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2,691,736

ELECTRICAL TRANSLATION DEVICE, INCLUDING SEMICONDUCTOR

Filed Dec. 27, 1950

FIG. 1

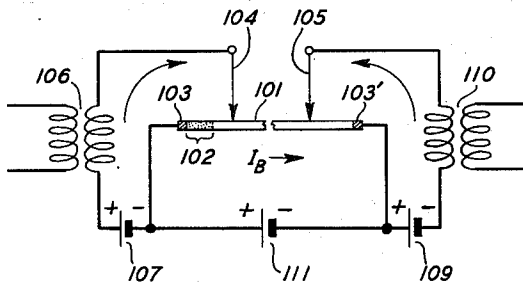


FIG. 4

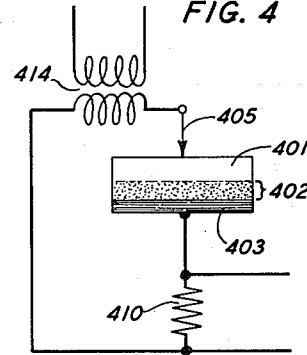


FIG. 3

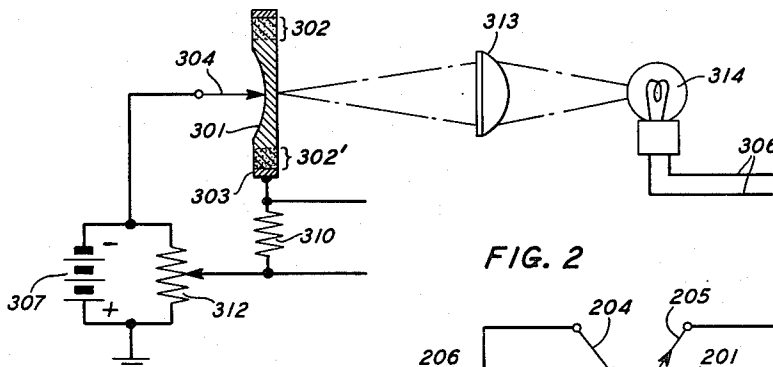
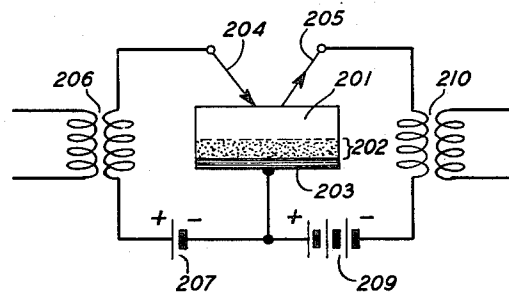


FIG. 2



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16 Claims. (Cl. 250-211)

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This invention relates to electrical translation devices employing semiconductors as their active elements.

The electrical characteristics of semiconductive materials such as silicon and germanium are largely determined by small traces of impurities or slight mechanical defects which are present on the surfaces or within the bodies of the materials. A pure crystal of silicon or germanium is made up of a cubic lattice in which each atom has four valence electrons, all of which are bound in the lattice. The presence of what is termed "significant" impurities disrupt the lattice structure. These impurities are of two different types; those designated "donor" impurities which, upon replacing an atom in a crystal lattice, supply more than the needed four valence electrons, and those designated "acceptor" impurities which supply less than the needed four valence electrons. The former type supplies unbonded electrons which serve as negative mobile charge carriers, and the latter, electron deficiencies or "holes" which serve as positive mobile charge carriers. A semiconducting material in which conduction by "holes" normally occurs is identified as P type, whereas the type in which the principal conduction occurs by electrons is identified as N type.

One type of semiconductive translator relies principally for its operation on the injection of charge carriers opposite in sign to those normally present in excess in the semiconducting material. These injected carriers change the conductivity of the material in the vicinity in which they are injected and also add current carriers which flow to an electrode identified generally as a "collector," which is biased in the reverse or low conductivity direction with respect to the semiconductive body. Semiconductive triodes, wherein carriers of a type opposite those ordinarily present in the body are injected from one electrode known as an "emitter" to modify the current flow in a collector circuit, are shown in several applications including application Serial No. 33,446, filed June 17, 1948, by J. Bardeen and W. H. Brattain, now Patent 2,524,035, issued October 3, 1950, and application Serial No. 50,894, filed September 24, 1948, by J. R. Haynes and W. Shockley, now Patent 2,600,500, issued June 17, 1952. In another form which these units may take, the absorption of light by germanium results in free electron-hole pairs; and the charge is separated and collected as a result of an electric field created by the collector. This type is disclosed in application Serial No. 85,788 of J. N.

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Shive, filed April 6, 1949, now Patent 2,560,606, issued July 17, 1951.

