July 19, 1966 I. SOMOS 3,261,985

CROSS-CURRENT TURN-OFF SILICON CONTROLLED RECTIFIER

Filed Dec. 21, 1962 2 Sheets-Sheet 1

FIG. 1.

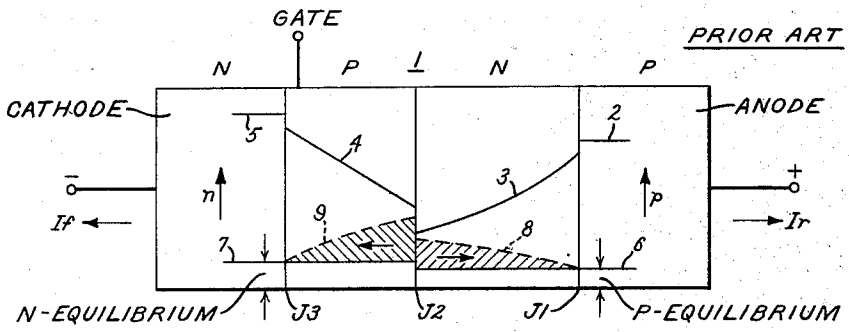


FIG. 2.

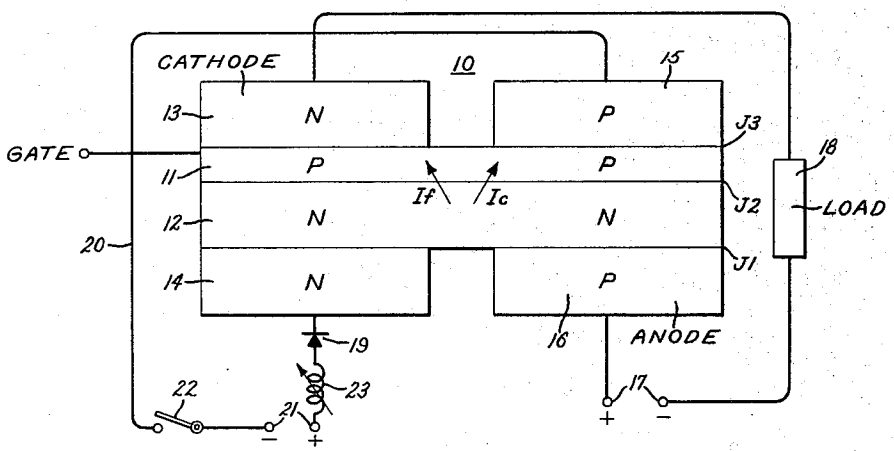
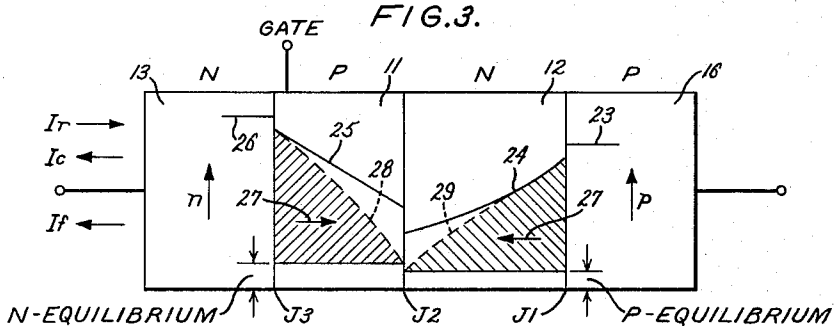


FIG. 3.



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FIG.4.

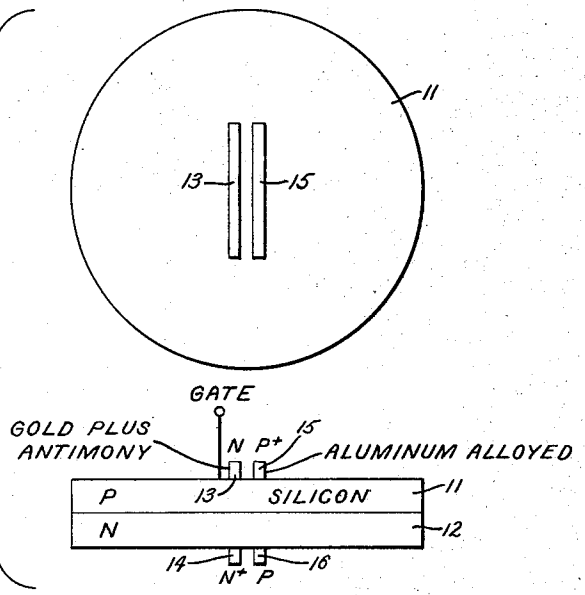


FIG.5.

