

PATENT SPECIFICATION

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(54) THYRISTOR

(71) We, BORG-WARNER CORPORATION, a Corporation organized and existing under the laws of the State of Delaware, United States of America, of 200 South Michigan Avenue, Chicago, State of Illinois 60604, 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:—

The present invention relates to a thyristor of four layer PNPN type.

Considerable effort has been expended in the semiconductor art to reduce the turn-off time of thyristors of the four-layer PNPN type. One significant improvement in this area is described in U.S. Patent Specification No. 3,638,042. That patent specification teaches the application of a sweep-out pulse across the center junction of a thyristor, that is, between the "normal" gate or P-layer adjacent the cathode and the N-layer between the anode and the normal gate. Application of the sweep-out pulse was facilitated by addition of an ohmic contact to the N-base region between the anode and the normal gate. While a substantial decrease in the device turn-off time has been realized with this arrangement, the thyristor described in the patent specification requires the addition of the added gate connection to the thyristor.

According to the present invention there is provided a thyristor comprising a body having four alternate layers of P-type and N-type semi-conductor material, in which the first P-layer has an ohmic contact attached to function as the anode, the first N-layer forms a first end junction with the first P-layer and has an ohmic contact attached to function as an anode-gate, the second P-layer forms a center junction with the first N-layer, the second N-layer forms

a second end junction with the second P-layer and has an ohmic contact attached to function as the cathode, such that the thyristor can be gated-on in use by applying to the anode-gate a potential which is negative with respect to the anode potential, and the first N-layer is substantially thicker than any of the other layers in the thyristor body.

If desired the thyristor operation may be enhanced by providing a distributed gate, that is, an extended contact area between the anode-gate N-layer and its ohmic contact.

Means may be provided for applying a sweep-out pulse between the anode-gate and the cathode during the turn-off operation. This signal sweeps out charge carriers at the center junction, between the N-base region and the adjacent P-base region, to reduce the turn-off time of the device.

The present invention will now be explained and described, by way of example, with reference to the accompanying drawings, wherein like reference numerals identify like elements, and wherein:

FIGURE 1 is a side view of a known thyristor arrangement;

FIGURE 2 is a side view of a thyristor which is useful in facilitating the understanding of this invention;

FIGURE 3 is an explanatory side view, and FIGURE 4 is a partial top view of a thyristor manufactured in accordance with this invention;

FIGURE 5 is a graphical illustration useful in understanding the manufacturing of the thyristor shown in FIGS. 3 and 4; and

FIGURE 6 is a schematic diagram, partially in block form, of the thyristor shown in Figure 2, together with appropriate circuits for energizing and operating the thyristor.

FIGURE 1 depicts a thyristor body

of a material such as silicon, having four alternate P and N conductive regions 11, 12, 13 and 14. The first P-layer or anode region 11 has an ohmic contact 15 affixed thereto, so that the P-layer 11 can function as the anode. An anode connection 16 is made to the wide area ohmic contact 15. The first N-layer 12, also called the N-base region, forms a first end junction J1 with the anode region 11. The second P-layer 13, also termed the P-base region, forms a center junction J2 with the N-base region. The second N-layer 14, the cathode region, forms a second end junction J3 with the P-base region. An ohmic contact 17 is applied to the P-base region 13 such that a normal gate connection 18 affixed to the contact 17 provides a path for the application of gating signals into the P-base region to forward bias the junction J3 and turn on the device. Another ohmic connection 20 is made to the cathode region 14, and a cathode connection 21 is connected to the ohmic contact 20.

The two outer regions 11 and 14 of the device are generally made of high conductivity P-type and N-type semi-conductive material, respectively. These regions form strong emitting junctions (J1 and J3) with the adjacent inner regions 12 and 13 of the semiconductor body 10, as the adjacent inner regions are formed of lower and opposite type conductivity material. The N-base region 12 has a lower conductivity than the P-base region 13, and the transition from the N-base 12 to the P-base 13 forms the center junction J2 of the composite PNP structure. In conventional devices, such as that shown in FIG. 1, the P-base region is the control region, and the control electrode (or gate) 17 is affixed to this region. In the illustration of FIG. 1 the semiconductor body is not to scale. Those skilled in the art will appreciate that the width and the doping (addition of impurities to alter the characteristics of each region) of the various regions is determined as the function of various considerations, such as forward voltage drop, reverse voltage blocking capability, triggering sensitivity, and so forth. Because of the voltage blocking capability requirements, the N-base region 12 is generally made much wider than the P-base region 13. In addition the body 10 of the device is bevelled or tapered as shown to enhance the voltage blocking capability. When a voltage is applied across junction J2, carriers are moved from the junction or transition between the regions 13 and 12 and there is a certain voltage gradient both through the junction and along side the outer wall of the device. The blocking capability of the device is increased if this voltage gradient can be reduced, and for this reason the bevel or