In the above and related types of devices the operating characteristics are controlled to a large extent by the tendency of the injected carriers to recombine with the carriers of opposite sign, thereby effectively removing them from the material. Thus, in a unit employing an N-type semiconductive body, wherein the normal carriers are electrons, the injected "holes" may combine with, or be filled by electrons before they reach the collector. If N_0 is the number of holes per unit volume, injected at a given time, let us say, $t=0$, the number of these holes which will remain after a time $t=t_1$ is given by the equation

$$N = N_0 e^{-\nu t}$$

where ν is called the "decay constant" the reciprocal of which is known as the "mean lifetime" of the injected holes.

This tendency toward recombination is present in two forms, volume recombination, and surface recombination, which as the names imply occur within the volume of the material and at the surface thereof, respectively, and may be represented by the formula $\nu = \nu_v + \nu_s$, where ν is the effective decay constant, ν_v is the volume decay constant, and ν_s is the surface decay constant.

The semiconductor structures of the types described require a substantial lifetime for the injected carriers, that is, that the "holes" or electrons persist in an unrecombined state in the semiconductor for a sufficient time to perform the tasks required of them.

In consequence of this, a large amount of effort has been expended in attempts to increase the mean life of injected carriers in germanium. Inasmuch as the carriers recombine on the surface, as well as in the volume of germanium, both rates of recombination have been investigated, with the result that the mean lifetime of carriers in the volume of germanium has been increased from the order of 20 microseconds to the order of 300 microseconds; and surface decay constant has been reduced from values of the order of 1000 centimeters per second to less than 80. For a more complete understanding of the various relations discussed in this specification, the reader is referred to chapter 12 of "Electrons and Holes in Semiconductors," by W. Shockley, D. Van Nostrand and Sons, 1950.

While such increases in carrier lifetimes are desirable, applicant has perceived that they are

often accompanied by a significant increase in undesirable effects which he attributes to unwanted or spurious carrier emission. Emission from any electrode, except an emitter, is unwanted, but may nevertheless occur in one degree or another depending on the potential of the electrode relative to the semiconductive body. The carriers so emitted tend to decay or recombine, and in many circumstances they are of no practical significance, but in long lifetime material they may persist long enough to reach, and mingle with, the "wanted" carriers, thereby impairing operations.

In a transistor of the type described, for example, in Patent 2,524,035, which has emitter and collector point contact electrodes in contact with one surface of a semiconductor body of N-type germanium, and a base electrode making low resistance contact with another surface thereof, if the base electrode is even slightly positive with respect to the block, it acts as a second source of positive carriers or "holes" which flow toward the collector in addition to the carriers from the emitter. Since the flow of these unwanted holes from the base electrode is not modulated in accordance with signal currents, distortion is caused in the signal output of the collector in so far as such unwanted holes reach the collector in substantial volume.

It is therefore a principal object of this invention to improve the operation of semiconductor translators, specifically by reducing the effect of unwanted carriers injected from certain of the electrodes.

This and other objects of the invention, which will be apparent hereinafter, are achieved in a semiconductor device in which a portion of the semiconductive body adjacent an electrode acting as a source of unwanted carriers is arranged to have a high effective decay constant so as to decrease the mean lifetime of such unwanted carriers selectively by a significant factor.

Depending on the circumstances, either the surface or the bulk of the aforesaid body portion (or both surface and bulk) may be treated to increase the decay constant for the purposes of the invention. Several methods for producing both high surface and volume decay constants are described in detail hereinafter.

A high surface decay constant may be brought about mechanically by sand-blasting the surface of the body portion or by various chemical means. These include boiling the semiconductor sample in water containing metallic ions, or placing the sample in a sol of antimony oxychloride in which the sample is given a negative potential, attracting antimony ions. The portion of the semiconductor sample from which it is desired to withhold treatment is given a temporary protective coating.

Several ways are also described for achieving high volume recombination constants. These include heating and quenching the aforesaid body portion, or bombarding the same with high energy particles such as alpha particles, deuterons and neutrons. The methods described may be applied to different types of semiconductor structures described which include transistor triodes of the conventional and filamentary types, a phototransistor, and also a rectifier.

Other objects or features of the invention will be apparent in the study of the specification hereinafter and the drawings, in which:

Fig. 1 represents an amplifier including a filamentary transistor in which a substantial portion

of the surface adjacent one of the base electrodes has been treated in accordance with the teachings of the present invention.

Figs. 2 and 3 represent circuits including a transistor triode and a phototransistor, respectively, which have been treated in accordance with the teachings of the present invention; and

Fig. 4 represents a rectifier in which a body portion adjacent the low resistance contact has been treated in accordance with the present invention.

