PATENT SPECIFICATION

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(54) SEMI-CONDUCTOR RECTIFIERS

(71) We, General Electric Company, a corporation organised and existing under the laws of the State of New York, United States of America, of 1 River Road, Schenectady, 12305, State of New York, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates in general to semiconductor rectifiers and more particularly to high speed semiconductor rectifiers and method for the manufacture thereof.

It is well known to improve the characteristics of certain types of semiconductor devices by the irradiation thereof with relatively high energy particles. For example, see the early work of Miller, U.S. Patent No. 2,868,988 wherein the irradiation of rectifiers to reduce transient reverse current is discussed. It was observed therein that bombarding a rectifier with high energy (2 MeV) electrons shortened the lifetime of charge carriers within the device and therefore increased the maximum useable frequency of the rectifier. The irradiation of rectifiers with a subsequent annealing step is described, for example, by Logan in U.S. Patent No. 3,173,882 wherein tunnel diodes are fabricated which are characterized by two discrete negative resistance, operating regions.

It has been recognized, for example, by Tarneja et al., U.S. Patent No. 3,809,582, that the irradiation of rectifiers for reducing the reverse recovery time thereof also increases the forward voltage drop of the rectifiers. It has been felt that the reduction in reverse recovery time which is achieved is sufficient to compensate for the increase in forward voltage which is characterized, therefore, as tolerable. Tarneja has also described in U.S. Patent No. 3,933,527 a method for tailoring the characteristics of rectifiers after fabrication by irradiation according to a formula set forth therein. In a still further patent, U.S. Patent No. 3,888,701, Tarneja et al. described the irradiation of semiconductor rectifiers followed by annealing at a relatively high temperature between 250°C and 350°C. The annealing is recognized to accomplish a decrease in the forward voltage drop and an increase in the reverse recovery time.

Our U.S. Patent 4,043,836 is concerned with irradiation of semiconductor devices at an elevated temperature. As was described in that application, high temperature irradiation allows the elimination of a long and therefore potentially costly annealing step following low temperature irradiation as had been theretofore required.

While the foregoing illustrates a generally increasing understanding of the mechanisms involved in the irradiation of semiconductor rectifiers and the improvements in characteristics which may be obtained thereby, there seems to have been little or no teaching of the optimization of the various methods and combinations of methods for improving the characteristics of semiconductor rectifiers by irradiation, annealing, and the like.

In accordance with the present invention there is provided a method for treating a semiconductor rectifier, the method comprising: heating the rectifier to a temperature in the range of 100° to 500°C, irradiating the rectifier while maintaining its temperature within the said range, and then annealing the rectifier at a temperature of between 280°C and 350°C for between two and ten hours.

It has been discovered that while the rates of change of forward voltage drop and of reverse recovery time are essentially constant during annealing, the rate of change of leakage current decreases with annealing time. It has further been found that in accordance with a particular example which will be more fully described hereinbelow, the leakage current is reduced to less than 50% of its unannealled value after only three hours of annealing. By comparing the rates of change of reverse recovery time and leakage current during annealing, it has been discovered that the rate of change of reverse recovery time is less than the rate of change of leakage current during the first three hours of annealing while the rate of change of reverse recovery time becomes greater than the rate of change of leakage current after ten hours of annealing. Therefore, by annealing the rectifier for a period of between two and ten hours, and preferably for a period of between three and six hours, depending on the annealing temperature, an optimum comprise is achieved between reverse recovery time, forward voltage drop, and leakage current.

The rectifier is preferably heated to a temperature within the range 250°C to 350°C, and annealed at a temperature of between 290°C and 310°C. In particular, the rectifier may be heated to a temperature of about 3500C and irradiated at that temperature.

The rectifier is preferably irradiated with electrons having energies of between 0.4 and 12.0 MeV for dosages between about 10^{13} e/cm^2 and 10^{16} e/cm^2.

Some examples of the invention will now be described with reference to the accompanying drawings in which:

Figure 1 is a flow chart diagram of a method for making a high speed semiconductor rectifier in accordance with this invention;

Figure 2 is a graphical representation of the relation between leakage current and annealing time for a semiconductor rectifier irradiated in accordance with this invention;

Figure 3 is a graphical representation of the relation between the reverse recovery time and annealing time for a semiconductor rectifier irradiated in accordance with this invention;

Figure 4 is a graphical representation of the relation between leakage current and reverse recovery time with annealing time as a parameter for a semiconductor rectifier irradiated in accordance with this invention;

Figure 5 illustrates apparatus suitable for performing the processes in accordance with this invention;

