1319796

PATENT SPECIFICATION (11) 1319796

DRAWINGS ATTACHED

(21) Application No. 57663/70 (22) Filed 4 Dec. 1970

(31) Convention Application No. 883897 (32) Filed 10 Dec. 1969 in

(33) United States of America (US)

(44) Complete Specification published 6 June 1973

(51) International Classification H01L 9/10

(52) Index at acceptance

H1K 211 212 238 288 312 577 578 579 581 583 584

(72) Inventor TOSHIO MISAWA

(19)



(54) IMPROVEMENTS IN OR RELATING TO AVALANCHE DIODES

(71) We, WESTERN ELECTRIC COMPANY, INCORPORATED, of 195 Broadway, New York City, New York State, United States of America, a Corporation organised and existing under the laws of the 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 to avalanche diodes.

United States Patent No. 2,899,652, describes how a multi-layer avalanche diode, now known as the Read diode, can be made to present a negative resistance, and, when placed in a suitable resonant circuit, generate microwave oscillations. An applied direct-current voltage periodically biases a p-n junction to avalanche breakdown, thereby creating current pulses each of which travels across a transit region within a prescribed time period. This transit time is arranged with respect to the resonant frequency of the external resonator such that radio-frequency voltages at the diode terminals are not of phase with current pulses in the diode. With an appropriately designed phase shift, the current through the terminals increases as the voltage across the terminals decreases, thus establishing a negative resistance. Ultimately, part of the direct-current energy applied to the diode is converted to radio-frequency energy in the resonator.

The Read diode is one of a class of diodes now generally known as IMPATT diodes (*im*pact *a*valanche and *t*ransit *t*ime), and is a 4-layer structure such as a p+nin+ configuration, in which the p-n junction is reverse-biased to avalanche. The *n* region is thin with respect to the *i* layer so that the current pulse will be well confined as is desirable for high efficiency. Best efficiency is obtained if the current density in the current pulse is high and if the current is 180 degrees out of phase with the external voltage. The complementary configuration, a n+pip+ structure, operates the same way.

While Read diodes have been operated successfully, their efficiency has been lower than predicted. We have discovered that the major cause of this inefficiency is "back-diffusion" of majority carriers in the current pulse, which occurs before it has drifted through the intrinsic or i-layer. Electrons of the current pulse tend to diffuse across the p-n junction and are trapped, i.e. accumulated, in the p+ layer when the remainder of the current pulse is transmitted through the transit region. These trapped carriers then diffuse back across the p-n junction and reduce the time for formation of the succeeding current pulse; this disrupts the synchronism of the current pulse with the external voltage.

According to this invention an avalanche diode comprises in succession between first and second contacts a rectifying junction, an avalanche region of high conductivity, and a transit region of low conductivity, said diode being such that when said junction is reverse-biased to avalanche breakdown a concentration of avalanche region majority charge carriers travels through said transit region to said second contact, and said diode being so constructed that, in operation, substantially no accumulation of avalanche region majority charge carriers occurs between said first contact and said junction.

In one embodiment of the invention said junction is formed with said avalanche region by a first semiconductor layer, and there is provided a second semiconductor layer between said first contact and said first layer, said first layer being of substantially lower conductivity than said second layer, whereby when, in operation, said diode is reverse-biased a substantial electric field extends through said first layer to substantially prevent accumulation of avalanche region majority charge carriers in said first layer. This electric field prevents carriers from being trapped or accumulated in the first layer, and instead, forces them towards the second contact. By making the first layer

thicker than the diffusion length of an avalanche region majority carrier, diffusion to the second layer is substantially precluded.

In another embodiment of the invention said first contact and said junction are constituted by a metal contact forming a Schottky barrier junction with said avalanche region. It is characteristic of a Schottky barrier that electron diffusion from the metal contact across the junction is substantially prohibited. Also, metal cannot trap electrons since it conducts electrons freely.

The invention will now be described with reference to the accompanying drawings which is not necessarily to scale and in which:

FIG. 1 shows a conventional Read diode in an oscillator circuit,

FIG. 1A is a graph of electric field distribution at one instant of time in the Read diode of FIG. 1;

FIG. 2 is a schematic illustration of a diode in accordance with the invention;

FIG. 2A is a graph of electric field distribution at one instant of time in the diode of FIG. 2; and

FIG. 3 is a schematic illustration of another diode in accordance with the invention.

Referring now to FIG. 1, an oscillator circuit comprises a Read diode 11, an inductance 12, a capacitance 13, a bias source 14, and a load 15. As shown, the Read diode 11 comprises a wafer having successive layers 16, 17, 18, 19 of p+, n, i, and n+ conductivity, respectively. The diode is located in the microwave resonator schematically represented by inductance 12 and capacitance 13. The rectifying p-n junction between the layers 16 and 17 is reverse-biased by voltage source 14. The oscillator circuit generates microwave oscillations that are transmitted for utilisation to load 15.