As pointed out above, the undesirable effects produced by unwanted carrier emission in a semiconductor translating device are substantially reduced in accordance with the present invention by recombining the unwanted carriers before they can reach the collecting area.

Several illustrative embodiments of the invention are shown in the drawings each of which includes a semiconductor body treated for unwanted carrier suppression, in accordance with one of the techniques to be described hereinafter.

Fig. 1 of the drawings shows the operating circuit connections for a semiconductor amplifier including a filamentary transistor such as disclosed in Fig. 1, of Patent 2,600,500, supra. The germanium semiconductor body of this structure is assumed to have been treated by sand-blasting or one of the other methods for reducing the recombination constant adjacent the base electrode.

Although the various means for increasing carrier recombination which are described hereinafter may often be used interchangeably, the choice of whether to use surface or volume recombination or a combination of the two depends on the particular transistor structure considered, and whether the mobile charge carriers travel near the surface or at a depth in the semiconducting block.

Referring now in detail to Fig. 1, the translation device shown comprises a body 101 of semiconductive material of one conductivity type throughout, and having ohmic connections, terminals or contacting means 103, 103' at its opposite ends which may comprise, for example, coatings of rhodium electroplated on the body to form non-rectifying junctions therewith. Connected directly between the terminals 103, 103' is a direct-current source 111, such as a battery, which supplies the biasing field for producing the current I_b threading the body 101 longitudinally. A contact point 104, for example, of tungsten or Phosphor bronze, engages the body 101 near one end thereof and is connected to the terminal 103 through a biasing source 107 in series with the secondary of the input transformer 106, which may be either resistive or inductive. A second contact point 105 which, for example, may also be of tungsten or Phosphor bronze, engages the body 101 in a region removed from the contact 104 and adjacent the other end of the body. Point 105 is connected to the terminal 103' through a biasing source 109 in series with the primary coil of the output transformer 110 which, like the input impedance 106, may be either resistive or inductive.

If, for example, the body 101 is of high back voltage N-type germanium, the polarities of the potential sources 107, 111 and 109 are as shown in Fig. 1. The contact 104 serves as the emitter; the contact 105 serves as the collector; and the terminals 103, 103' serve as base electrode contacts. Specifically, the terminal 103 is connected to the positive side of the source 111. The emit-

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ter 104 is biased to a sufficient positive potential with respect to the terminal 103 so that positive current flows from the emitter 104 into the body 101; and the collector 105 is biased negatively with respect to the terminal 103 by connection to source 109. The direction of current flow in the external circuit is as shown by the arrows in the emitter and collector circuits of Fig. 1. If the body 101 is of P-type material, the polarities of the sources 107, 109 and 111 will be reversed. In general, the bias on the emitter 104 should be low, for example, of the order of 0.1 volt; and the bias on the collector 105 should be relatively large, of the order of some 10 to 100 volts.

As has been pointed out hereinbefore, if the body 101 is of N-type material, "holes" are injected into the body at the emitter 104 and flow toward the collector 105, thereby tending to effect modulation of the collector current. The transit time of the holes from emitter to collector is a function of the distance between them and also the biasing or accelerating field due to the source 111. The holes (or carriers) flow down the germanium rod toward the collector point 105 under the influence of electric field with a velocity which is given by the mobility of the "holes" multiplied by the electric field. In addition, since the plated electrode 103 on the left is positive with respect to the semi-conductor block, it also acts as a source of "holes" which tend to flow down the germanium rod producing a large unwanted injected hole concentration at the collector.

The distortion produced by the injection of holes from the plated electrode 103 is substantially reduced by the sand-blasting or other techniques to be described hereinafter which are applied to the end of the rod 101 surrounding this electrode. For example, the treated portion is extended inwardly along the length of the rod a little over a millimeter from this electrode. In a case where the cross-sectional dimensions of the rod were of the order of 0.5 of a millimeter, this sand-blasting treatment served to reduce the lifetime of the carriers from more than 100 microseconds to approximately 3 microseconds. Further, since the electrical field which is produced in the rod 101 by the current I_b is less than 10 volts per centimeter, the unwanted carriers spend more than 6 microseconds in the treated section 102. Thus, the number of these unwanted carriers is reduced by more than a factor of 10 by this device.

In order to prevent effective numbers of unwanted carriers from flowing across the germanium rod, when using higher electric fields of the order of 30 volts per centimeter, a long treated section of approximately 3 millimeters has been found desirable.

