

March 26, 1957

K. G. MCKAY
SIGNAL TRANSLATING DEVICE

2,786,880

Filed June 16, 1951.

2 Sheets-Sheet 1

FIG. 1

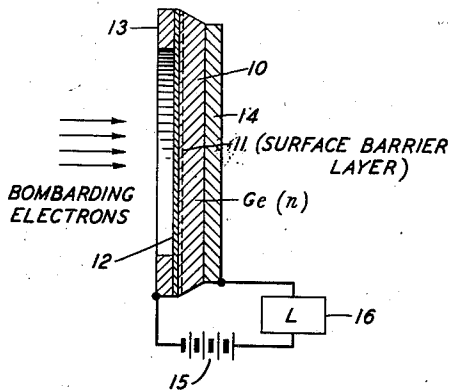


FIG. 2

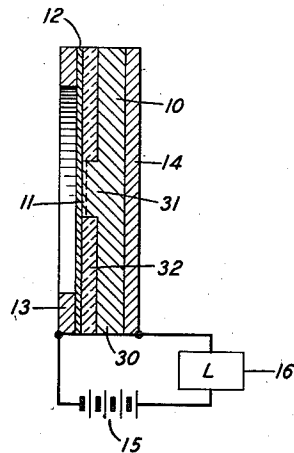
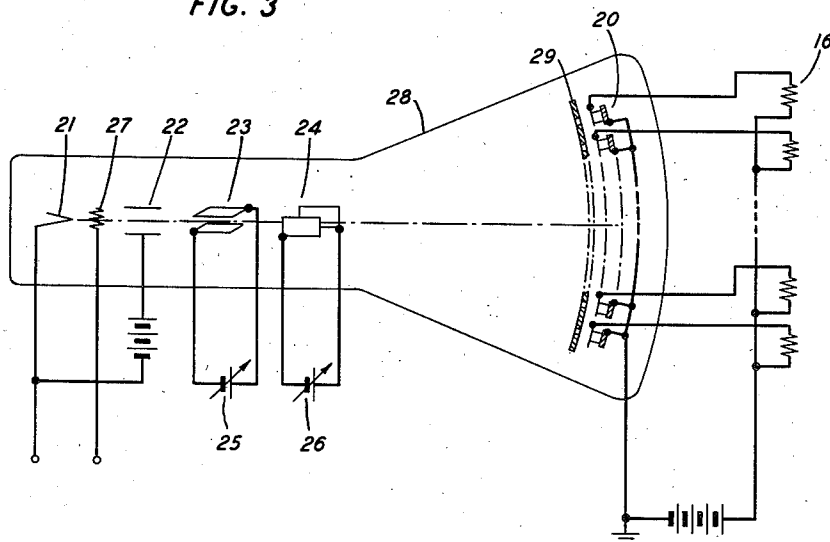


FIG. 3



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FIG. 4

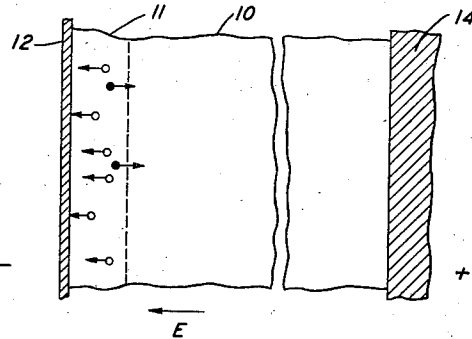


FIG. 5

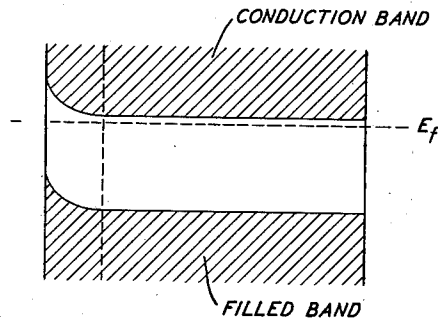
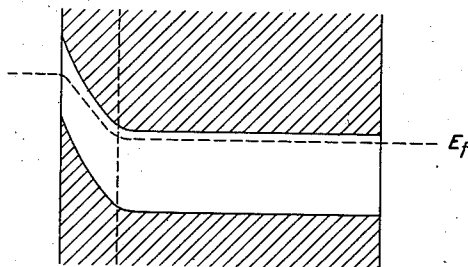


FIG. 6



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SIGNAL TRANSLATING DEVICE

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12 Claims. (Cl. 136—89)

This invention relates to signal translating devices in which electrical conductivity is induced in a body of semiconductive material, and more particularly to translating devices in which a body of impurity-type semiconductive material is subjected to electron bombardment.