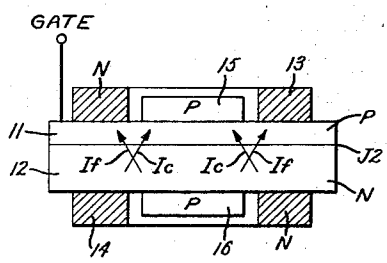
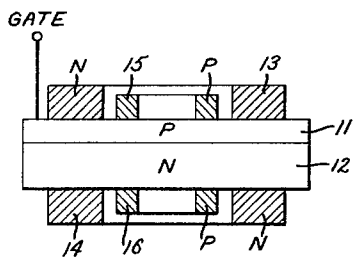


FIG.6.



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CROSS-CURRENT TURN-OFF SILICON CONTROLLED RECTIFIER

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9 Claims. (Cl. 307—88.5)

This invention relates to semiconductor devices and, more particularly, to PNPN semiconductor devices of the type that is capable of being switched readily between two extremes of impedance and an object of the invention is the provision of a simple, reliable and improved device of this character.

More specifically, the invention relates to PNPN semiconductor devices of the type known as silicon controlled rectifiers. Such a device typically comprises a body of silicon having a pair of main electrodes, known as anode and cathode, and a control electrode or gate, with three alternately poled PN (rectifying) junctions being disposed in series between the main electrodes. It has the characteristic of being capable of remaining in either a high impedance condition (in which it blocks current in either direction) or a low forward impedance condition (in which it freely conducts conventional current from anode to cathode) without a continuously applied control signal. Silicon controlled rectifiers are functionally similar to gas tube thyratrons, which are capable of controlling large amounts of current by means of relatively small power pulses. Although a silicon controlled rectifier may readily be transferred from the high impedance mode of operation to the low impedance mode in response to the supply of relatively small firing pulses of current to the gate, switching from the low impedance condition to the high impedance condition to effect turnoff is much more difficult. A conventional manner of effecting turnoff of a silicon controlled rectifier has been to apply a reverse voltage to its anode and cathode. This reverse voltage causes a reverse recovery current through the device which removes the carriers from the end junctions of the device in a brief interval, e.g., 1 to 5 microseconds. The remaining carriers, particularly those in the vicinity of the middle PN junction, disappear by recombination because the reverse current is terminated when the carrier concentrations at the end junctions reach the equilibrium point. The recombination time is relatively long and makes the turnoff time correspondingly long. If the reverse bias voltage is terminated before recombination has proceeded substantially to completion and forward bias voltage exists across the anode and cathode, the silicon controlled rectifier will break over and start conducting again. Accordingly, a further object of this invention is the provision of a silicon controlled rectifier in which the high impedance condition or blocking state is attained and complete turnoff effected in a substantially shorter time, i.e., within a few microseconds of initiation of the turnoff operation.

In carrying the invention into effect in one form thereof, the intermediate P zone of a PNPN semiconductor silicon controlled rectifier is provided with an auxiliary electrode of P type conductivity material and the intermediate N type conductivity zone is provided with another auxiliary electrode of N type conductivity material so that these electrodes and the intermediate P and N zones of the P and N device constitute a diode having a rectifying junction in common with the middle rectifying junction of the PNPN device. Connections are provided for supplying a reverse voltage to these auxiliary electrodes to cause current through such diode rectifier that crosses the main current path in the device and removes the injected minority carriers from the common middle

junction thereof, whereby the PNPN semiconductor device will immediately regain its blocking state.

For a better and more complete understanding of the invention, reference should now be had to the following specification and to the accompanying drawings in which:

FIG. 1 is a block layer diagram of a conventional prior art silicon controlled rectifier with characteristic curves of the injected minority carrier concentration within each of the separate P and N zones represented by characteristic curves.

