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SILICON POWER RECTIFIER
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FIG. 1

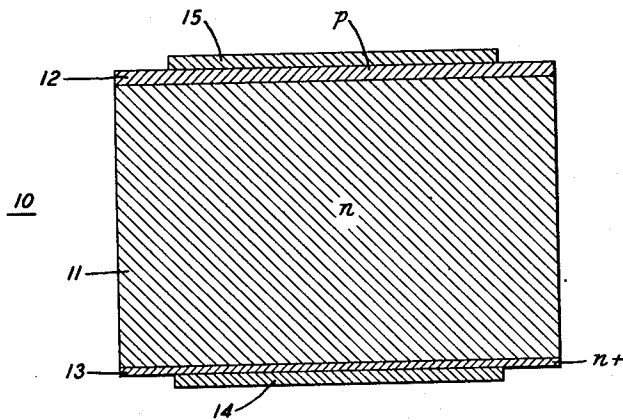
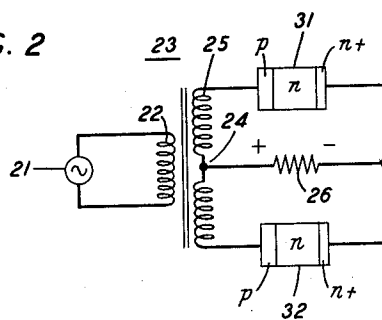


FIG. 2



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SILICON POWER RECTIFIER

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3 Claims. (Cl. 317—240)

The present invention relates to rectifying semiconductive elements and more particularly to silicon rectifiers. It is a continuation-in-part of my application Serial No. 414,275 filed March 5, 1954, which has been abandoned.

An object of the invention is to increase the power handling capacity of a semiconductive rectifier.

Related objects are to improve the efficiency and reduce the size of semiconductive rectifier elements and also to permit operation at higher ambient temperatures.

To these ends, the invention provides a novel form of semiconductive rectifier.

Conduction occurs in electronic semiconductors by means of two types of charge carriers, electrons and holes. These carriers can be provided in the semiconductor in several ways including the presence of certain elements in the crystal structure which have either an excess or deficit of valence electrons so that they provide a source of unbound holes or electrons which can be moved by the application of external voltage to the crystal structure. Generically, those conductors wherein conduction is largely by electrons are called n-type while those where conduction occurs by holes are called p-type. Where it is desirable to identify the conductivity characteristics of the materials with greater particularity, n+ and p+ are used to identify regions which have a more marked predominance of the characteristic type of charge carrier. Those elements constituting impurities which contribute unbound electrons to semiconductors are termed donors while those elements which contribute unbound holes are termed acceptors. Acceptors and donors are referred to as significant impurities to distinguish them from other materials which may be present in the semiconductor. The conductivity transition region between zones of opposite conductivity type in a semiconductive body is known as a p-n junction.

The most important problem in the design of a rectifier element is that of internal losses which result in overheating the rectifier. If the rectifier has appreciable resistance to current flow in the forward direction, considerable power is dissipated therein when large currents are drawn. This results both in a loss in efficiency and also in heating of the element which is undesirable, since it limits the current which can be safely drawn.

Another contribution to internal loss comes from the reverse currents drawn. If this is large, as in germanium, it can be the limiting factor rather than the current in the forward direction. Moreover, since some internal loss is unavoidable another important factor in a rectifier's capacity for power handling is the amount of heat which it can safely dissipate, i. e. its ability to withstand rises in temperature above the ambient. Germanium, for example, which in many respects is well suited for use as a semiconductive rectifier material is unable to tolerate appreciable rises in temperature from the ambient.

Various materials have been used hitherto for forming semiconductive rectifiers, but none has proven completely satisfactory in both the matter of internal losses and the ability to operate successfully at high temperatures. Accordingly, with the rectifiers of the prior art, elaborate cooling precautions must be taken when large currents are drawn.

The present invention provides a rectifier which is

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characterized by both low internal losses and a capacity for tolerating substantial temperature rises.

A feature of the present invention is a rectifying element which comprises a single crystal purified silicon body having a terminal n-type zone characterized by a concentration of phosphorus significant impurities, a terminal p-type zone characterized by a concentration of boron significant impurities, and an intermediate zone having a resistivity higher than that of the terminal zone of corresponding conductivity type. In the preferred embodiment to be described in detail, an n-type zone is sandwiched between a vapor-solid boron-diffused p+ type zone and a vapor-solid phosphorous diffused n+ type zone.