It has been found that bombardment of a homogeneous body of a selected insulating or semiconductive material with electrons of sufficient energy reduces the electrical resistance the body offers to the flow of current between a pair of spaced electrodes in contact therewith. The resistance in the presence of electron-bombardment induced conductivity (as the effect has been called) may be so much less than the normal resistance of the body that the body may be used as an electrical switch that is effectively opened or closed by turning off or on, or deflecting, a beam of bombarding electrons. Related devices have been proposed in which the beam is modulated by a signal to cause corresponding modulation of the inter-electrode resistance and of the current in an output circuit in which the body is connected.

A general object of the present invention is to improve devices of the kind to which it relates.

A further object is to increase the speed with which the resistance of the body responds to a change in bombardment, and thereby to secure, e. g., either faster and more sharply defined switching action or faithful reproduction of a modulating signal over a wider range of modulation frequencies.

Another object is to increase the magnitude of the response to bombarding electrons of given energy or, conversely, to reduce the electron energy required to produce a given response.

Still another object is to increase the magnitude of the response of the body to a given change in the energy of the bombarding electrons without substantially reducing the speed of response.

Other objects of the invention are to provide a device of the kind described that is rugged, stable, reproducible, and of relatively large power-handling capacity.

In accordance with a feature of the present invention the electron-bombarded body, or target, comprises a plate of semiconductive material in which a barrier layer extends along and closely adjacent to the bombarded surface. Another feature resides in a large-area electron-permeable electrode disposed on the bombarded surface in cooperative relation with the barrier layer. In accordance with another and more specific feature the barrier layer is a surface barrier layer and overlaid by a semi-transparent film of metal. A further feature resides in the use of germanium as the semiconductive material, germanium being peculiarly adapted to certain purposes of the invention as will appear hereinafter.

A specific embodiment of the invention later to be described in detail includes a monocrystalline plate of n-type germanium that has on one of its major faces a large-area metal electrode providing a low-resistance ohmic contact to the plate, and that has a second electrode in the form of a film of copper on its other major

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face. A surface barrier layer formed in the germanium underlies the copper film and separates the latter from the remainder of the plate. Connected to the two electrodes is a work circuit, or output circuit, that includes a biasing voltage source poled to develop a reverse voltage across the barrier layer. Provision is made also for directing a controllable beam of bombarding electrons against the film-covered surface of the plate.

The nature of the present invention and its various features, objects and advantages will appear more fully from a consideration of the embodiments illustrated in the accompanying drawings and the following description thereof.

In the drawings:

Figs. 1 and 2 illustrate alternative semiconductor structures in accordance with the invention; Fig. 3 illustrates an electronic switching and modulating system employing these semiconductor structures; and Figs. 4, 5 and 6 are explanatory diagrams.

Referring briefly now to Fig. 1 there is pictured a semiconductor device of the kind described comprising, superficially, a plate 10 of semiconductive material with a surface barrier layer 11 at its left-hand surface, a collector electrode 12 comprising a thin film of metal covering that surface, a thick metal ring 13 in contact with the outer face of the film, and a heavy metal base electrode 14 covering the right-hand surface of plate 10. A work circuit connected to ring 13 and electrode 14 includes a biasing battery 15 and a load 16.

Base electrode 14, which should be of a good conducting material such as silver or copper, is attached to plate 10 in known manner to provide a low-resistance ohmic contact to the plate. It may be made thick enough to lend mechanical strength to the entire device. Collector electrode 12 can be formed on the forward, or left-hand, face of plate 12 by vapor deposition of a metal. Copper is well adapted for this use for it combines in high degree two properties that are significant for the purposes of the invention, namely, electrical conductivity and penetrability of bombarding electrons. Ring 13, which also may be of copper, is cold-soldered or otherwise attached to film 12, and by virtue of the fact that it surrounds the bombarded area of the film it provides a relatively low-resistance connection from all parts of the area to the point at which the external circuit is connected.