Referring now to Figure 1, a process for providing a rectifier having optimized reverse recovery time, forward voltage drop and leakage current is illustrated in block-diagram flow chart form. In accordance with a first step 10, a rectifier is provided which is preferably a high voltage, relatively high current rectifier as, for example, a rectifier having a reverse breakdown voltage on the order of 1800 volts and a forward current carrying capacity on the order of 400 amps. While a particular type of rectifier will be described in conjunction with the explanation of an exemplary embodiment of this invention, it will be understood by those skilled in the art that the principles taught herein and the invention which is described are equally applicable to a wide range of rectifier types and are not, therefore, limited to those particular embodiments described. An exemplary rectifier of a type to which this invention is suitable for application is one having a P+NN+structure, the rectifier being fabricated in an N conductivity type semiconductor wafer of a thickness, for example, of 11 or 12 mils and a resistivity of 60 to 90 ohm centimeters. Typically, semiconductor layers are formed on opposite surfaces of a wafer of the type described by diffusion of impurity atoms into said surfaces. For example, a P+ conductivity type region might advantageously be formed by the diffusion of gallium to a surface concentration of 5×10^{18} atoms per centimeter cube, and a thickness of about 3 mils. Similarly, an N+ conductivity type layer of a thickness of approximately 2 mils might readily be formed by the diffusion of phosphorus to a concentration of between 5×10^{18} and 1×10^{20} atoms per centimeter cube, concentrations on the order of 10^{19} being preferred. After diffusion, electrodes are conveniently formed by the deposition of metal on said surfaces, aluminum being typically employed. It will be understood by those skilled in the art that a semiconductor rectifier of the type described is more or less conventional and as such forms no part of the present invention except insofar as here it illustrates an exemplary rectifier of the type to which the teachings of this invention might advantageously be directed.

After metallization, a rectifier of the type described is, in this example, heated to a temperature exceeding 150°C and then subjected, without substantial cooling, to a high temperature irradiation step 12. Irradiation is performed at a temperature between 150°C and 500°C, and preferably in the range of 250 to 350°C. Irradiation is performed with electrons having energies in the range of 0.4 to 12 MeV. Irradiation is performed for a time sufficient to achieve a dosage of between 5×10^{13} and 5×10^{15} electrons per cm^2 and more preferably in the range of 10^{14} to 10^{15} electrons per cm^2. As will be appreciated by one skilled in the art, the time of irradiation necessary to achieve the foregoing densities depends upon the magnitude of the electron flux. Typically, times of irradiation on the order of between about 20 seconds and 120 seconds at a flux level of about 10×10^{12} e/cm^2 sec. are expected to provide satisfactory results.

After high temperature irradiation step 12, the rectifier is annealed at a temperature in the range of 280° to 350°C and preferably between 290° and 310°C for a time between 2 hours and 10 hours and preferably between 3 hours and 6 hours.

The precise duration and conditions of the foregoing steps may vary somewhat from the preferred values set forth and may be readily determined by one skilled in the art and in accordance with the principles heretofollow.

Referring to Figure 2, the relation between leakage current and annealing time is illustrated in graphical form. Curves 16, 18, and 20 represent devices irradiated in accordance with the foregoing procedure for 50, 40, and 30 seconds, respectively, at 1.5 MeV, corresponding to dosages 2.3×10^{14}, 1.9×10^{14}, and 14×10^{14} e/cm^2, respectively. The leakages illustrated are in milliamps at 175°C and an applied potential of 1800 volts for a device of the type hereinabove described. It will be appreciated by reference to Figure 2 that while the leakage current continues to decrease with increasing annealing time, the rate of change of leakage current with respect to time decreases with increasing time and, in fact, the percentage of reduction of leakage current is greater than 50 after three hours of annealing. After approximately ten hours, the rate of change of leakage current with time approaches nearly zero and essentially no further advantage may be expected to be obtained.

By contrast, the relation between reverse recovery time, t_{rr}, and annealing time is illustrated graphically in Figure 3. Again curves are illustrated for devices which have been irradiated for varying times at an elevated temperature. Curve 22 represents devices which have been irradiated for 35 seconds, curve 24—40 seconds, and curve 26—50 seconds at a dosage rate of 4.67×10^{12} e/cm^2 sec. Comparison of Figures 2 and 3 readily reveals that while leakage current decreases at a decreasing rate with annealing time, reverse recovery time increases at a substantially constant rate with increasing annealing time. Accordingly, and as has been described, the best compromise between leakage current and reverse recovery time, that is to say, the lowest leakage current consistent with a short reverse recovery time, is achieved by annealing for less than ten hours. It will be recalled that the rate of decrease in leakage current as a function of time decreases to essentially zero after ten hours of annealing. To the extent that leakage current remains therefore essentially the same while reverse recovery time continues to increase, it will be appreciated that further annealing is undesirable.

