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SEMICONDUCTIVE DEVICES

2,805,347

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FIG. 1

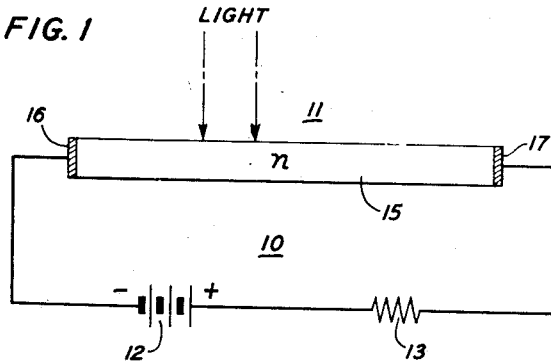


FIG. 2

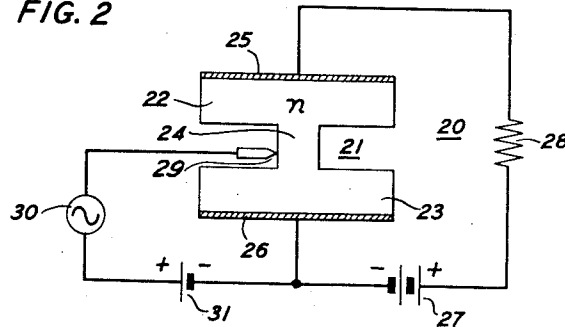
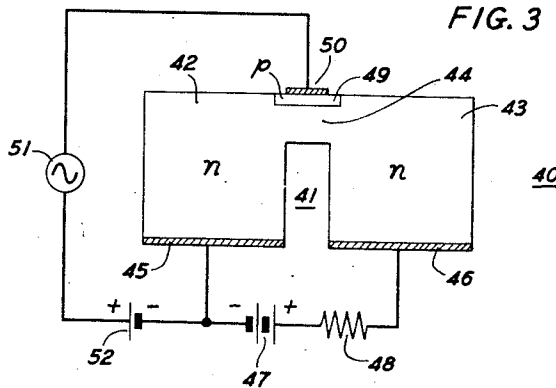


FIG. 3



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SEMICONDUCTIVE DEVICES

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10 Claims. (Cl. 250-211)

This invention relates to semiconductive devices and more particularly to semiconductive devices which include a body of semiconductive material which has a large concentration of "temporary traps."

In our paper entitled "Temporary traps in silicon and germanium," published in the Physical Review, volume 90, pp. 152-153, there is reported evidence indicating the existence of trapping centers, other than recombination centers, for minority carriers in silicon and germanium. It is characteristic of semiconductors that there exist therein two types of charge carriers, electrons and holes, of opposite charge. The minority carrier is that charge carrier constituting less than half of the total number of carriers. Specifically, on bodies of n-type and p-type silicon at room temperatures and of n-type germanium at temperatures of -80° C. and lower, it is reported that some of the carriers are found to experience an extraordinarily long delay in their transit between two spaced electrodes connected to the body. A qualitative explanation of these observations is made in terms of a simple trap model as follows. For low degrees of excitation, some of the added minority carriers are caught in "traps" where they remain temporarily during which time the conductivity of the body is greatly enhanced because of the extra added majority carriers in the body, and then they are ejected back into the conduction stream and recombined after which event the conductivity of the body is reduced since there are no longer any extra added majority carriers. Moreover, it is pointed out that there has been found to exist at least two sets of volume traps, deep and shallow, with each of which there is associated a characteristic delay or trapping duration, as well as surface traps. A trap is a center in the crystal lattice capable of trapping charge carriers, and, according to prevailing theory, is the result of an imperfection in the crystal lattice.

A general object of the present invention is to utilize this discovered property to the creation of useful devices.