FIG. 2 is a diagram of a PNPN semiconductor silicon controlled rectifier device embodying the invention.

FIG. 3 is a block layer diagram of a portion of a PNPN silicon controlled rectifier embodying the invention with injected carrier concentration within each of the separate P and N zones represented by characteristic curves to facilitate an understanding of the operation of the invention.

FIG. 4 comprises a plan view and a view in front elevation of a PNPN silicon controlled rectifier embodying the invention.

FIG. 5 is a view in elevation, partly in section of a modification and

FIG. 6 is a sectional view of another modification.

Referring now to the drawings, and particularly to FIG. 1, a conventional silicon controlled rectifier device 1 is conventionally illustrated as having four zones arranged in succession with contiguous zones of opposite conductivity type so that in order from right to left the zones are designated PNPN. The junctions between contiguous P and N zones in order from right to left are denoted J1, J2 and J3. The end P zone functions as an anode and the end N zone functions as a cathode. Connected by ohmic contact to the intermediate P zone is a gate conductor denoted GATE. With the anode connected to the positive terminal of a suitable source and the cathode connected to the negative terminal, forward conduction through the PNPN silicon controlled rectifier can be initiated by supplying a firing pulse of current to the gate contact to switch the device from the blocking state to the conducting state. During its normal conducting state the forward current is in the direction of the arrow designated *If* and the distribution of injected minority carrier concentration in the forward direction in the four zones is represented by the solid line curves 2, 3, 4 and 5. The P equilibrium value in the internal N zone is represented by the horizontal line 6 and the N equilibrium value in the internal P zone is represented by the horizontal line 7.

Conventional practice in turning off the silicon controlled rectifier has been to apply a negative bias voltage or in other words to reverse the polarity of the voltage supplied to the anode and cathode. When this reverse voltage is applied, the holes and electrons in the vicinity of the two end junctions J1 and J3 (FIG. 1) diffuse to these junctions and produce a reverse (recovery) current in the external circuit that is represented by the arrow designated *Ir*. The directions of movement of the injected minority carriers in the intermediate P and N zones during this process of removal from the end junctions is represented by the arrows in the shaded areas. Within one or two microseconds after the application of the reverse voltage this reverse current *Ir* sweeps the injected minority carriers from the end junctions J1 and J3. The carrier distribution in the intermediate N zone is then represented by the broken line curve 8 and the carrier distribution in the intermediate P zone is represented by the broken line curve 9. Thus, as indicated by these carrier distribution curves the concentration of injected carriers at the end junctions J1 and J3 is reduced to the equilibrium value. This is accomplished within a few microseconds of the application of reverse bias

voltage and these junctions then assume a blocking state. Recovery of the silicon controlled rectifier is not complete, however, because there is still a high concentration of injected minority carriers in the vicinity of the middle junction J2. All these carriers represented by the shaded areas under curves 8 and 9 must disappear by recombination because the reverse (recovery) current ceases when injected minority carriers are swept out of the end junctions J1 and J3 and the carrier distribution at these junctions attains equilibrium value. After the hole and electron distribution at junction J2 has decreased to a low value as a result of the recombination process, this junction regains its blocking state and a forward voltage may be applied to the silicon controlled rectifier without causing it to turn on. However, this recombination process takes a relatively long time, e.g., between 10 and 200 microseconds and this makes the turnoff time correspondingly long. In certain applications, such for example as high frequency inverters a long turnoff time is disadvantageous.

The present invention greatly reduces the turnoff time, e.g., it reduces it to the order of one or two microseconds. In the embodiment of this invention that is diagrammatically represented in FIG. 2, the four zone semiconductor device **10** has an intermediate P zone **11** and an intermediate N zone **12**. These zones and the junction between them may be formed from a wafer of silicon by any suitable method such, for example, as precision gaseous diffusion techniques. In a fairly typical device the thickness of this wafer may be approximately 10 mils and its diameter may be in the neighborhood of 1.5 centimeters. On a portion of the flat outer surface of the P zone **11** is formed a zone **13** of N type conductivity, and on a portion of the parallel outer surface of the intermediate N zone **12** in register with the opposite end N zone **13**, there is disposed an auxiliary zone **14** of N type conductivity. Zones **13** and **14** may be formed of any suitable material and in any appropriate manner, e.g., they may be formed of gold foil plus antimony and may be formed on the surfaces of zones **11** and **12** by alloying the gold foil plus antimony strip into the surfaces of the silicon wafer or by any other suitable method. These zones **13** and **14** may also be formed by gaseous diffusion and masking techniques or by the vapor deposition method that is known in the art as the epitaxial process.