Figure 4 illustrates the trade-off between leakage current and reverse recovery time for semiconductor rectifiers processed in accordance with this invention, including as an additional parameter the time of annealing after high temperature irradiation. Curves 28, 30, 32, and 34 illustrate the relation between leakage and reverse recovery time for semiconductor rectifiers having annealing times of 0, 3, 6, and 10 hours, respectively. Those skilled in the art will readily appreciate that the most desirable curve is that curve lying closest to the origin of the axes of Figure 4. It will be seen by reference to Figure 4 that curve 32 provides the greatest degree of improvement in ultimate device characteristics over curves 28 which describes a non-annealed device. Both curves 30 and 34 describe devices wherein the improvement in the compromise between leakage current and reverse recovery time is less than that described by curve 32. Curve 30 describes a compromise which results from an annealing time which is shorter than optimum while curve 34 describes the characteristics of a device annealed for a time longer than optimum. It will be appreciated, however, that each of curves 30, 32, and 34 describes characteristics which are an improvement over the non-annealed characteristics described by curve 28.

It will be understood by those skilled in the art that while Figure 4 represents the presently preferred irradiation and annealing conditions for a device as hereabove described, where devices are desired to be optimized which differ somewhat from the device described herein, somewhat different conditions may provide the optimum compromise among leakage, reverse recovery time, and forward voltage drop.

Figure 5 illustrates diagrammatically an arrangement of apparatus for the high temperature irradiation and annealing of semiconductor devices in accordance with this invention. A conveyor belt 36 of conventional type is utilized to sequentially pass semiconductor devices 38 through 40 beneath irradiation means 42 and through furnace means 44. While Figure 5 illustrates apparatus utilizing a conveyor belt, it will be appreciated by those skilled in the art that other methods for exposing the semiconductor devices to the appropriate conditioning environments may be employed as, for example, by merely moving the devices physically from a kiln to an irradiation site and then returning them to the same or another kiln or oven to sequentially perform the heating, irradiation, and annealing steps in accordance with this invention. The apparatus of Figure 5 is preferably constructed so that pellets 38 remain in oven 40 for a time sufficient to increase their temperature to about 300°C. They are then moved under the irradiation source 42 without being allowed to cool significantly so that irradiation is performed while the temperature of the devices is substantially at about 300°C. Where desired, irradiation source 42 may be incorporated within oven 40 to insure that irradiation occurs at a high temperature. The irradiation source 42 may be any type of irradiation source known to those skilled in the art such as, for example, an electron accelerator or other high energy electron producing device which provides electrons having an energy in excess of .4 MeV. In accordance with one embodiment of this invention, an electron source 46 is provided along with an evacuated tube 48 which is maintained at the pressure on the order of 10^{-6} torr and which is sealed at the end remote from the electron source by a thin titanium window. Devices 38 are irradiated, in accordance with this invention, to a dosage of between 10^{13} and 5×10^{16} e/cm^2, and more preferably to a dosage between 10^{14} and 10^{15} e/cm^2. The time of irradiation depends upon the flux of the electron stream.

After irradiation, devices 38 are moved by conveyor 36 to annealing oven 44 where they are heated to a temperature of between about 280° and 350°C and more preferably to a temperature of between about 290° and 350°C for between three and ten hours and more preferably three and six hours. While conveyor 36 is illustrated as a single belt, it may be desirable to provide two or more distinct conveyor structures along with means for transferring pellets 38 therebetween in order to accomplish the heating, irradiation, and annealing steps in accordance with this invention. For example, those skilled in the art will appreciate that the heat which occurs in oven 40 and the irradiation source 42 may be accomplished relatively quickly and therefore that a single conveyor may be employed. Annealing within oven 44 is carried out for a time relatively long compared with heating and irradiation and, therefore, a separate slower moving conveyor may advantageously be employed.

After annealing and cooling, the devices are complete insofar as this invention is concerned and may be packaged in accordance with their ultimate purpose. A thin enclosure may be provided for surrounding the semiconductor devices during the irradiation portions of the process. Typically, one or two mil aluminum may provide improved heat retention during the annealing step without the necessity for either positioning the irradiation device 42 within oven 40 or for substantially increasing the energy thereof due to absorption by the enclosure. Similarly, a hot plate or the like may be provided at the irradiation site for heating the devices to or maintaining them at the desired temperature for irradiation.