As pointed out in an earlier paragraph, the effective decay constant in a given semiconductive body is the sum of the surface decay constant and the volume decay constant. Correspondingly, the following reciprocal relationship applies to the effective lifetime constant τ :

$$\frac{1}{\tau} = \frac{1}{\tau_s} + \frac{1}{\tau_v} \quad (1)$$

Particularly in those embodiments in which the carriers travel near the surface of the semiconductive material, such as the filamentary transistor described in the foregoing paragraphs, the effective lifetime τ of the carriers is, to a much larger extent, a function of the surface decay constant μ_s than of the volume decay constant μ_v . By the method of sand-blasting, or

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certain of the other techniques to be described, it is possible to produce a surface decay constant in excess of 104 centimeters per second, thereby reducing the mean effective lifetime for carriers, which is of the order of 100 microseconds in long lifetime germanium, tenfold, or even a hundred-fold.

In determining how large an area to treat, one may be guided by the formula given in the early part of the specification relating to the exponential decay of carriers in semi-conducting material, which is derived by W. Shockley in chapter 12 of "Electrons and Holes in Semiconductors," supra.

$$N = N_0 e^{-\mu t} \quad (2)$$

In the filamentary transistor, in which the unwanted carriers move along the semiconductive filament under the impetus of an applied electrical field, the Formula 2 takes a modified form:

$$N = N_0 e^{-\frac{\mu l_1}{\mu_p E}} \quad (3)$$

assuming the value

$$\frac{l_1}{\mu_p E}$$

is substituted for t , the time of transit of the carriers, where

l_1 = the path length traveled by carriers;

μ_p = mobility constant for positive mobile carriers which is 1700 cm.²/volt second for germanium; and

E = the electric field strength in volts per centimeter along the filament; which will be assumed to be of the order of 10 volts in the present illustration.

Assume it is desired to make the ratio

$$\frac{N}{N_0}$$

approximate 0.1. According to tabular values the exponent

$$-\frac{\mu l_1}{\mu_p E} \text{ must approximate } 2.3 \quad (4)$$

Neglecting the volume decay constant, the surface decay constant may be computed from the following approximate formula, which holds true for those structures in which the cross-sectional dimensions are 0.5 of a millimeter or larger:

$$\mu_s = D_p \left[\left(\frac{\pi}{a} \right)^2 + \left(\frac{\pi}{b} \right)^2 \right] \quad (5)$$

where D_p is the diffusion constant, which is 44 cm.²/second for positive carriers in germanium; and a and b are the cross-sectional dimensions of the rectangular filament in centimeters.

Substituting (5) in (4):

$$-\frac{\mu l_1}{\mu_p E} = \frac{D_p \left[\left(\frac{\pi}{a} \right)^2 + \left(\frac{\pi}{b} \right)^2 \right] l_1}{\mu_p E} = 2.3 \quad (6)$$

or

$$l_1 = \frac{2.3 \times \mu_p E}{D_p \left[\frac{\pi^2}{a^2} + \frac{\pi^2}{b^2} \right]}$$

$$= \frac{2.3 \times 1700 \times 10}{44 \left[\left(\frac{\pi}{0.05} \right)^2 + \left(\frac{\pi}{0.05} \right)^2 \right]} = \text{approx. } 0.15 \text{ cm.}$$

These computations neglect the recombination of carriers in the germanium sample before treatment, which is so small in long lifetime germa-

mium as to introduce an insignificant error in the result. Hence, the length for the treated area surrounding the positive low contact electrode is of the order of 0.15 centimeter.

Approximately 0.2 of a centimeter at one or the other end of the rod is sand-blasted to a maximum degree of roughness in a blast of air containing carborundum or similar abrasive material, during which process the remaining portions of the body are protected in some manner, such as with a covering of gummed cellulose tape. Following this step, a section nearest that end, having an approximate length of 0.05 of a centimeter, is plated with rhodium for low resistance contact electrodes. This leaves about 0.15 of a centimeter of sand-blasted surface adjacent the positive base electrode to act as a recombination surface. The effectiveness of the sand-blasting technique in increasing the decay constant of a given semiconductive surface depends at least partly on the fact that the actual surface area is greatly increased by the irregularities so produced. The central portion of the germanium rod may be given the usual treatment to provide long lifetime for carriers, such as disclosed, for example, in application Serial No. 175,648, filed by J. R. Haynes and R. D. Heidenreich, July 24, 1950. One of the methods disclosed in the foregoing application for treating a germanium element to produce longer lifetime of carriers involves immersing the portion to be treated in a colloidal solution of very fine particles of antimony oxychloride. The negatively charged colloidal particles are plated onto the desired portion of the germanium element by cataphoresis, the element being maintained at a positive potential with respect to the solution.

A substantial increase in the surface decay constant can also be obtained chemically by electrolytic treatment of a portion of the germanium sample, such as described above, in a sol of antimony oxychloride.

