consists of a flow of electrons from the collector to the base electrode, crossing the barrier more on its way. A hypothesis as to the mechanism by which this component is produced is not necessary for the amplification process to follow.

There is a potential hill at the contact point between the collector electrode and the surface layer which offers an impedance to the flow of electrons from the electrode into the semiconductor. In the absence of bias, the height of this hill, indicated by E_0 in Figs. 13 and 15, is the energy required to take an electron from the metal and place it in the conduction band of the semiconductor. When the collector is biased in the reverse direction, the effective height of the hill, and so the impedance of the contact point, are reduced by the electric field across the layer and barrier which acts in such a direction as to pull electrons from the electrode. This effect is to increase the flow of electrons into the semiconductor in a way which is similar to the enhancement of current from a thermionic cathode by field-induced emission. When the emitter is connected, and a current of hole flows to the collector, the accumulation of the positive charges of these holes in the vicinity of the collector tends to make the potential fall more rapidly with depth into the material, and so results in an increase in field and a decrease in the effective height of the hill, i. e., in the impedance of the contact point. Thus any increase in that component of the collector current which originates at the emitter is accompanied by a corresponding increase in the other component of the collector current, namely, in the flow of electrons to the base electrode. Hence the total change in collector current may be greater than the change in the emitter current.

From the foregoing description it will be clear that if it is desired to employ a semiconductor block of which the main body is of P-type so that the conductivity of the thin surface layer, whether due to impurities or to space charge effects, is of N type, the polarities of all of the bias sources of Figs. 2, 10, 11 and 12 are to be reversed. It is also to be understood that the magnitudes of the biases for best operation will depend on the semiconductor material employed and on its heat treatment and processing. Furthermore, it is possible to use a P-type layer of one semiconductor material on an N-type body of some other semiconductor material or vice versa. All such variations are contemplated as being within the spirit of the invention.

The invention is not to be construed as limited to the particular forms disclosed herein, since these are to be regarded as illustrative rather than restrictive.

What is claimed is:

1. A circuit element which comprises a block of semiconductive material of which the body is of one conductivity type and a thin surface layer is of the opposite conductivity type, an emitter electrode making contact with said layer, a collector electrode making contact with said layer disposed to collect current spreading from said emitter electrode, and a base electrode making contact with the body of the block.

2. Apparatus as defined in claim 1 wherein the block is of germanium.

3. Apparatus as defined in claim 1 wherein the block is of N-type germanium and the surface layer is of P-type germanium.

4. Apparatus as defined in claim 1 wherein the block is of high back voltage germanium and to at least a part of one surface of which an anodic oxidation treatment has been applied.

5. Apparatus as defined in claim 1 wherein the block is of high back voltage germanium and to at least a part of one surface of which an anodic oxidation treatment has been applied.

6. A circuit element which comprises a semiconductive supporting body, a thin surface layer of semiconductor material supported by and in electrical contact with said body and differing in conductivity type therefrom, an emitter electrode making contact with said layer, a collector electrode in contact with a different part of the element from the part contacted by said emitter electrode and disposed to collect current spreading from said emitter electrode, and a base electrode making contact with the body.

7. Apparatus as defined in claim 6 wherein the area of contact of the emitter electrode with the semiconductor layer is large compared with the layer thickness.

8. Apparatus as defined in claim 6 wherein the emitter electrode is a point contact.

9. Apparatus as defined in claim 6 wherein the emitter electrode and the collector electrode are point contacts.

10. Apparatus as defined in claim 6 wherein the collector electrode and the collector electrode make rectifier contact with the body by way of the semiconductor layer.

11. Apparatus as defined in claim 6 wherein the collector electrode is spaced from the emitter electrode by a distance of the order of 5 to 2 mils.

12. Apparatus as defined in claim 6 wherein the collector electrode is spaced from the emitter electrode by a distance which is small compared with the semiconductor layer area but large compared with the layer thickness.

13. Apparatus as defined in claim 6 wherein the semiconductive supporting body is separated from the surface layer by a high resistance barrier, and wherein the base electrode makes contact with said body over a wide area of a surface thereof which is opposite to the surface bearing the semiconductive layer.

14. In combination with apparatus as defined in claim 6, means for biasing the emitter electrode with respect to said semiconductive layer in a sense to supply charge theretto of the sign for which the layer is conductive, and means for biasing the collector electrode to collect charges of the same sign.

15. In combination with apparatus as defined in claim 6, a work circuit interconnecting the collector electrode with the base electrode, and connections for applying a signal voltage between the emitter electrode and the base electrode.