The use of p-n junctions in semiconductive bodies as rectifying barriers is well known to the prior art, but results comparable to those provided by embodiments of the invention have not hitherto been attained in such prior art semiconductive bodies.

There are various reasons for the improvements made possible by the practice of the invention. First, the choice of purified silicon as the semiconductive body material provides initial advantages which are multiplied by its association with the chosen significant impurities.

Silicon can be made to have a very low resistance to forward currents and a very high resistance to reverse currents. Silicon is very stable electronically up to 200° C., permitting heating to this point with little serious effect. This is in marked contrast to other semiconductive materials, such as germanium.

Further, the particular choice of boron as the acceptor for doping the p-type surface zone makes possible a thin low-resistance diffused p-type terminal layer. Such a boron-diffused layer is found to lend itself readily to low-resistance ohmic connection. This is of considerable importance if internal losses are to be minimized.

Similarly, the particular choice of phosphorus as the donor for doping the n+ type zone makes possible a thin low-resistance terminal layer. By suitable choice of the resistivities of the p-type and n-type zones, an n+ type surface zone can be localized contiguous to the n-type zone by the vapor diffusion of phosphorus with no appreciable effect on the boron p-type layer. Moreover, the provision of a phosphorous-diffused n+ type layer makes possible low-resistance ohmic connection to the n-side of the rectifying junction. This is important for the following considerations. To make a low-resistance ohmic connection to a surface of a semiconductor, it is found important to make contact to a low-resistance zone.

Accordingly, to make a low-resistance ohmic connection to the p-type terminal zone, it is important to have a low-resistance p-type zone. However, to provide good reverse characteristics in a p-n junction, it is important to have a high resistivity in at least one of the two zones forming the junction. Therefore, to achieve good reverse characteristics it becomes necessary to associate with the low-resistance p-type zone a relatively high-resistance n-type zone. It is difficult to make a low-resistance ohmic connection to the high-resistance n-type zone, but by providing a thin terminal n+ type zone by additional doping with phosphorus for connection thereto, there is effectively made possible a low-resistance ohmic connection to the n-type zone.

An important specific feature of the invention is a particular design which provides extremely low internal losses and possesses advantages in its relative simplicity of preparation. This design comprises a single crystal silicon body having a relatively thick intermediate n-type zone of a resistivity of about 0.3 ohm-centimeter, one thin terminal diffused p-type zone having a concentration of boron impurities resulting in a resistivity of about 0.001 ohm-centimeter, and another thinner terminal diffused n+

type zone having a concentration of phosphorous impurities resulting in a resistivity of about 0.01 ohm-centimeter, together with rhodium ohmic connections to the two terminal zones.

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

Fig. 1 represents a cross section of a rectifier element in accordance with the invention; and

Fig. 2 shows two rectifier elements connected for providing full-wave rectification of an alternating signal.

In the rectifying element 10 shown in Fig. 1 and of a design which forms a specific feature of the invention, a single crystal silicon body comprises an intermediate n-type zone 11 of 0.3 ohm-centimeter resistivity and about 30 mils thickness, a terminal p-type zone 12 about 1.5 mils thick and having a concentration of boron which results in a resistivity of 0.001 ohm-centimeter, and a terminal n+ type zone 13 about 0.5 mil thick having a concentration of phosphorous impurities which results in a resistivity of 0.01 ohm-centimeter. Such a body can be formed conveniently, for example, by vapor-solid diffusion techniques of the kind described in copending application Serial No. 414,272, filed March 5, 1954 by C. S. Fuller and having a common assignee. It is characteristic of such vapor-solid diffusion techniques that the significant impurity is diffused from a vapor state into the solid semiconductor without any significant melting of the semiconductor so that there is a minimum disruption of the homogeneity of its monocrystalline structure. Typically, an n-type conductivity silicon cylindrical wafer is heated in a boron trichloride atmosphere at a temperature of approximately 1250° C. for about twenty-three hours to form a thin p-type conductivity surface on the wafer. The p-type layer is then removed from one flat end surface of the wafer to expose the n-type zone. Further, heating in a phosphorous atmosphere at a temperature of 1230° C. for about one and a half hours results in the formation of an n+ type layer over the n-type surface which was exposed. As a result of this particular selection of resistivity characteristics, the surface of the low-resistance p-type zone is found to be unaffected by the phosphorous atmosphere, eliminating the need for further treating of the p-type zone. To achieve this simplification of forming, it is important to have a p-type layer of resistivity lower than that of the n+ type layer. This forms one factor why the design described is found superior to the alternative design also in accordance with the invention which utilizes a silicon body having a p-type intermediate zone, a thin n-type terminal zone having a concentration of phosphorous impurities, and a still thinner p+ type terminal zone having a concentration of boron impurities. In the process being described particularly, it is then necessary to grind off the cylindrical surface which surrounds the wafer to form a simple stack of n+ type, n-type, and p-type zones. An alternative technique for forming suitable bodies is described in copending application Serial No. 477,535, filed December 24, 1954, by L. Derick and C. J. Frosch and having a common assignee.