Curve 21 of FIG. 1A shows the distribution of electric field with respect to distance in diode 11. When the reverse-bias voltage is initially applied, the electric field is sufficiently high at the p-n junction between layers 16 and 17 to cause avalanche breakdown. This in turn forms a concentration of majority carrier electrons in layer 17 which drifts as a current pulse across intrinsic layer 18 to the positive diode contact. The frequency of the external microwave resonator is arranged with respect to the transit time of the current pulse and the time taken for current pulse formation such that the current in the diode is 180° out of phase with respect to the external diode voltage applied by the resonator. As the current pulse drifts across the transit region defined by the intrinsic layer 18, the electric field at the p-n junction falls below the avalanche breakdown value. After the current pulse has reached the positive contact, the electric field at the p-n junction again reaches the avalanche breakdown value to form another current pulse, and the process repeats itself.

The *n* layer 17 is made thin with respect to the transit region defined by layer 18 to give a confined avalanche breakdown as is indicated in FIG. 1A, with a resulting confined current pulse of high current density. In theory, this permits the diode to be designed to give a 180° phase shift between the current pulse and the external voltage for maximum negative resistance and efficiency, but in practice it has been known for a number of years that the diode of FIG. 1 is incapable of generating a microwave output with efficiencies approaching those predicted by theory.

Any high density current concentration in a semiconductor tends to diffuse in both directions from the centre of the concentration. In the device of FIG. 1, even though the electric field attracts the current pulse as a unit toward the positive contact, there is a significant diffusion current in the direction of the negative contact across the p-n junction. As shown in FIG. 1A, there is substantially no electric field in the p+ layer 16 because of the high conductivity of that layer. Thus, electrons that may diffuse into layer 16 are trapped or accumulated there because they are not influenced by any substantial electric field.

After the current pulse has moved into the layer 18 towards the positive contact, electrons in layer 16 tend to diffuse again across the p-n junction back into layer 17. These electrons reduce the time required for formation of the succeeding current pulse and thereby reduce device efficiency.

Referring now to FIG. 2, a diode 23 that may be used in the circuit of FIG. 1 comprises layers 24, 25, 26, 27 and 28 of p+, p, n, *i* and n+ conductivity, respectively. The diode differs from diode 11 essentially in the inclusion of the *p* layer 25 between p+ layer 24 and *n* layer 26. The p+ layer 24 permits a good ohmic contact to be made to the wafer, while *p* layer 25 ensures the formation of a significant electric field between the p+ layer 24 and the p-n junction of layers 25 and 26.

The curve 29 of FIG. 2A shows the electric field established in diode 23 at the time of initial avalanche breakdown at the p-n junction. Because of the relatively lower conductivity of the *p* layer 25, the electric field extends through the *p* layer rather than dropping precipitously at the p-n junction as in FIG. 1A. A highly concentrated current pulse is formed in the n-type layer 26 and the diode operation is essentially the same as that in FIG. 1. However, electrons that diffuse across the p-n junction into layer 25 are not trapped or accumulated because they remain under the influence of the electric field. As

such, they are attracted toward the positive contact immediately and will not interfere with the formation of a subsequent current pulse. Thus, just prior to the formation of the succeeding avalanche breakdown at the p-n junction, *n* layer 26 will be a "swept out" or depleted region which is free of majority carrier electrons.

A diode may typically be formed by epitaxial or diffused layers formed on a silicon substrate. Typical dimensions may be as follows:

p+ layer— .5 microns;
p layer— .4 microns;
n layer— .6 microns;
i layer—4 microns; and
n+ layer (substrate)—50 microns.

The conductivities of the layers in carriers per cm^3 may be as follows:

p+ layer—10^{20};
p layer— 6×10^{15}
n layer— 3×10^{16};
i layer—less than 10^{15}; and
n+ layer—10^{20}.

Complementary silicon diodes with opposite conductivity types may be made with substantially the same dimensions and carrier concentrations as given above, that is, the diode may be of the form n+npip+. The diode could also be made of other well known semiconductor materials such as germanium, and could be modified in various other ways as will be apparent to those skilled in the art.

Another diode is illustrated in FIG. 3 in which the semiconductor wafer of the diode comprises layers 32, 33 and 34, of n, i and n+ conductivity, respectively. Positive contact 35 is the usual ohmic contact, but contact 36 forms a Schottky barrier 37 with the *n* layer 32. Junction 37 is reverse-biased by an external voltage to the avalanche breakdown value.

Back-diffusion of electrons across the junction 37 occurs as in the diode in FIG. 1 except that the metal contact 36 is incapable of trapping or accumulating the electrons. Free electrons do not affect the atomic equilibrium of metal, and, after the current pulse leaves layer 32 in its transit across layers 33 and 34, no substantial diffusion across junction 37 can occur as a result of stored electrons in the metal contact 36. Hence, if the Schottky barrier junction 37 is well made with a minimum of "leakage", the *n* layer 32 can be substantially depleted of electrons prior to the formation of the succeeding current pulse and the diode is capable of operating with high efficiency.