16. A circuit element which comprises a block of semiconductive material characterized by fixed charges of one side and having a thin surface layer, separated from the main body of the block by a high resistance barrier, characterized by mobile charges of the same sign, a base electrode in contact with said body, an emitter electrode in contact with said layer, a potential source connected to said base electrode and to said emitter electrode to bias said emitter electrode in a sense to supply mobile charges of the same sign to said layer, a collector electrode in contact with said layer, and a potential source connected to said base electrode and to said collector electrode to bias said collector in a sense to establish an electric field across said layer between said collector electrode and fixed charges in the body of said block.

17. A circuit element which comprises a semiconductive body, a thin surface layer of semiconductive material separated from said body by a high impedance contacting barrier, at least two rectifier electrodes, of which one is a sharp point of conductive material, in close-spaced contact with said surface layer, and a third electrode in contact with said body.

18. A circuit element which comprises a block of semiconductive material, an electrode making low resistance contact with a part of the surface of the block, a plurality of electrodes making rectifier contact with other parts of the surface of the block, connections including said first-named electrode for applying a forward direction bias to one of said rectifier contact electrodes, and connections including said first-named electrode for applying a reverse direction bias to another of said rectifier electrodes.

19. A circuit element which comprises a block of semiconductive material, an electrode making low resistance contact with a part of the surface of the block, a plurality of electrodes making rectifier contact with other parts of the surface of the block, connections including said first-named electrode for applying a smaller forward direction bias to one of said rectifier contact electrodes, and connections including said first-named electrode for applying a larger reverse direction bias to another of said rectifier electrodes.

20. A circuit element which comprises a block of semiconductive material, an electrode making low resistance contact with a part of the surface of the block, a plurality of electrodes making rectifier contact with other parts of the surface of the block and spaced apart by a distance which is not greater than the smaller dimension of the block, connections including said first-named electrode for applying a smaller forward direction bias to one of said rectifier contact electrodes, and connections including said first-named electrode for applying a larger reverse direction bias to another of said rectifier electrodes.

21. In combination, a block of semiconductive material, a collector electrode making rectifier contact therewith, a second electrode connected to said block, a circuit including a source of voltage and a load connected to said collector electrode and to said second electrode, said source being so poled as to draw reverse current from the block through said source, and another electrode making rectifier contact with the block and disposed to control the magnitude of the current from the block through said first contact.

22. The combination recited in the preceding claim in which said semiconductive material comprises germanium.

23. A translating device comprising a semiconductive, three electrodes in contact therewith, a high impedance output circuit including two of said electrodes and making a high resistance reverse-rectifier contact therewith by way of one of said two electrodes, and a low impedance input circuit including one of the first-recited electrodes and the third electrode and making a low-resistance forward-rectifier contact therewith by way of the third of said electrodes.

24. A circuit element which comprises a block of semiconductive material, an electrode making low resistance contact with a part of the surface of the block, an emitter electrode and a collector electrode making rectifier contact with other parts of the block, means for biasing the emitter electrode for conduction in the forward direction, means for biasing the collector electrode for conduction in the reverse direction, connections for applying a signal between the low resistance electrode and the emitter electrode to introduce a current of mobile charge into said block at low impedance by way of said emitter electrode, which charges are of signs opposite to the signs of the mobile charges normally present in excess in the semiconductive material under equilibrium conditions, connections for withdrawing said charges from said block at high impedance by way of said collector electrode, whereby the voltage across said collector electrode contact contains a component which is an amplified version of the signal voltage, said charges acting, by reason of their accumulation in the block in the vicinity of the collector electrode, to modify the impedance of its contact to current flowing from the low resistance contact electrode to the collector electrode, whereby the current drawn from the collector electrode contains a component which is an amplified version of the signal current.

25. A circuit element which comprises a block of semiconductive material of which the body is of one conductivity type while a thin surface layer is of the opposite conductivity type, an emitter electrode making contact with the surface layer, a collector electrode making contact with the surface layer and disposed to collect current spreading from the emitter electrode, a base electrode making contact with the body of the block, an input circuit including a source connected to the base electrode and to the emitter electrode, respectively, and an output circuit including a load connected to the base electrode and to the collector electrode, respectively.

26. A circuit element which comprises a block of semiconductive material of which the body is of one conductivity type while a thin surface layer is of the opposite conductivity type, an emitter electrode making contact with the surface layer, a collector electrode making contact with the surface layer and disposed to collect current spreading from the emitter electrode, a base electrode making contact with the body of the block, an input circuit including a source connected to the base electrode and to the emitter electrode, respectively, and an output circuit including a load connected to the collector electrode and to the base electrode, respectively.