tapered configuration shown generally in FIG. 1 is conventionally utilized. The shape of the thyristor body is generally like the frustum of a cone. In this arrangement the PN junction J1 with the illustrated bevel is generally a "good" junction, in that it provides good reverse voltage blocking capability. However the center junction J2 is not as effective in blocking as the junction J1, and the junction J2 affects the forward blocking capability of the device.

In the turn-off of a conventional thyristor of the silicon controlled rectifier (SCR) type, the turn-off is generally initiated by applying a reverse voltage to make the SCR anode negative with respect to its cathode. At the end of the turn-off interval, a forward voltage is generally re-applied to the device. The rate of rise of this voltage leads, in connection with the device capacitance, to a displacement current which causes a certain amount of charges to be injected again into the structure. This can increase the device turn-off time or even cause switching of the device back into the conductive state. The effect of the rate of voltage rise is known as "dv/dt effect".

FIGURE 2 illustrates a thyristor body comprising an ohmic contact 25 is affixed to the N-base region 12, and an anode-gate connection wire 26 is connected to the ohmic contact 25. There is no ohmic contact or any other connection made to the P-base region 13. Accordingly to turn on the device shown in FIG. 2, after a potential is applied to the anode 15 which is positive with respect to that on the cathode 20, a signal or potential is applied to the anode-gate connection 26 which is negative relative to the potential applied over conductor 16 to the anode 15.

Another difference as respects construction of the thyristor shown in Figure 2 and that shown in Figure 1 is the direction of the bevel of the thyristor body. That is, in Figure 2 the uppermost P-region, the anode region, has the smallest diameter of the frusto-conical thyristor body, and the dimension gradually increases through the cathode region or the last N-layer 14. Those skilled in the art will appreciate that the degree of bevel need not be uniform or continuous, but it is generally simpler to manufacture the thyristor body with a uniform bevel or slope.

In the configuration of FIGURE 2, the forward blocking capability is greatly enhanced, because of the direction of the bevel at the PN junction J2. However the reverse voltage blocking capability, by reason of the direction of the bevel at junction J1, is debilitated compared to the structure of FIGURE 1. Even if the direc-

tion of the bevel is changed, as will become apparent from the subsequent explanation it is convenient to provide the anode-gate connection through the anode region 11 to the N-base region 12, rather than the simple illustration shown in FIG. 2. Accordingly this intrusion through the anode layer 11 to form the connection to the N-base region 12 would itself deteriorate the reverse voltage blocking capability, absent any consideration of the direction of the bevel of the semiconductor body.

Accordingly a significant part of the inventive contribution is the appreciation that a thyristor body formed as shown in FIG. 2 can be utilized, even with a greatly reduced reverse voltage blocking capability. This realization is based in part upon the comprehension that thyristor bodies are frequently used in inverter circuits for translating a direct voltage into an alternating voltage output signal. When so used, it is common to have a diode connected in parallel with the SCR, but in the opposite current conducting direction, in the inverter circuit. See for example FIG. 6 in U.S. Patent Specification No. 3,594,630, where diodes 37 and 38 are coupled in parallel with SCR's 12 and 28, respectively. Thus the appreciation of this inverter use of a thyristor body shaped as shown in FIG. 2 contributes both to the utility and to the understanding of the present invention.

As noted above, the ohmic connection 25 in FIG. 2 is illustrated as applied to the side of the thyristor body for simplicity of explanation. Various gate configurations are possible. One such is an annular gate 25 as depicted in FIGS. 3 and 4. The gate could also be of the interdigitated type, or comprise a plurality of islands distributed over the area of the base region 12. The annular gate configuration was selected to prove the operability of the thyristor in accordance with this invention, and it has been satisfactorily demonstrated with this arrangement. It will be understood however, that as the area devoted to the gate becomes larger, the effective anode area for the device will be correspondingly reduced, with a consequent reduction in current handling capability.