Low-resistance ohmic connections are made to the two terminal zones by electroplating with a suitable noncontaminating metal, such as rhodium, to form coatings 14, 15. Copper leads may then be connected to these coatings 14, 15.

A design of the kind described has provided satisfactorily for an extended period average currents of 15 amperes from a rectifying area of a square centimeter with no special provisions for cooling. Such a performance would be considered remarkable in the light of prior art rectifier standards.

Fig. 2 illustrates schematically the manner in which two rectifying elements can be utilized to provide full-wave rectification of an alternating signal. The alternating voltage to be rectified is applied from a suitable

source 21 to the primary winding 22 of the power transformer 23. The center tap 24 of the secondary winding 25 of the transformer is connected to one side of the load, shown here schematically as the resistance 26, the other side of which is connected to the large area metallic coatings plated or fused to the n+ type terminal zones of rectifying elements 31 and 32. The two terminals of the secondary winding 25 are connected, respectively, to the large area metallic coatings plated or fused to the p-type terminal zones of elements 31 and 32. It will be evident that various other configurations are possible for providing full-wave rectification.

A rectifying element of the kind described can obviously be built in various shapes and sizes to adapt it for specific capacities of power handling. Its capacity to handle currents is determined primarily by its surface area. Its ability to withstand high reverse voltages is found to be determined by the resistivities of the two zones forming the p-n junction, higher resistivities being necessary to withstand higher reverse voltages. The rectifying element described specifically is designed to withstand reverse voltages of about 95 volts, the substitution of an intermediate zone of 3.0 ohm-centimeters resistivity would make it possible to withstand reverse voltages of about 225 volts.

Moreover, although in the specific embodiment, the silicon wafer with which one began was all n-type, such as may be provided by doping the silicon melt from which the silicon crystal is grown with a suitable donor, such as arsenic, alternatively one may begin with a silicon body which is all p-type, such as may be provided by doping the silicon melt with a suitable acceptor, such as gallium. In such an event, there would result a rectifying element in which the silicon body comprises a p-type zone intermediate between p+ type and n-type surface zones characterized by predominances of boron and phosphorus impurity atoms, respectively.

What is claimed is:

1. A rectifying element comprising a substantially monocrystalline silicon wafer having an intermediate zone of relatively high specific resistivity of one conductivity type, a first low specific resistivity terminal zone contiguous with one side of the intermediate zone in which boron is the predominant significant impurity, and a second low specific resistivity terminal zone contiguous with the opposite side of the intermediate zone in which phosphorus is the predominant significant impurity, and a pair of electrodes, each making low ohmic resistance connection to a different one of said two terminal zones.

2. A rectifier element comprising a substantially monocrystalline silicon wafer having an intermediate zone of a relatively high specific resistivity of one conductivity type, a first low specific resistivity terminal zone which is vapor-solid boron-diffused contiguous with one surface of the intermediate zone, and a second low specific resistivity terminal zone which is vapor-solid phosphorus-diffused contiguous with the opposite surface of the intermediate zone, and a pair of electrodes, each making low ohmic resistance connection to a different one of said two terminal zones.

3. A rectifying element comprising a substantially monocrystalline silicon wafer having an n-type intermediate zone, a first vapor-solid boron-diffused p+ type terminal zone contiguous with one side of the intermediate zone, and a second vapor-solid phosphorus-diffused n+ type terminal zone contiguous with the opposite side of the intermediate zone, and a pair of electrodes each making low ohmic resistance connection to a different one of said two terminal zones.

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