27. A circuit element which comprises a block of semiconductive material of which the body is of one conductivity type while a thin surface layer is of the opposite conductivity type, an emitter electrode making contact with the surface layer, a collector electrode making contact with the surface layer and disposed to collect current spreading from the emitter electrode, a base electrode making contact with the body of the block, an input circuit including a source connected to the emitter electrode and to the base electrode, respectively, and an output circuit including a load connected to the collector electrode and to the base electrode, respectively.

28. A translating device comprising a semiconductive body, a thin surface layer of semiconductive material supported by and in electrical contact with said body and differing in conductivity type therefrom, an emitter electrode making contact with said layer, a collector electrode making contact with said layer disposed to collect current spreading from said emitter electrode, and a base electrode making contact with said body, said emitter electrode and said collector electrode being spaced apart a distance which is not greater than the smaller dimension of said layer.

29. A translating device comprising a semiconductive body, a thin surface layer of semiconductive material supported by and in electrical contact with said body and differing in conductivity type therefrom, an emitter electrode making contact with said layer, a collector electrode making contact with said layer disposed to collect current spreading from said emitter electrode, and a base electrode making contact with said body, said emitter electrode and said collector electrode being spaced apart a distance which is not greater than the smaller dimension of said layer.

30. A translating device comprising a semiconductive body, a thin surface layer of semiconductive material supported by and in electrical contact with said body and differing in conductivity type therefrom, an emitter electrode making contact with said layer, a collector electrode making contact with said layer disposed to collect current spreading from said emitter electrode, and a base electrode making contact with said body, said emitter electrode and said collector electrode being spaced apart a distance which is not greater than the smaller dimension of said layer, and a connection between said base electrode and said emitter electrode for applying a signal between said base electrode and said emitter electrode.

31. A translating device comprising a semiconductive body, a thin surface layer of semiconductive material supported by and in electrical contact with said body and differing in conductivity type therefrom, an emitter electrode making contact with said layer, a collector electrode making contact with said layer disposed to collect current spreading from said emitter electrode, and a base electrode making contact with said body, said emitter electrode and said collector electrode being spaced apart a distance which is not greater than the smaller dimension of said layer, and a connection between said base electrode and said collector electrode for applying a signal between said base electrode and said collector electrode.

32. A translating device comprising a body of semiconductive material, which material normally contains an excess of mobile charges of one sign over mobile charges of the other sign, a base electrode making low resistance contact with said body, an emitter electrode making contact with said body at a region spaced from said base electrode, an input circuit connected between said base and emitter electrodes and including a source for biasing said emitter electrode in the forward direction and for supplying a signal to said input circuit, said signal and other sign as said normally predominant charges, and an output circuit connected between said collector and base electrodes and including a source for biasing said output circuit in the reverse direction and for applying to said output circuit a signal which is amplified with respect to said signal and of the same sign as said signal.

33. A translating device comprising a body of semiconductive material, which material normally contains an excess of mobile charges of one sign over mobile charges of the other sign, collector and base connections to said body, a source of input energy, means separate from said collector and base connections and including said source for applying to a region of said body spaced from said collector connection energy to establish in said region mobile electric charges of said other sign, and an output circuit connected between said collector and base connections and including said source for applying to said collector connection a bias of the polarity opposite to the sign of said established charges, thereby to attract to said collector connection said established charges.

34. A circuit element comprising a body of semiconductive material, one portion of which is of one conductivity type and another portion of which is of different conductivity type, an emitter electrode engaging the first portion of the body, a collector electrode engaging the body to collect current flowing in the body by reason of said emitter electrode, and a base electrode providing a low-resistance connection to said other portion of the body to vary the magnitude of said current.

JOHN BARDEEN.
WALTER H. BRATTAIN.

Certificate of Correction

Patent No. 2,524,035
October 3, 1950
JOHN BARDEEN ET AL.

It is hereby certified that error appears in the printed specification of the above-numbered patent requiring correction as follows:

Column 6, line 54, for "or" read are; column 8, line 75, for "and" read and; column 17, line 52, for the word "side" read sign, and that the said Letters Patent should be read as corrected above, so that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 2nd day of January, A. D. 1951.

[SEAL]

THOMAS F. MURPHY,
Assistant Commissioner of Patents.

United States Patent 2,524,035, John Bardeen and Walter H. Brattain, Three-Electrode Circuit Element Utilizing Semiconductive Materials: three sheets of drawings, specification and certificate of correction, from the scan of the printed patent.

The spelling and punctuation are those of the printed patent. Text and drawings of a US patent, typically not subject to copyright (USPTO).

patents.google.com/patent/US2524035A