The practical device depicted in FIGS. 3 and 4 was produced from a monocrystalline silicon pellet of circular cross section generally referenced 30. The pellet had a diameter of 5/8 inch and a thickness of approximately 0.009 inch, or about 229 microns. The N-base region 12 included an upper channel portion 31, providing an extended annular surface for access to the N-base region. The width of channel 31 is about 0.15 centimeter, and its mean radius about 0.4 centimeter. The anode

region 11 of P-type conductivity was formed by local diffusion of boron after silicon dioxide masking of the area corresponding to the N-type channel 31. The end junction J1—at the bottom of anode region 11 adjacent the N-base region 12—lies about 50 microns below the top of the anode region 11. The impurity concentration distribution (see FIG. 5) in the anode region is Gaussian, with a concentration at the surface of about 2×10^{18} atoms/cm³. The N-base region 12, which has the characteristic of the starting material, has a uniform concentration of about 2×10^{14} atoms/cm³. The thickness of the N-base region 12, from the bottom of the anode region 11 to the center junction J2, is about 129 microns. The P-base region 13 is formed by diffusing boron simultaneously with formation of the anode region, and thus P-base region 13 has similar characteristics. The thickness of the P-base region 13, from junction J2 to junction J3, is about 30 microns. The cathode region 14 of N-type conductivity is formed by diffusion of phosphorus into the P-region 13, on the cathode side. The concentration distribution in the cathode region 14 is Gaussian, with a concentration at the lower surface of cathode region 14 (as viewed in FIG. 3) of about 5×10^{19} atoms/cm³. The distance from junction J3 to the lower surface of cathode region 14 is about 20 microns.

The semiconductor body 30 is mounted on a molybdenum base 27 to provide a more rugged structure than otherwise would be the case. This mounting is done by an alloying technique, using a gold/antimony preform 28 as an intermediate member. Anode region 11 is provided with a disc-shaped center ohmic contact 15 and an outer ring-shaped ohmic contact 15', and anode-gate region 12 is provided with a ring-shaped contact 25; these contacts are provided by plating or evaporation techniques. In general the edge portions of the device are bevelled to minimize field effects and increase the forward blocking capability of the device, as has already been described.

FIG. 6 illustrates a thyristor of the type described above with reference to FIG. 2, connected in an actual operating circuit.

As will be readily understood by those skilled in the art, the operating circuit of Figure 6 can be readily connected to the thyristor of Figs. 3 and 4. A suitable energizing unit, shown as a battery 35, is connected in series with a resistor 36 between conductors 37, 38. In turn these conductors are coupled to the anode output conductor 16 and to the cathode connector 21, to supply energy to the thyristor. A turn-off circuit 40 is shown coupled between con-

ductors 37, 38. This turn-off circuit can be any suitable arrangement, such as the turn-off circuit 24 illustrated in Fig. 1 of U.S. Patent Specification No. 3,638,042. In general battery 35 and circuit 40 can be considered means for energizing and for effecting turn-off of the thyristor 30. Turn-on circuit 41, shown coupled between the anode and the anode-gate, can be any suitable unit for providing a potential negative on the anode-gate with respect to that present at the anode, to trigger the thyristor into conduction.

The background description of providing sweep-out action across the center junction J2 is described at length in U.S. Patent Specification No. 3,638,042. In general this sweep-out reduces the thyristor turn-off time, by removing the charges that would otherwise recombine over a considerably long time period. Accordingly one suitable sweep-out circuit 42 is illustrated for providing the requisite potential between the cathode and the anode-gate region to effect the sweep-out action. Circuit 42 includes an SCR 43 coupled in series with a capacitor 44 between the conductor 26 affixed to the anode-gate region and the circuit conductor 45, coupled over cathode conductor 21 to the ohmic cathode connection. A diode 46 and a resistor 47 are coupled in series as shown between the gate of SCR 43 and conductor 45. Another diode 48 is coupled as shown between the anode and the cathode of SCR 43.

When the thyristor or control switch 30 in FIG. 6 is in its blocking state, capacitor 44 is charged to the applied forward blocking voltage over a path including diode 48. The capacitor charge has the polarity indicated in FIG. 6. When turn-on circuit 41 is energized to provide a negative-going signal over line 26 with respect to the potential on conductor 16, thyristor 30 is gated on and conducts heavily, and the voltage between its anode and cathode thus is reduced to a very low voltage. Capacitor 44 is isolated from this voltage reduction by the diode 48 and the SCR 43.