On another portion of the flat outer surface of P zone **11** is formed an auxiliary zone **15** of P type conductivity; similarly on the exposed lower surface of N zone **12** is formed a zone **16** of P type conductivity in register with the auxiliary P zone **15**. Consequently, as is shown in FIG. 2, the end P zone **16** of my invention is laterally offset with respect to the end N zone **13**. The P zones **15** and **16** may be formed in any suitable manner. For example, they may be formed by alloying aluminum strip into the exterior surfaces of the silicon wafer, i.e., zones **11** and **12** or by utilizing diffusion and masking or epitaxial processes. A gate conductor, designated GATE is connected to the P conductivity type zone **11**. In some cases with the use of appropriate circuitry the auxiliary P zone **15** may be used as the gate contact.

The zones **16**, **12**, **11** and **13** constitute a four zone PNPN semiconductor device and together with the gate constitute a silicon controlled rectifier of which the end P type conductivity zone **16** constitutes the anode and the end N type conductivity zone **13** constitutes the cathode. This rectifier has three alternately poled rectifying junctions J1, J2 and J3 in series between anode and cathode. For conduction in the forward direction, the anode **16** is connected to the positive terminal of a supply source **17** and the cathode **13** is connected through a load **18** to the negative terminal of the source, whereby forward voltage is supplied to the terminal zones of the rectifier. Conduction of main or load current by the PNPN silicon controlled rectifier is initiated by supplying a firing pulse of current to the GATE. For this purpose, as is well known in the art, suitable external triggering means (not shown) can be connected between the intermediate P zone **11** and the cathode **13**. Due to the laterally offset arrangement of the anode **16** and the cathode **13**, the main current conduction takes place in a diagonal direction through the silicon controlled rectifier from the anode **16** at the lower right hand corner of the device through N type zone **12**, P type zone **11** to the cathode **13** in the upper left hand corner of the device This forward current traverses an appreciable area in the midsection of the middle NP junction J2 of the device **10** in the direction generally indicated by the arrow *If*.

The auxiliary N type zone **14**, N type zone **12**, P type zone **11** and auxiliary P type zone **15** constitute a PPNN semiconductor device which in practical effect is a PN diode having a single rectifying junction J2 in common with the middle junction J2 of the PNPN device. The auxiliary zones **14** and **15** have been so arranged that this PPNN diode device provides an auxiliary conducting path along a diagonal that crosses the diagonal main conducting path of the PNPN device. In this diode device the auxiliary N type zone **14** and the auxiliary P type zone **15** serve as turnoff electrodes having terminals which may be connected through an external diode rectifier **19** and the conductor **20** to a suitable source of direct voltage that is represented by supply terminals **21**. A suitable switching device **22** is included in these connections.

As shown, the diode rectifier **19** in the external circuit is connected to conduct in the direction of reverse current through the PN diode **15**, **11**, **12**, **14**. This reverse current is represented by the arrow Ic. It will be noted that both the auxiliary current Ic, which flows in a reverse sense between the P and N auxiliary electrodes **15** and **14** of the diode rectifier, and the main current *If*, which flows in a forward sense between the anode **16** and the cathode **13** of the PNPN device, pass through the common junction J2 from zone **12** to zone **11** in the same electrical direction but on cross diagonal paths, with the auxiliary current crossing the main current over the whole area of J2 that is traversed by the latter. Typically, the voltage source **17** for the PNPN silicon controlled rectifier may be in the neighborhood of 400 volts whereas the voltage of source **21** for the PPNN diode device may be a very much lower value.

To turn on the PNPN silicon controlled rectifier **10** with forward bias voltage being supplied from the source **17** through the load to the anode **16** and cathode **13**, a pulse of firing current is supplied to the GATE from external triggering means. This causes the PNPN path to switch from its high impedance to its low impedance state and to become conducting in the forward direction with the result that forward current is supplied to the load **18**. During conduction in the forward direction the distribution of injected carriers in the individual P-N-P-N zones **16**, **12**, **11** and **13** respectively is represented in the concentration diagram in FIG. 3 by the solid line curves **23**, **24**, **25** and **26** respectively. A comparison of FIG. 3 and FIG. 1 indicates that the concentration distribution of injected carriers during normal main current conduction in the forward direction is essentially the same as in the case of the conventional silicon controlled rectifier.