While this invention has been described utilizing electron irradiation as the preferred method for reducing the lifetime of high speed rectifiers in order to achieve the advantages hereof, it will be understood by those skilled in the art that other forms of lattice-damage causing irradiation may advantageously be employed where desired with attendant modification of the times and dosages employed. For example, gamma or neutron irradiation may be employed; Gamma irradiation being preferred insofar as the dosage may be accurately controlled and irradiation may be performed relatively inexpensively. Proton irradiation although utilizable in theory is not to be preferred insofar as the penetration is much greater than that obtained with the foregoing types.

WHAT WE CLAIM IS:—

1. A method for treating a semiconductor rectifier, the method comprising: heating the rectifier to a temperature in the range of 100°C to 500°C, irradiating the rectifier while maintaining its temperature within the said range, and then annealing the rectifier at a temperature of between 280°C and 350°C for between two and ten hours.
2. A method according to Claim 1 in which the rectifier is heated to a temperature within the range of 250°C to 350°C.
3. A method according to Claim 1 or Claim 2 in which the rectifier is annealed at a temperature of between 290°C and 310°C.
4. A method according to Claim 2 or Claim 3 in which the rectifier is heated to a temperature of about 300°C. and the rectifier is irradiated at this temperature.
5. A method according to any one of the preceding claims in which the rectifier is irradiated with electrons having energies between 0.4 and 12.0 MeV.
6. A method according to Claim 5 in which the irradiation has a concentration of between 10^{13} and 10^{16} e/cm^2.
7. A method according to Claim 5 in which the rectifier is irradiated for between 20 and 60 seconds at a flux rate of about 5×10^{12} e/cm^2 sec.
8. A method according to any one of the preceding claims in which the rectifier is annealed for between three and six hours.
9. A method according to Claim 8 in which the rectifier is annealed at a temperature of about 310°C.
10. A method according to Claim 5 in which the rectifier is irradiated for between 30 and 50 seconds at a flux rate of about 4.7×10^{12} e/cm^2 sec.
11. A method according to Claim 6 in which the rectifier is irradiated to a concentration of between 10^{14} and 10^{15} e/cm^2.
12. A method according to Claim 1 and substantially as herein described with reference to the accompanying drawings.

BROOKES & MARTIN,
High Holborn House,
52/54 High Holborn,
London WC1V 6SE.
Agents for the Applicants.

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1587363 COMPLETE SPECIFICATION

1 SHEET *This drawing is a reproduction of the Original on a reduced scale*

FIG.1.

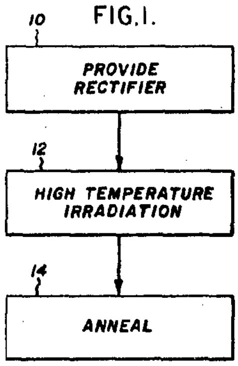

FIG.2.

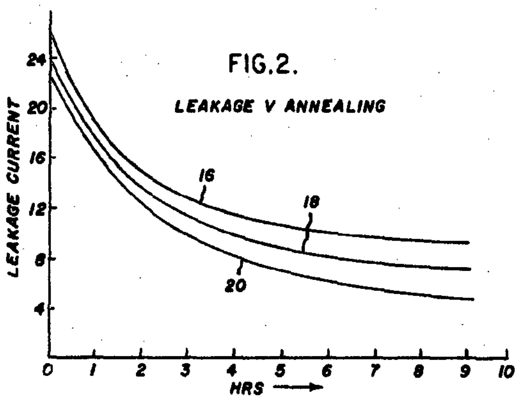

FIG.3.

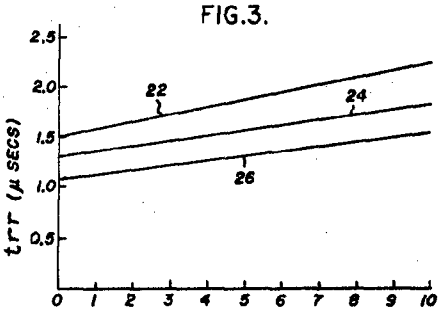

FIG.4.

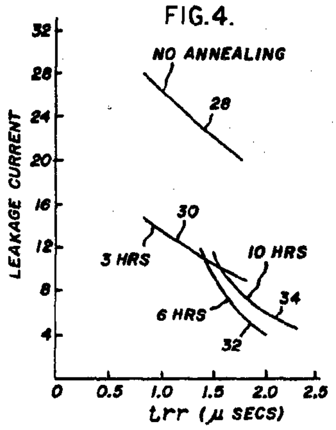

FIG.5.