In the turn-off of thyristor 30, when junction J3 breaks down, a triggering signal is passed over conductor 45, limiting resistor 47, and diode 46 to the gate of SCR 43, turning on SCR 43. Conduction of SCR 43 completes a circuit from the capacitor 44 over line 26 to the ohmic connection of the anode-gate region 12, providing the requisite pulse signal to sweep out the carriers adjacent the center junction J2, which charge carriers would otherwise take a considerably longer time to recombine. This sweep-out action reduces the turn-off time of thyristor 30.

The thyristor thus constructed has been tested in the 100 ampere forward current

range for evaluation of turn-off time and dv/dt capability improvements. The turn-off time with conventional turn-off conditions was in the 25 to 30 microseconds range. With a 2 ampere sweep-out pulse through the center junction J2 after anode recovery, the turn-off time was reduced to 12 to 15 microseconds, or by as much as 50%. Without this sweep-out pulse, the device had a maximum dv/dt capability of about 100 volts/microsecond; with a pulse applied to the anode-gate, no dv/dt effects were noticeable, even at 300 volts/microsecond.

WHAT WE CLAIM IS:—

1. A thyristor comprising a body having four alternate layers of P-type and N-type semiconductor material, in which the first P-layer has an ohmic contact attached to function as the anode, the first N-layer forms a first end junction with the first P-layer and has an ohmic contact attached to function as an anode-gate, the second P-layer forms a center junction with the first N-layer, the second N-layer forms a second end junction with the second P-layer and has an ohmic contact attached to function as the cathode, such that the thyristor can be gated-on in use by applying to the anode-gate a potential which is negative with respect to the anode potential, and the first N-layer is substantially thicker than any of the other layers in the thyristor body.

2. A thyristor according to claim 1, wherein a base member is affixed to the second N-layer to provide mechanical strength during the manufacturing and assembling operations, which base member is substantially thicker than the entire thyristor body.

3. A thyristor according to claim 1 or 2, wherein an extended contact area is provided between the first N-layer and its ohmic contact to form a distributed gate connection.

4. A thyristor according to claim 3, wherein the extended contact area of the first N-region, which projects to an end surface of the thyristor body, is generally circular, and wherein an annular gate contact is affixed to the extended circular N-layer surface to provide a distributed gate connection.

5. A thyristor according to any one of claims 1 to 4, further comprising electrical circuits coupled between the anode and cathode of the thyristor, for energizing and for turning off the thyristor, a turn-on circuit, coupled between the anode and the anode-gate of the thyristor, for gating on of the thyristor, and a sweep-out circuit, coupled between the anode-gate and the cathode, for applying a sweep-out pulse across the thyristor center junction during

ductors 37, 38. This turn-off circuit can be any suitable arrangement, such as the turn-off circuit 24 illustrated in Fig. 1 of U.S. Patent Specification No. 3,638,042. In general battery 35 and circuit 40 can be considered means for energizing and for effecting turn-off of the thyristor 30. Turn-on circuit 41, shown coupled between the anode and the anode-gate, can be any suitable unit for providing a potential negative on the anode-gate with respect to that present at the anode, to trigger the thyristor into conduction.

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2. A thyristor according to claim 1, wherein a base member is affixed to the second N-layer to provide mechanical strength during the manufacturing and assembling operations, which base member is substantially thicker than the entire thyristor body.

3. A thyristor according to claim 1 or 2, wherein an extended contact area is provided between the first N-layer and its ohmic contact to form a distributed gate connection.

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5. A thyristor according to any one of claims 1 to 4, further comprising electrical circuits coupled between the anode and cathode of the thyristor, for energizing and for turning off the thyristor, a turn-on circuit, coupled between the anode and the anode-gate of the thyristor, for gating on of the thyristor, and a sweep-out circuit, coupled between the anode-gate and the cathode, for applying a sweep-out pulse across the thyristor center junction during



the turn-off of the thyristor to reduce the thyristor turn-off time.

6. A thyristor constructed and arranged to operate substantially as hereinbefore described with reference to and as shown in Figures 3 to 5 of the accompanying drawings.

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