The invention is predicated in part on the discovery that usefully large concentrations (i. e. more than 10^{13} per cm.³) of deep traps exist at room temperature in n-type silicon material formed by the method described in the copending application Serial No. 432,638, filed May 27, 1954, by C. S. Fuller. In this method a single crystal silicon seed is lowered into a silicon melt and then, while the melt is being agitated, it is slowly pulled vertically therefrom through a cooling zone at a rate no greater than the rate of solidification of the silicon uplifted by the seed crystal. Unless donor impurities are added to the melt, the silicon crystal normally grows in the form of a p-type filamentary rod. However, by suitable heating in the temperature range between 350° C. and 500° C. for from one to 48 hours the core of the rod is converted to n-type material. It is such n-type material that has been found to have at room temperatures an especially large concentration of slow traps having a time constant of approximately 250 seconds, which makes it well suited for use in the practice of the

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invention. It is found to be important that the melt be agitated during the growing process since material grown without agitation is found not to have a large concentration of traps. The agitation of the melt preferably is realized by rotation of the silicon rod during growing. In material formed in this way the effectiveness of the trapping centers for use in accordance with the principles of the invention is found to be dependent on its resistivity after heating. In particular, it is found that for such material of resistivity higher than 100 ohm-cm., the Fermi level characteristic of the material is so high that most of the slow traps of the kind described above are normally filled so that the increase in conductivity is limited, while for such material of resistivity lower than 10 ohm-cm. the number of additional electrons freed to the conduction band by the trapping of holes is so small a fraction of the number of electrons already in the conduction band that the increase in conductivity is small. For these reasons, it appears that such n-type material of resistivity from 10 ohm-cm. to 100 ohm-cm. is most useful for exhibiting this enhanced conductivity effect. In particular, the effect is most pronounced with such material of a resistivity of approximately 20 ohm-cm. Techniques for controlling the resistivity are set forth in the aforementioned Fuller application.

Moreover, it has also been found that to a lesser but still appreciable extent volume traps of this kind are characteristic of monocrystalline silicon which is grown to be n-type initially by the addition of suitable donor impurities to a melt which is agitated during the growing.

There will be disclosed, by way of example for purposes of illustration, a number of devices making use of this enhanced conductivity effect among which there will be included a light integrating photocell and several novel forms of low frequency solid state amplifiers.

The invention will be more fully understood from the following more detailed description taken in conjunction with the accompanying drawings in which:

Fig. 1 shows a light integrating system utilizing a novel silicon photocell in accordance with one embodiment of the invention; and

Figs. 2 and 3 show low frequency solid state amplifiers utilizing novel silicon amplifying elements in accordance with further embodiments of the invention.

Referring now more particularly to the drawings, in the light integrator 10 shown in Fig. 1, a photocell 11 is shown serially connected with a voltage source 12 which, although shown as D.-C. may be A.-C., and a load 13 which, for example, may be the coil of a relay. The photocell 11 includes an elongated body 15 of n-type silicon material formed in the manner described above so as to be characterized by a large concentration of temporary traps, and electrodes 16 and 17 which make ohmic contact with opposite ends of the silicon body and by which the body is connected in series with the voltage source 12 and the load 13. The body 15 is oriented so that the light to be integrated is incident on one of its broad surfaces. The thickness of the body is preferably about 20 mils thick inasmuch as useful radiation cannot be expected to penetrate into the body more than this, and sufficient thickness is needed to overcome surface recombination effects and maintain a high lifetime in the body. The width and length of the broad surface on which the radiation impinges are primarily chosen with regard to the amount of power needed by the load, a larger surface area being desirable the larger the current needed for the load. Moreover, in the interest of efficiency the total impedance of the body at saturation should be chosen to match substantially the impedance of the load.