For example, a suitable sol for this purpose may be prepared by adding 0.2 of a gram of antimony trichloride to 100 centimeters of distilled water. The reaction $\text{SbCl}_3 + \text{H}_2\text{O} \rightarrow \text{SbOCl} + 2\text{HCl}$ takes place to produce a white precipitate of SbOCl. In addition to the large precipitated particles which settle down, there is produced a colloidal solution of very fine SbOCl. In solution, the antimony oxychloride dissociates, producing positive ions of antimony and negative ions of oxygen and chloride. Hence, if the germanium sample to be treated is made negative by a potential of the order of 1.5 volts with respect to an anode, which may be copper or some similar metal, the positive ions of metallic antimony are deposited on the germanium surface. This process is preferably carried on for a period of ten minutes, the duration of treatment determining the amount of metallic antimony deposited. During this process, those portions of the germanium body from which it is desired to withhold treatment are coated with a protective agent, such as polystyrene dissolved in toluene or cerosine wax. After the metallic film has been deposited on the desired portion, the sample can be rinsed in either high purity distilled water or in alcohol, and the protective coating dissolved in toluene prior to applying "long lifetime" treatment, such as previously described, to the remaining portions of the body. During this treatment, the "short lifetime" portions of the body are protected with polystyrene paint which is later removed by dissolving in toluene. The germanium body is then

in condition to be associated with its cooperative elements in the unit in which it is to be used.

Another method of obtaining the desired result is by boiling the semiconductor element to be treated for a period of ten minutes in water containing zinc ions, or another significant impurity, having a minimum concentration of the order of 10 parts per million. After this step, those portions in which it is desired to retain short lifetime characteristics are coated with polystyrene dissolved in alcohol, while the "long lifetime" treatment, such as referred to hereinbefore, is applied to the remaining portions of the body. The polystyrene coating is removed from the short lifetime portions by dissolving it in toluene.

It should be noted that if, instead of surface recombination techniques, volume recombination techniques such as described hereinafter, are applied to the filamentary transistor structure described, a shorter section of the rod can be treated.

In addition to the embodiment just described, in which the mobile carriers move through the semiconducting body primarily under the impetus of an electrical field, there are several other practical embodiments, such as shown in Figs. 2, 3 and 4 of the drawings, in which the motion of the carriers through the body is principally by diffusion. In each case, a section of the germanium in the immediate vicinity of the electrode producing the unwanted carriers is treated to provide a short lifetime for these carriers. This recombination section is indicated in each case by the dotted areas of the schematic drawing.

Fig. 2 shows a semiconductor triode of the type described in detail in J. Bardeen and W. H. Brattain, Patent 2,524,035, which may, for example, include a disc-shaped block of germanium 201 about 0.6 of a centimeter in diameter and 0.1 of a centimeter thick processed in accordance with the disclosure of J. Bardeen and W. H. Brattain, supra, to provide a body of N-type germanium. A first electrode 204, denoted the "emitter," comprising a material such as tungsten, copper or Phosphor bronze, makes rectifying contact with the germanium. A second similar electrode 205, positioned close to the emitter, also makes rectifying contact with the boundary surface. Alternatively, this electrode may comprise a small spot of metal, such as gold, evaporated into the upper surface, through which a central hole or slot has been pressed. A third electrode 203 consists of a contacting metal film such as rhodium which has been plated onto the N-type body of the germanium. A small positive potential bias of the order of a few tenths of a volt is applied to the emitter electrode 204 with respect to the base electrode 203 from the biasing source 207. A larger negative bias of the order of 40 volts is applied to the collector electrode 205 with respect to the base electrode 203. Input signals may be applied between the emitter and base electrodes through the primary coil of input transformer 206, which may be either resistive or reactive. The primary coil of output transformer 210 is connected between the collector and base electrodes. In the disclosure of Bardeen-Brattain, supra, it is pointed out that if P-type germanium is substituted for N type in the semiconductor block, the device will function with the biasing sources in reversed polarity to those shown.

With the biasing voltages given, for suppressing unwanted carriers injected from the base electrode 202, the treated portion of the block

is of the order of a few tenths of a millimeter thick.

The extent of the semiconductor body to be treated can be determined as follows:

Since the mobile carriers move through the semiconductor principally by diffusion, Equation 2 may be modified as follows:

$$N = N_0 e^{-\sqrt{\frac{l^2}{D_p \tau}}} \quad (7)$$

by substituting the relationships:

t_1 (transit time of the carriers) =

$$\frac{\text{distance}}{\text{velocity}} = \frac{l}{\sqrt{\frac{D_p}{\tau}}} = \sqrt{\frac{l^2 \tau}{D_p}}$$

and

$$\nu = \frac{1}{\tau}$$

where

N = the number of mobile charge carriers arriving at the collecting area;

N_0 = the number of mobile charge carriers emitted;

e = the natural logarithmic constant;

l = path distance from the emitting to the collecting area;

D_p = the diffusion constant for positive carriers in the material traversed; and

τ = the effective lifetime of the carriers = $\frac{1}{\nu}$, the effective decay constant for the semiconductor material.