To turn off the PNPN silicon controlled rectifier **10**, i.e., to enable the PNPN path through zones **16**, **12**, **11** and **13** to regain forward blocking ability, the switching device **22** is closed to apply a reverse bias voltage across the PPNN diode **15**, **11**, **12**, **14**. This immediately results in an auxiliary current Ic in the diagonal diode path having the same electrical direction across the middle junction J2 as the main current *If* then flowing in the PNPN silicon controlled rectifier path. The current Ic, which is a reverse current in the diode path, effects a net removal of the injected minority carriers

from the NP junction J2. The directions of movement of the carriers in this removal process from the middle junction are represented by the arrows **27** in the shaded areas of the intermediate P and N zones in FIG. 3. As shown, the directions are oposite to the directions represented by the arrows in FIG. 1 produced by the conventional turnoff method. Within a period of approximately one microsecond after initiation of turnoff, the carriers are swept out of the middle junction J2 and the concentration in the intermediate P and N zones **11** and **12** is represented by the broken line curves **28** and **29**. As indicated by these curves the concentration at the middle junction is reduced to the equilibrium values on both sides of this junction and this prepares the junction to regain its blocking ability. However, at this instant recovery of the PNPN silicon controlled rectifier is not complete owing to the concentration of carriers at the end junctions J1 and J3 as represented by broken line curves **28** and **29**. Consequently, the auxiliary current Ic, which is the recovery current for the junction J2, continues until these carriers are all removed and then terminates. Upon termination of the auxiliary current the junction J2 regains its blocking state. Recovery of the PNPN silicon controlled rectifier **16, 12, 11** and **13** is now complete, and main current conduction will not resume even though the device remains connected to the forward voltage source **17**. The time required from initiation of the auxiliary current in the PPNN diode until complete turnoff and recovery of the PNPN silicon controlled rectifier is complete is of the order of a few microseconds.

The auxiliary current Ic required to reduce the injected carriers in the intermediate P and N zones **11** and **12** to equilibrium is very considerably smaller than the forward current If of the silicon controlled rectifier. Consequently, a high value forward current can be interrupted by a low value current pulse. For example, a forward current of 200 amperes can be interrupted by a low value current pulse of 20 amperes.

In the form that is illustrated in FIG. 4 the end N type conductivity zone **13** of the PNPN semiconductor device and the additional P type conductivity zone **15** of the PPNN diode device have the form of parallel, closely spaced rectilinear strips that are located on opposite sides of an axis generally perpendicular to the NP junction of the internal zones **12** and **11** of the device; the end P type conductivity zone **16** (anode) and the additional N type conductivity zone **14** will have the same form.

In the modification that is illustrated in FIG. 5 the end N type conductivity zone **13** (cathode) of the PNPN device has the form of an annulus and the additional end P type conductivity zone **15** of the PPNN device has the form of a circular disk within the annulus **13**. Similarly, the additional end N type conductivity zone **14** has the form of an annulus disposed in register with the cathode **13**, and the end P type conductivity zone **16** (anode) has the form of a coaxial disk within the annulus.

In this modification main current traverses a predetermined annular area of the middle junction J2 of the PNPN silicon controlled rectifier device in the direction represented by the arrows If. The reverse current of the PPNN diode path takes place in the same electrical direction across the same annular area of the common middle junction J2 on a cross diagonal axis as indicated by the arrow Ic. Instead of being in the form of disks the zones **15** and **16** may be in the form of rings as illustrated in the modification of FIG. 6. The operation of the modifications illustrated in FIGS. 5 and 6 is the same as described in connection with FIG. 2.

The device may also be utilized in present inverter circuits in which turnoff in each cycle is effected by applying a reverse bias voltage to the anode and cathode.

When thus used a constant D.-C. bias voltage will be applied to the diode electrodes **14** and **15**. In this case, owing to the reverse bias voltage applied to the anode and cathode the turnoff is in accordance with the process herein described and referred to as the conventional process. However, the turnoff time will be reduced to the range of 5–10 microseconds or less.