In such an arrangement when radiation first illuminates the silicon body 15, it creates electron-hole pairs in the

body of which the holes are caught in the traps, but electrons (equal in number to the number of trapped holes if space charge neutrality is to be maintained) add to the number of free electrons in the conduction band. In ordinary silicon material with no traps present the hole-electron pairs produced by the light decay in the normal lifetime of the minority carriers in silicon, ordinarily a matter of a few tens of microseconds. In the material of body 15 with traps present, the holes are trapped and so unable to recombine with the electrons for times as long as a thousand seconds and so the number of conduction electrons is increased. As a result, the conductivity of the body increases gradually so long as the traps are being filled, and after all the traps are filled it assumes a steady state saturation value. The conductivity at this saturation value may be many times what it is in comparable material in which no traps are present, i. e. the resistivity of the body after all the traps have been filled may be a small fraction of what it was initially.

For times up to the time constant of the traps and until saturation is reached, the conductivity of the body is a function of the total illumination to which the body has been exposed, and hence the instantaneous current flowing through the load at any time up to the time constant of the traps and saturation represents an integration of the total illumination incident on the body since current flow was initiated. Accordingly, the cell 11 serves as an exposure meter for providing a measure of the total illumination incident on the body since activation began. If the radiation is intermittent, it is important that the off intervals be small relative to the time constant of the traps. For specific applications, the parameters can be adjusted so that after a predetermined amount of illumination has fallen on the body and the instantaneous current has reached a preassigned level, a relay whose coil forms the load 13 is actuated.

Similarly, such a system 10 can readily be used as a dosimeter for use with gamma or X-rays, if radiation of this kind instead of visible light is made to penetrate the body 15 to create the hole-electron pairs. Moreover, it can be seen that such an arrangement can be used in computers of the analog type for performing integrating operations.

Figs. 2 shows a solid state amplifier 20 designed for operation at low frequencies. The amplifier includes a semiconductive device 21 which comprises an n-type silicon body of material formed in the manner described having a large concentration of traps. The nature of the traps built into the body determines the upper frequency limit of the operating range, since the gain which can be achieved is related directly to the ratio of the time constant of the traps to the lifetime of the minority carriers in the material. For example, material which includes a large concentration of traps having a time constant of several hundred seconds will be primarily useful for operation at frequencies of a fraction of a cycle per second. For operation at higher frequencies, the traps used should be those of a shorter time constant. The silicon body includes two enlarged end portions 22, 23 and a constricted portion 24 intermediate between the two end portions. Electrodes 25 and 26 make ohmic connections to the two end portions. A D.-C. voltage source 27 and a load 28 are serially connected between electrodes 25 and 26.

In operation, an input signal is used to vary the conductivity of the silicon body whereby the current flowing through the load 28 is varied correspondingly. The conductivity of the body is changed by the injection of minority carriers, in this case holes, into the body. To this end, a rectifying connection is made by means of the point contact electrode 29 to the constricted portion 24 of the body, and a signal source 30 and a D.-C. voltage source 31 are connected serially between rectifying contact 29 and ohmic electrode 26. The injection of

minority carriers into a semiconductive body in this way is a technique now well understood.

The use of material having a large concentration of temporary traps in an amplifier of this kind makes possible very high amplification factors. The holes injected by means of rectifying contact 29 are trapped in temporary traps of the kind described, but for the maintenance of space charge neutrality, their trapping results in a corresponding increase in the number of electrons in the conduction band in the body. Accordingly, the conductivity of the body is increased by the injection of holes in a manner controlled by the input signal and the current through the load varies correspondingly. The frequency response is limited by the decay characteristics of the trapping. The longer the holes remain trapped the lower the highest frequency of the input signal which can be faithfully reproduced at the load. The amplification factor is increased by injecting the holes into a constricted portion of the body as shown since the conductivity of the entire body is to a considerable extent controlled by the conductivity of this constricted portion.