Making substitutions in Equation 7, it can be shown that in order to reduce the number of unwanted carriers by one-tenth, the path length L through the treated area interposed between the electrode source of these carriers and their collecting point should represent approximately two diffusion path lengths, a diffusion path length being defined as that distance in which the carrier concentration attenuates by a factor e^{-1} , assuming there are no additional carrier injections. This term is further defined by Shockley in chapter 12 of "Electrons and Holes in Semiconductors," cited above. As pointed out before, if the value

$$\frac{N}{N_0}$$

is to approximate one-tenth, then referring to Equation 7 and the exponential tables, it is seen that the value

$$\sqrt{\frac{l^2}{D_p \tau}}$$

must be slightly greater than 2. Hence, to reduce the number of carriers by a factor of about 10, the path length L through the treated area should have a length of the order of $2\sqrt{D_p \tau}$, where D equals the diffusion constant of the medium, and τ the effective lifetime of the injected carriers, or alternatively,

$$2\sqrt{\frac{D_p}{\nu}}$$

where ν is the effective decay constant.

In the embodiment under description, since the body of the semiconductor is of such thickness that the mobile charge carriers travel at some depth from the surface, techniques which increase the volume decay constant, rather than the surface decay constant, are most effective in reducing the lifetimes of the unwanted carriers.

In the cases in which a high volume recom-

bination rate is desired the following methods have been found suitable.

The simplest of these involves heating the desired portions of the sample under treatment with a small blow torch or in a small induction furnace to a temperature greater than 500° C. for a time interval of the order of seconds. In the case of N-type material the treated sample is tested with a thermoelectric tester to determine the depth of the layer which has been converted to P type. Successive etches are carried out until the surface is shown to be N type. A suitable thermoelectric testing device for this purpose is disclosed by W. C. Dunlap in the General Electric Review, vol. 52, page 9, 1949.

Another method comprises bombardment of either N or P-type germanium with high energy particles, which may include deuterons and protons as produced in a cyclotron or other nuclear accelerating device, and alpha particles from natural radioactive substances such as radium or plutonium.

In changing the lifetime of N-type germanium by nuclear bombardment, the depth and intensity of the change is dependent on the energy of the bombarding particles and the period of exposure of the body to these particles. The function of the bombarding particles is to produce recombination centers in the germanium which facilitate the combination of holes and electrons therein. By exposing the sample for a relatively short time, the resistivity of the irradiated section is increased so that it is possible by this method to reduce the carrier lifetimes to less than a microsecond. In the case of N-type germanium care should be taken, however, to prevent the process being carried too far, thus preventing the conversion of the treated end section from N to P-type germanium, since the bombarding particles tend to form P-type centers in the germanium along with the recombination centers. For example, in order to change the specific resistance of a sample from 3 to 15-ohm-centimeter, thereby causing the mean lifetime of the carriers to be reduced to less than one microsecond, the sample is exposed for an interval of approximately fifteen seconds to a beam of high energy particles, such as 14 m. e. v. deuterons from a cyclotron or other source, having an intensity of 0.15 microampere per square inch, which corresponds to a bombardment by 9×10^{11} deuterons per second per square inch of the surface area of the exposed sample. The depth of penetration of the high energy particles, and hence, the thickness of the layer affected, increases with particle energy. The portion of the semiconductor structure which it is desired to preserve with the lifetime characteristics unchanged is covered by a mask of lead or some other material of such thickness and character as to be impervious to the nuclear bombardment.

In the conventional transistor device described, the treatment described in accordance with the present invention operates to reduce the collector current by reducing the carrier injection from the base electrode. This serves to increase the percentage modulation of signals impressed on the emitter, and reduce distortion from unwanted spurious effects caused by injection of carriers at the base.

Fig. 3 shows the application of a recombination section, such as described, to a phototransistor of the type disclosed in Fig. 1 of application Serial No. 85,788, filed April 6, 1949, by J. N. Shive, now Patent 2,560,606, issued July 17, 1951. The appa-

ratus illustrated may comprise, for example, a disc 301 of high back voltage N-type germanium produced, for example, in the manner disclosed in application Serial No. 638,351, filed December 29, 1945, by J. H. Scaff and H. C. Theuerer, now Patent 2,602,211, issued July 8, 1952, and having its surfaces etched as disclosed in that application, and application Serial No. 44,241, filed August 14, 1943, by J. N. Shive. Advantageously, the unit may be given an electrical-forming treatment similar to that described in the Shive application. In a specific embodiment, the treated and formed wafer 301 may be 0.15 of an inch in diameter, have an over-all thickness of 0.01 of an inch, and a minimum thickness at the point contact region of 0.002 of an inch. To serve as a base electrode, an ohmic contact 303 is made with the peripheral surface of the disc, which may take the form of a rhodium coating electroplated on this surface, or alternatively, a cured silver paste.