No attempt has been made in Fig. 1 to suggest the relative orders of magnitude of the various dimensions involved, but a specific example may serve that purpose. The plate 10 may comprise, for example, a disc of n-type germanium 2.5 millimeters in diameter and 0.5 millimeter thick with a surface barrier layer about 1 micron (i. e. 10^{-3} millimeters) thick. The copper film 12 may be several hundred Angstrom units in thickness, e. g. 400 Å. (i. e., 4×10^{-5} millimeters). Another parameter is the energy of the bombarding electrons, and in the example given this may be about fifteen thousand electron volts.

The superior performance of devices embodying the present invention I attribute to effects that may be explained, together with further details of construction, with reference to Figs. 4, 5 and 6. Fig. 4 may be understood as representing a portion of a device such as that last described comprising the semiconductive body portion 10, its surface barrier layer 11 extending between film electrode 12 and an inner boundary indicated by broken line, and base electrode 14. Fig. 5 is a corresponding (qualitative) energy level diagram for electrons. The latter shows that from the barrier layer to electrode 14 the Fermi level (E_F) lies closely adjacent the lower edge of the conduction band, which is the case in an n-type semiconductor (such as germanium with a trace of arsenic

or other donor impurity in it). The diagram shows also the sharp inclination of the adjacent edges of conduction and filled (or valence-bond) bands that is characteristic of a barrier layer, or exhaustion layer, such as the surface barrier layer 11.

When a reverse bias voltage is applied through electrodes 12 and 14, that is, a bias voltage such that the semiconductive body 10 is positive with respect to collector electrode 12, the effective resistance of the barrier layer 11 becomes many times higher than the resistance of the rest of the body, and the energy diagram takes the modified form shown qualitatively in Fig. 6.

Consider now the effect of electrons bombarding the conductive film 12. Some of these are intercepted by the film, but most of the others pass through it with only slightly diminished energy into the semiconductive material. Here their principal effect is to disrupt electron-pair bonds in the crystal lattice structure and thereby to generate pairs of holes and electrons that are free to diffuse and to drift. The depth to which the bombarding electrons penetrate is a known function of their energy and the density of the semiconductive material (H. Bethe, *Annalen der Physik*, vol. 5, p. 325, 1930), and it is independent of the presence or absence of a barrier layer. In accordance with an important feature of the present invention the electron penetration is confined to the barrier layer and more specifically, for optimum results, it is adjusted to substantially coincide with the thickness of the barrier layer. Germanium is particularly advantageous in this connection for the electron energy required to just penetrate a surface barrier layer in this material is far less than for others. It is only of the order of fifteen thousand electron volts for 1 micron penetration and fifty thousand volts for 10 microns.

Under the influence of the reverse electric field the holes generated in the barrier layer by the breaking of electron pair bonds drift toward the electrode 12 and are there collected, while the electrons simultaneously freed in the barrier layer drift toward the opposite electrode 14. The opposite motions of these two sets of mobile charge carriers of opposite sign have an additive effect in producing flow of current in the reverse direction through the external circuit, and it is their motion through the electric field that is manifest in the external circuit. The nature of the barrier layer is such that the applied electric field is largely concentrated across it, and because of the thinness of the barrier layer the potential gradient through it is several orders of magnitude greater than that in the remainder of the body. Hence, the holes generated in the barrier layer are swept rapidly, under the influence of this intense field, to electrode 12 and the electrons freed in the barrier layer are swept rapidly through it in the opposite direction. Hence, too, the total electric field that acts upon, and contributes energy to, any carrier passing from one side of the barrier layer to the other, is almost as great as the total electric field available between the two terminals.

It will be understood, then, that the mobile charge carriers produced by the electron bombardment are generated in a region, sharply localized along the path between the two electrodes, where substantially the entire applied electric field is concentrated, and that these carriers move so rapidly through the region as to minimize loss of them by recombination in transit.