The device may also be used, with appropriate circuitry, as a square wave generator. For this purpose, an adjustable impedance **23** is included in series relationship in the PPNN diode circuit. By adjusting this impedance the current Ic may be adjusted to a value less than the critical value required to effect complete turnoff action. As a result, refiring of the device occurs after interruption of the forward current and this procedure is repeated continuously to provide continuous oscillation.

Alterations and modifications will readily suggest themselves to persons skilled in the art without departing from the true spirit of this invention or from the scope of the annexed claims.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. A semiconductor translating device comprising:

(a) a circular semiconductor single crystal silicon wafer having a main P type conductivity zone and a contiguous main N type conductivity zone in flat face to flat face contact,

(b) the exterior flat face of each of said main zones being provided with a radially centrally disposed zone of one type conductivity and a surrounding concentric annular zone of the opposite type conductivity to constitute

(1) a PNPN semiconductor device with the terminal P and N zones constituting an anode and a cathode respectively and

(2) a PPNN semiconductor device having terminal electrodes and a PN junction in common with the middle junction of said PNPN semiconductor device,

(c) one of said main zones of said PNPN device being provided with means for receiving a pulse of firing current to initiate conduction through said PNPN device, and

(d) means for supplying a voltage to said terminal electrodes of said PPNN device to cause a reverse current through said PPNN device when said PNPN device is conducting to remove injected carriers from said common junction to terminate conduction through said PNPN device.

2. A semiconductor translating device comprising:

(a) a semiconductor body including four zones arranged in succession with contiguous zones of opposite conductivity type to constitute a PNPN semiconductor device having three PN junctions disposed in generally parallel planes and having an axis that is perpendicular to all of said planes, with the end P and N zones of said PNPN device being respectively located on opposite sides of said axis,

(b) the intermediate P zone of said PNPN device being provided with means to receive firing current to turn on said PNPN device,

(c) the intermediate P and N zones of said PNPN device each being provided with a turnoff electrode on the opposite side of said axis from the corresponding end zone of said PNPN device thereby to provide a diode rectifier having a single rectifying junction that is in common with the middle PN junction of said PNPN device and having a conducting path that crosses the conducting path between the end zones of said PNPN device and

(d) said turnoff electrodes being adapted to receive a voltage having a polarity to cause a reverse current through said diode when said PNPN device is conducting to remove injected carriers from said common junction thereby to turn off said PNPN device.

3. A semiconductor translating device comprising:
(a) a semiconductor body having a wafer-like zone of P type conductivity and a contiguous wafer-like zone of N type conductivity in flat face to flat face contact to form an internal PN junction therebetween, said body having an axis of symmetry that is generally perpendicular to said junction,
(b) each of said zones having an exterior flat face disposed parallel to said internal PN junction and provided with two parallel strip zones of opposite conductivity types with the P type strip zones arranged on one side of said axis and the N type strip zones arranged on the opposite side of said axis thereby to constitute
(1) a PNPN semiconductor device and
(2) a PN diode provided with P and N type conductivity turnoff electrodes and having a PN junction in common with said internal junction of said PNPN device and a conducting path that crosses the conducting path of said PNPN device,
(c) one of the zones of said PNPN device being provided with means for receiving a pulse of firing current to initiate conduction through said PNPN device, and
(d) terminals connected to said turnoff electrodes and adapted to be connected to a source for supplying to said turnoff electrodes a voltage having a polarity for causing a reverse current through said diode to remove injected carriers from said common junction to effect turnoff of said PNPN device.

4. A semiconductor translating device comprising:
(a) a circular semiconductor body having a wafer-like P type conductivity zone and a contiguous wafer-like zone of N type conductivity in flat face to flat face contact,
(b) the exterior flat face of both of said zones being provided with an inner annular zone of one type conductivity and an outer concentric zone of the opposite type conductivity thereby to constitute
(1) a PNPN semiconductor device and
(2) a PN diode device having turnoff electrodes and having a PN junction in common with the middle junction of said PNPN device and a conducting path that crosses the conducting path of said PNPN device
(c) said wafer-like P zone of said PNPN device being provided with means for receiving a pulse of firing current to initiate conduction through said PNPN device, and
(d) terminals connected to said turnoff electrodes and adapted to be connected to a source for supplying to said turnoff electrodes a voltage having a polarity to cause reverse current through said diode to remove injected carriers from said middle junction to effect turnoff of said PNPN device.