The treated portion 302 of the disc is produced by any of the techniques in accordance with the present invention described hereinbefore for increasing either the surface or volume decay constants. If, for example, sand-blasting is used, this treatment preferably takes place before the plating-on of the base electrode, the treated portion forming an annular ring extending inwardly a distance of the order of 0.010 of an inch from the periphery of the plated section for a reduction of carrier injection by more than a factor of 10.

The collector electrode 304 is biased negatively with respect to the base 303 by a potential source 307, across which is connected the potential divider 312. In the present illustrative example, the biasing potential may be of the order of 20 to 100 volts. The load resistance 310, which may assume values of the order of 10,000 to 25,000 ohms, may be connected between the collector electrode 304 and the base electrode 303. Opposite the disc or wafer 301 is a lens 313, which functions to concentrate light from a source 314 upon a restricted region of the surface of the disc 301 axially opposite the collector 304. The source 314, which is connected to the input terminal 306, may be, for example, a tungsten filament operated at about 2900 degrees absolute.

The principal purpose in modifying the phototransistor to include a recombination section 302, such as described, is to reduce the current which flows when there are no light signals falling on the germanium disc from the source 313, and which is primarily caused by current carriers flowing into the germanium disc from the electrode 303, which is slightly positive with respect to the disc.

In addition to the transistor applications described, the teachings of the present invention may also be applied to semiconductor devices of a different type, such as rectifiers having only two electrodes, one making high resistance contact with the body, and the other making low resistance contact therewith.

Such an embodiment is shown in Fig. 4 of the drawings which discloses a simple semiconductor diode of a type well known in the art. In this embodiment, treatment in accordance with the present invention of the portion surrounding the low resistance electrode contact serves to reduce unwanted hole emission, which has a tendency to establish a reverse current through the rectifier, reducing its efficiency. Referring to Fig. 4, a germanium body 401, of roughly similar dimen-

sions to the germanium body described with reference to Fig. 2, includes a low resistance electrode 403 of rhodium or similar metal plated on one surface thereof, and a high resistance point contact 405 of tungsten or Phosphor bronze on the opposite surface. The circuit is completed through the secondary coil of input transformer 414, one terminal of which is connected to the point contact 405, and the other terminal of which is connected through load resistor 410 to the low resistance terminal 403. The portion 402 adjacent the plated electrode 403 is treated as previously described to decrease that portion of the current which is produced by carrier injection from this electrode due to its intermittently positive potential with respect to the block. For this application, one of the types of volume recombination is used, the dimensions of the treated portion being similar to those described with reference to the transistor of Fig. 2.

Although a number of specific embodiments of the present invention have been shown and described by way of illustration, it is apparent that within the scope of this invention, there are many possible modifications not shown.

What is claimed is:

1. A translation device comprising in combination a body of semiconductor material, a source of signal current, emitting means in contact with the surface of said body for supplying mobile charge carriers to said body under control of signal current from said source, contacting means in contact with said block in a position which is substantially removed from said emitting means, said contacting means having a potential with respect to the body of said block which is of the same sign as that of said mobile charge carriers, said contact means acting as a source of unwanted charge carriers uncontrolled by said signal current, a first region of said semiconductor located between said contacting means and a second region which surrounds said emitting means, wherein said first region has a decay rate for said mobile charge carriers, of the order of at least ten times as great as the decay rate in said second region.

2. A translation device in accordance with claim 1 wherein said first region has a surface decay constant which is at least of the order of 10^4 centimeters per second.

3. A translation device in accordance with claim 1 in which the volume decay constant of said first region is at least ten times that of said second region.

4. A translation device comprising in combination a semiconductive body of N-type germanium, a source of signal current, an emitter in contact with a surface of said body for supplying positive mobile charge carriers to said body under control of said signal current, a collector in contact with said body for receiving positive current carriers from said emitter, an electrode making low-resistance contact with said body and having a slightly positive potential relative to said body, whereby said electrode acts as a source of additional positive mobile charge carriers, said body having a first region adjacent said electrode and a second region surrounding said emitter and collector, wherein said first region has a substantially higher decay rate for said current carriers than said second region.

5. A translation device in accordance with claim 4 wherein said first region has a surface decay constant which is of the order of at least 10 times that of said second region.