The effect of bombarding electrons that penetrate beyond the barrier layer depends on the volume recombination or bulk lifetime constant of the semiconductive material and also on the diffusion constant of the material. The electric field outside the barrier region may be too weak to cause any significant drifting of the carriers generated by bombardment but such carriers nevertheless tend to spread in all directions with a certain average velocity (the diffusion velocity) that is characteristic of the material. The average distance they diffuse, or the fraction of them that will diffuse a given distance, depends

on how quickly they recombine and disappear or, in other words, on the lifetime constant of the material. Some holes generated beyond the barrier layer can be expected accordingly to reach that layer by diffusion and to be swept through it by the high field prevailing in that region. Although such holes contribute to the flow of current in the external circuit it is to be noted that their contribution is delayed by the time required for them to diffuse to the barrier layer, and that this time delay varies as the square of the distance travelled. In response to a sharp rectangular pulse of bombarding electrons, therefore, the current increases abruptly, due to the carriers generated in the barrier layer, and then rises progressively more slowly to a somewhat higher value as holes generated elsewhere in the body diffuse to the barrier layer. At the end of the pulse, similarly, the current decreases abruptly and then more slowly approaches its minimum value as the diffusing holes recombine or are collected.

The bombardment, then, is confined to the barrier layer if one wishes to minimize the current rise and decay times, but it can be extended somewhat beyond the barrier layer if greater efficiency is desired. The high diffusion velocity of germanium makes this material peculiarly well adapted for present purposes, for the bombarding electrons may be allowed to penetrate as much as about 10 microns beyond the barrier layer without reducing the response time of the device enough to be significant for many practical purposes. Germanium, furthermore, provides essentially constant carrier concentration over a range of temperatures around room temperature, and it therefore is relatively insensitive to limited temperature variations. Silicon has these properties to a lesser extent and like germanium involves no problem of stoichiometric composition.

Fig. 3 illustrates schematically a practical application of the invention in which semiconductor devices 20 such as those shown in Figs. 1 and 2 are associated with respective work circuits and selectively operated by an electron beam. The devices 20 are arrayed within one end of the envelope 21 of an electron beam tube in a position to be bombarded selectively by the beam originating at the other end. The beam source is shown as an electron gun comprising a cathode 21 and accelerating electrode 22 although it will be evident that numerous other structures, including the linear electron accelerator, are suitable for the purpose. Two pairs of deflecting plates 23 and 24 enable deflection of the beam to any particular target or device 20 under the control of respective voltage sources 25 and 26. The latter may provide for deflection of the beam along a cyclically repeated path or otherwise as desired. As each device 20 is struck in turn by the beam, its resistance is reduced many-fold from an approximately open-circuit value to an approximately short-circuit value. The device thus serves as a switch to close its individually associated work circuit represented at 16, and the arrangement in Fig. 3 may be used to close momentarily a multiplicity of circuits in cyclically repeated succession. The switching operation gives rise to a voltage pulse in the work circuit, and in some applications such pulses are useful in themselves. With a current multiplication of between 1000 and 10,000 in the barrier layer, an electron beam of 10 microamperes could produce a pulse of several volts in a 100-ohm work circuit. Pulses of the order of 10^{-9} seconds duration at intervals of 10^{-8} seconds could readily be produced if the beam is deflected at a reasonably high rate and a suitably apertured plate 29 is disposed in front of the array, in which case corresponding modulated currents will appear in the several loads 16 as the beam is moved to strike the associated devices 20 in succession.

The operation of the Fig. 3 system may be improved by employing an opaque envelope 28, for the elements 20 tend to be photosensitive. The elements are somewhat photovoltaic and when provided with a biasing voltage they exhibit a photoresistance effect large enough to make

them useful as photometers or as photoelectric translating devices operative over a wide band of modulating frequencies. The photoresponse can be reduced, of course, with some loss in efficiency, by making the film 12 so thick that it is opaque itself.

An improved form of the target device 20, illustrated in Fig. 2, may be described briefly as being the same as the Fig. 1 device except for the replacement with insulating material of an annular portion of the semiconductive plate at the forward face thereof. The modified plate 30 then comprises a disc-like portion in contact with electrode 14 and a central raised portion or boss 31. Surrounding the boss is a washer 32 of insulating material (a plastic or ceramic, e. g.) the forward face of which is flush with the top of the boss and forms a continuous surface therewith. It is to this surface that metal film 12 is applied. The barrier layer 11 is confined to the top of the boss as shown. In this construction the diameter of the barrier layer is just equal to the diameter of the bombarding electron beam, and this has the two-fold advantage of providing maximum resistance in the unbombarded condition and maximum ratio of response to barrier capacity. Further, the base electrode is of comparatively large diameter, which makes for low contact resistance, and it provides adequate mechanical support for the rest of the structure.