The amplifier 40 shown in Fig. 3 differs from that shown in Fig. 2 only in the manner in which the holes are injected into the n-type body. Accordingly, the amplifier 40 includes an n-type silicon body 41 characterized by a large concentration of temporary traps and comprising two enlarged end portions 42, 43 and an intermediate constricted portion 44. Electrodes 45, 46 make ohmic connection to the end portions 42, 43, respectively, between which are serially connected a D.-C. voltage source 47 and a load impedance 48. In this arrangement, holes are injected into the body by means of a p-n junction in the manner familiar to workers in the transistor art. To this end, there is formed adjacent to, or as part of the constricted portion 44 a p-type zone 49 as, for example, by diffusing an acceptor impurity therein for converting the conductivity type of such a part of this constricted portion. An electrode 50 makes ohmic connection to this p-type zone 49. The signal source 51 and the D.-C. biasing supply 52 are connected serially between electrodes 45 and 50. The D.-C. supply 52 is poled to bias the p-n junction formed by zone 49 in the forward direction for the injection of holes. The principles of operation of such an amplifier are similar to those described for the amplifier 20 as shown in Fig. 2.

The measurement of the lifetime of minority carries in silicon which has a significant concentration of traps of the kind described is not readily achieved by the usual techniques. Such measurements are necessary since lifetime is an important design characteristic. In such measurements, it is first necessary to keep the traps filled or saturated so that only the normal recombination of minority carriers occurs. To this end, steady light of intensity sufficient to keep the traps filled is directed on the body upon which is superimposed intermittent light. Then by measurement either of the rate of decay of the conductivity of the body during the off intervals of the intermittent light or of the increased conductivity of the on intervals of the intermittent light there is derived the lifetime of the minority carriers in the body.

It is to be understood that the specific embodiments described above are merely illustrative of the general principles of the invention. Various other arrangements can be devised by one skilled in the art without departing from the spirit and scope of the invention. In particular, although the invention has been described with reference to specific material which has been found to contain a usefully high concentration of traps of the kind necessary to the practice of the invention, various other semiconductive materials having a usefully large concentration of these traps can be used in the manner illustrated. Moreover, it should be obvious that various other devices may be constructed making use of the properties discovered in a manner within the scope of the invention.

What is claimed is:

1. In combination, a semiconductive device including a semiconductive body of a material characterized by a large concentration of temporary traps which are distinguished by their ability to entrap charge carriers, a pair of electrodes making ohmic connection at two spaced regions along the surface of said body, and means for injecting minority carriers into said body at a region between said spaced regions, and voltage supply means and a load connected serially between said electrodes.

2. The combination of claim 1 further characterized in that the means for injecting minority carriers into said body comprises a source of radiation which impinges on said body for creating hole-electron pairs therein.

3. The combination of claim 1 further characterized in that the means for injecting minority carriers into said body comprises an electrode in rectifying contact with said body.

4. The combination of claim 1 characterized in that the means for injecting minority carriers into said body comprises means for a p-n junction biased in a forward direction.

5. In combination, a semiconductive device including an n-type semiconductive body of monocrystalline silicon which has been pulled from a silicon melt which was agitated during the pulling and then has been heated to provide a large concentration of temporary traps, a pair of electrodes making ohmic connections at two spaced regions along the surface of said body, and voltage supply means and a load connected serially between said electrodes.

6. An exposure meter for integrating incident radiation comprising the combination recited in claim 5 positioned to have radiation incident on said body in a region between said spaced regions for creating hole-electron pairs in said body.

7. An amplifier comprising the combination recited in claim 5 and means for injecting holes into said body at a region between said spaced region under the control of a signal to be amplified.

8. A semiconductive device including a semiconductive body of monocrystalline silicon of a resistivity between 10 ohm-cm. and 100 ohm-cm. grown by pulling from a silicon melt which was agitated during pulling and heated to between 350° C. and 500° C. for from one to 48 hours to provide n-type conductivity, and a pair of electrodes forming ohmic connection to said body at regions spaced apart therealong.

9. An exposure meter comprising a semiconductive device according to claim 8, positioned to have the radiation to be integrated incident on the body of said device at a region intermediate between the spaced regions, and a load and voltage supply serially connected between the electrodes.

10. An amplifier comprising a semiconductive device according to claim 8, means for injecting holes into the body of said device at a region intermediate the spaced regions under control of a signal to be amplified, and a load and voltage supply serially connected between the electrodes.

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