6. A translation device in accordance with claim 4 in which the volume decay constant of said first region is of the order of at least 10 times that of said second region.

7. A translation device comprising in combination a body of semiconductive material, a point contact electrode making high-resistance contact with one surface of said body, a second electrode making low-resistance contact with another surface of said body, the said body having a relatively low decay constant for uncombined current carriers in a first region adjacent said point contact electrode, and a relatively higher decay constant for uncombined current carriers in a second region adjacent said second electrode, wherein said second region extends of the order of at least 2 diffusion lengths along the path of mobile charge carriers emitted from said second electrode and passing through said second region to said first region.

8. A translation device in accordance with claim 7 in which said second region has a surface decay constant which is of the order of 10^4 centimeters per second.

9. A photoelectric translation device comprising a body of semiconductive material having a thin portion between two opposite faces thereof, a point contact engaging one face of said body at said thin portion, an ohmic connection to said body at a position spaced from said contact, a substantial region of said body surrounding said ohmic connection having a decay constant which is of the order of at least 10 times that of the region of said body engaged by said point contact, and means for directing a ray of energy against a face of said body opposite said point contact.

10. A translation device in accordance with claim 9 in which said region surrounding said low-resistance contact has a surface decay constant which is of the order of at least 10^4 centimeters per second.

11. A circuit element which comprises a block of semi-conductor material predominantly comprising a given conductivity type, an emitter electrode making contact with said block and injecting current carriers of a given polarity into said block, a collector electrode disposed in engagement with the said block to collect current flowing into the block by way of the emitter electrode, a base electrode making contact with the body of the block to vary the magnitude of said current, wherein said base electrode is the source of unwanted current carriers of the same polarity as the carriers injected by said emitter electrode, and wherein a substantial region adjacent said base electrode has a decay constant for said carriers which is of the order of at least 10 times the decay constant in the remaining portions of said block.

12. A circuit which comprises in combination a block of semiconductive material having a body which is of one conductivity type and a thin surface layer which is of the opposite conductivity type, an emitter electrode making contact with the surface layer and injecting current carriers of a given polarity into said block, a collector electrode making contact with the surface layer and disposed to collect current spreading from said emitter electrode, a base electrode making ohmic contact with the body of said block, said base electrode functioning as a source of unwanted current carriers, a region of said block ad-

jacent said base electrode having a decay constant for said current carriers which substantially exceeds the decay constant for current carriers in the remaining portion of said block, an input circuit including a source of biasing current connected between said emitter and base electrodes, and an output circuit including a load and a biasing source connected between said collector and base circuits.

13. A signal translating device which comprises in combination an elongated body of semiconductive material, ohmic contacts plated at two spaced positions on said body, a pair of rectifying contacts at two spaced positions on said body intermediate said ohmic contacts, a first one of said rectifying contacts functioning as a source of injected current carriers, an input circuit connected between said first rectifying contact and a first one of said ohmic contacts nearest thereto, said second rectifying contact functioning to collect the current carriers flowing from said first rectifier contact, an output circuit connected between the second one of said ohmic contacts and said second rectifying connection, a biasing means connected between said ohmic contacts, and to said rectifying contacts, wherein a substantial region adjacent said first ohmic contact has a decay constant for current carriers which is substantially larger than that of the portions of said block adjacent said rectifying contacts.

14. A signal translating device in accordance with claim 13 in which said region surrounding said first ohmic contact has a surface decay constant of the order of at least 10^4 centimeters per second.

15. In combination an electrical device comprising a body of semiconductive material having mobile charge carriers of predetermined sign normally in excess therein, a first electrode in ohmic contact with said body, a rectifying connection to said body, a circuit connecting said electrode and rectifying connection and including an electrical source such that said electrode is at least intermittently at a potential of said predetermined sign relative to said body, a body portion adjacent said first electrode and interposed in the path of carriers tending to flow from said first electrode to said rectifying connection, said body portion having a decay constant at least 10 times that of the remainder of said body and a length of at least 2 diffusion lengths in the direction of said flow.

16. An electrical semiconductor device comprising a body of semiconductive material, a base electrode and a rectifying electrode to said body, said body comprising two principal portions interposed between said two electrodes, of which one is adjacent said base electrode, and has an effective decay constant at least 10 times that of the other of said body portions.

References Cited in the file of this patent

UNITED STATES PATENTS

Number	Name	Date
2,402,661	Ohl	June 25, 1946
2,502,479	Pearson et al.	Apr. 4, 1950
2,502,488	Shockley	Apr. 4, 1950
2,544,211	Barton	Mar. 6, 1951
2,561,411	Pfann	July 24, 1951
2,570,978	Pfann	Oct. 9, 1951