In one instance in practice the device 20 was constructed of monocrystalline high-back-voltage germanium having a resistivity of 6 ohm-centimeters at room temperature. The rear face was sandblasted and a gold electrode was evaporated over it. The forward face was treated in a manner set forth in detail in the application of J. R. Haynes and R. D. Heidenreich Serial No. 175,648, filed July 24, 1950, now Patent 2,722,490, granted Nov. 1, 1955, as follows. The surface was mechanically polished, chemically etched, rinsed in methyl alcohol, immersed for five minutes in an electrolytic solution of antimony oxychloride at 1.5 volts positive, and again rinsed in methyl alcohol. The copper film was then evaporated onto the surface under high vacuum. (The edge of the plate 10 may be bevelled as shown in Fig. 1 to prevent the copper from depositing itself on the exposed edge of the barrier layer formed by the foregoing treatment.)

In another instance the foregoing electrolytic process was omitted and the surface was treated instead with nitric acid to alter the surface state of the germanium and to produce the desired surface barrier layer. On the latter there is left a thin film of germanium oxide, of monomolecular thickness, e. g.; the acid treatment is not carried so far as to produce a layer of oxide of any substantial thickness.

It will be evident to those skilled in the art that the invention is susceptible of embodiment in various forms in addition to the specific forms disclosed herein.

What is claimed is:

1. In combination, a plate of semiconductive material having a barrier layer at one of the two major surfaces thereof, a collector electrode comprising a film of metal on said one surface, a base electrode in low-resistance contact with the other of said surfaces, means to project electrons through said film to said barrier layer, and a utilization circuit connected to said electrodes and including a voltage source poled to apply a reverse bias to said barrier layer.

2. In combination, an electric discharge tube including a body of impurity-type semiconductive material, a collector electrode comprising a film of metal covering a portion of the surface of said body, a base electrode in low resistance contact with a portion of said body separated from said collector electrode, said body having a barrier layer therein juxtaposed to said metal film and separating

said film from said base electrode, means to project a stream of bombarding electrons through said film to a depth of penetration not substantially beyond the inner boundary of said barrier layer, and circuit means connected to said electrodes for applying a reverse bias to said barrier layer.

3. A combination in accordance with claim 2 in which said barrier layer is a surface barrier layer of the order of a micron in thickness.

4. A combination in accordance with claim 2 in which said inner boundary of said barrier layers is separated by not more than several microns from said film of metal.

5. A combination in accordance with claim 4 in which said semiconductive material is germanium.

6. In combination, an electric discharge tube including a body of semiconductive material, means including an electron-emissive cathode in said tube for directing bombarding electrons against a portion of the surface of said body, a first electrode permeable to said bombarding electrons and extending over said bombarded surface portion in contact with said body, a second electrode in contact with said body, said body including a barrier layer juxtaposed to said first electrode, and a source of biasing voltage and a work circuit connected to said electrodes.

7. A combination in accordance with claim 6 in which said first electrode comprises a film of metal.

8. A combination in accordance with claim 6 in which said semiconductive material is an impurity-type crystalline semiconductive material.

9. A combination in accordance with claim 6 in which said semiconductive material is selected from the group consisting of germanium and silicon.

10. A combination in accordance with claim 6 in which the inner boundary of said barrier layer lies within several microns of said bombarded surface.

11. In combination, an electron beam tube including a plate of germanium, a base electrode in ohmic contact with a first major surface of said plate, a collector electrode comprising a translucent metallic film on a second major surface of said plate, said plate having a surface barrier layer extending over said second surface and separating said electrodes, means including an electron-emissive cathode in said tube for bombarding said plate through said metallic film with a beam of electrons having a depth of penetration substantially equal to the thickness of said barrier layer, a work circuit connected to said electrodes, circuit means for applying a reverse biasing voltage to said surface barrier layer, and means to modulate said beam.

12. In combination, an integral body of semiconductive material in the form of a plate with a boss on one face thereof, a washer of insulating material around said boss and forming a continuous surface with the top of said boss, said boss having a surface barrier layer therein extending over the said top thereof, an electrode comprising a film of conductive material extending over said barrier layer and washer, and a base electrode in contact with the other face of said plate.

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