5. A semiconductor rectifier comprising:
(a) a semiconductor body having a wafer-like zone of P type conductivity and a contiguous wafer-like zone of N type conductivity in face-to-face contact to form an internal PN junction therebetween, said P zone and said contiguous N zone respectively having outer surfaces that are generally flat and parallel to each other;
(b) a first portion of the outer surface of said P zone being provided with an end zone of N type conductivity and a first portion of the outer surface of said contiguous N zone being provided with an end zone of P type conductivity to form a PNPN semiconductor device, with the end P zone and the end N zone constituting main electrodes of said PNPN device;
(c) means connected across at least one of the PN junctions of said PNPN device for initiating main current conduction through said PNPN device;

(d) a second portion of said outer surface of the first-mentioned P zone being provided with a first auxiliary electrode and a second portion of said outer surface of the contiguous N zone being provided with a second auxiliary electrode to form a PN diode whose PN junction is in common with the internal PN junction of said PNPN device, said PN diode providing between said auxiliary electrodes a conducting path for auxiliary current that crosses the main current in said PNPN device; and
(e) means connected to said auxiliary electrodes for initiating auxiliary current conduction in a reverse direction through said PN diode to remove injected carriers from said common middle junction to effect turnoff of said PNPN device.

6. The rectifier of claim 5 in which said end N zone is laterally offset with respect to said end P zone and in register with said second auxiliary electrode, and in which said first auxiliary electrode is laterally offset with respect to said second auxiliary electrode and in register with said end P zone.

7. For use in combination with a load current circuit, a firing current circuit, and a turnoff current circuit, a semiconductor translating device comprising:
(a) a semiconductor body including four zones arranged in succession with contiguous zones being of opposite conductivity types to provide a PNPN semiconductor device having a PN junction, an NP junction, and another PN junction in series between the terminal P and N zones thereof;
(b) means for serially connecting said terminal P and N zones in the load current circuit, whereby load current can flow in a forward direction between said terminal P zone and said terminal N zone when the PNPN device is turned on;
(c) means for interconnecting one of said four zones of said body and the firing current circuit to supply a firing current to turn on the PNPN device;
(d) a pair of auxiliary electrodes respectively connected to the intermediate P and N zones of said body to provide therewith a diode rectifier having a single rectifying junction that is in common with said NP junction of the PNPN device, said auxiliary electrodes being so arranged that reverse current therebetween crosses said load current over the whole NP junction area that is traversed by said load current; and
(e) means for serially connecting said auxiliary electrodes in the turnoff current circuit, the latter means being so arranged that the turnoff current will flow in a reverse direction through said diode rectifier to remove injected carriers from said common NP junction to effect turnoff of the PNPN device.

8. The semiconductor translating device of claim 7 in which the means for interconnecting one of said four zones of said body and the firing current circuit comprises a gate contact connected to the intermediate P zone of said body.

9. For use in combination with a first voltage source having relatively positive and negative terminals and a second voltage source having relatively positive and negative terminals, a semiconductor translating device comprising:
(a) a semiconductor body including four zones arranged in succession with contiguous zones being of opposite conductivity types to provide a three-junction PNPN semiconductor device, the terminal P and N zones of said body, respectively constituting anode and cathode of the device, being laterally offset with respect to each other;
(b) means for connecting said anode to a positive terminal of the first voltage source and said cathode to a negative terminal of the first voltage source;

(c) first and second turnoff electrodes respectively connected to the intermediate P and N zones of said body to provide therewith a diode rectifier having a PN rectifying junction in common with the middle junction of the PNPN device, said first turnoff electrode being formed by P type conductivity material and being disposed in register with said anode, and said second turnoff electrode being formed by N type conductivity material and being disposed in register with said cathode; and

(d) means for connecting said first turnoff electrode to a negative terminal of the second voltage source and said second turnoff electrode to a positive terminal of the second voltage source to cause a reverse current through said diode rectifier thereby to remove injected carriers from said common middle junction to effect turnoff action of the PNPN device.

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