WHAT WE CLAIM IS:—

1. An avalanche diode comprises in succession between first and second contacts a rectifying junction, an avalanche region of high conductivity, and a transit region of low conductivity, said diode being such that when said junction is reverse-biased to avalanche breakdown a concentration of avalanche region majority charge carriers travels through said transit region to said second contact, and said diode being so constructed that, in operation, substantially no accumulation of avalanche region majority charge carriers occurs between said first contact and said junction.

2. A diode as claimed in claim 1 wherein said junction is formed with said avalanche region by a first semiconductor layer, and there is provided a second semiconductor layer between said first contact and said first layer, said first layer being of substantially lower conductivity than said second layer, whereby when, in operation, said diode is reverse-biased a substantial electric field extends through said first layer to substantially prevent accumulation of avalanche region majority charge carriers in said first layer.

3. A diode as claimed in claim 2 wherein said first layer is thicker than the diffusion length of an avalanche region majority charge carrier.

4. A diode as claimed in claim 1 wherein said first contact and said junction are constituted by a metal contact forming a Schottky barrier junction with said avalanche region.

5. An avalanche diode substantially as herein described with reference to FIG. 2 or FIG. 3 of the accompanying drawing.

6. A microwave oscillator arrangement including a diode as claimed in any one preceding claims, a d.c. bias source for reverse-biasing said diode to avalanche breakdown, and a resonant circuit so coupled to said diode and of resonant frequency such that, in operation, energy from said source is converted to r.f. energy.

C. S. T. BUCKLEY,
Chartered Patent Agent,
5 Mornington Road,
Woodford Green,
Essex.
Agent for the Applicants.

Printed for Her Majesty's Stationery Office, by the Courier Press, Leamington Spa, 1973.
Published by The Patent Office, 25 Southampton Buildings, London, WC2A 1AY, from which copies may be obtained.

such, they are attracted toward the positive contact immediately and will not interfere with the formation of a subsequent current pulse. Thus, just prior to the formation of the succeeding avalanche breakdown at the p-n junction, *n* layer 26 will be a "swept out" or depleted region which is free of majority carrier electrons.

A diode may typically be formed by epitaxial or diffused layers formed on a silicon substrate. Typical dimensions may be as follows:

p+ layer— .5 microns;
p layer— .4 microns;
n layer— .6 microns;
i layer—4 microns; and
n+ layer (substrate)—50 microns.

The conductivities of the layers in carriers per cm^3 may be as follows:

p+ layer—10^{20};
p layer— 6×10^{16}
n layer— 3×10^{16};
i layer—less than 10^{15}; and
n+ layer—10^{20}.

Complementary silicon diodes with opposite conductivity types may be made with substantially the same dimensions and carrier concentrations as given above, that is, the diode may be of the form n+npip+. The diode could also be made of other well known semiconductor materials such as germanium, and could be modified in various other ways as will be apparent to those skilled in the art.

Another diode is illustrated in FIG. 3 in which the semiconductor wafer of the diode comprises layers 32, 33 and 34, of n, i and n+ conductivity, respectively. Positive contact 35 is the usual ohmic contact, but contact 36 forms a Schottky barrier 37 with the *n* layer 32. Junction 37 is reverse-biased by an external voltage to the avalanche breakdown value.

Back-diffusion of electrons across the junction 37 occurs as in the diode in FIG. 1 except that the metal contact 36 is incapable of trapping or accumulating the electrons. Free electrons do not affect the atomic equilibrium of metal, and, after the current pulse leaves layer 32 in its transit across layers 33 and 34, no substantial diffusion across junction 37 can occur as a result of stored electrons in the metal contact 36. Hence, if the Schottky barrier junction 37 is well made with a minimum of "leakage", the *n* layer 32 can be substantially depleted of electrons prior to the formation of the succeeding current pulse and the diode is capable of operating with high efficiency.

WHAT WE CLAIM IS:—

1. An avalanche diode comprises in succession between first and second contacts a rectifying junction, an avalanche region of high conductivity, and a transit region of low conductivity, said diode being such that when said junction is reverse-biased to avalanche breakdown a concentration of avalanche region majority charge carriers travels through said transit region to said second contact, and said diode being so constructed that, in operation, substantially no accumulation of avalanche region majority charge carriers occurs between said first contact and said junction.

2. A diode as claimed in claim 1 wherein said junction is formed with said avalanche region by a first semiconductor layer, and there is provided a second semiconductor layer between said first contact and said first layer, said first layer being of substantially lower conductivity than said second layer, whereby when, in operation, said diode is reverse-biased a substantial electric field extends through said first layer to substantially prevent accumulation of avalanche region majority charge carriers in said first layer.

3. A diode as claimed in claim 2 wherein said first layer is thicker than the diffusion length of an avalanche region majority charge carrier.

4. A diode as claimed in claim 1 wherein said first contact and said junction are constituted by a metal contact forming a Schottky barrier junction with said avalanche region.

5. An avalanche diode substantially as herein described with reference to FIG. 2 or FIG. 3 of the accompanying drawing.

6. A microwave oscillator arrangement including a diode as claimed in any one preceding claims, a d.c. bias source for reverse-biasing said diode to avalanche breakdown, and a resonant circuit so coupled to said diode and of resonant frequency such that, in operation, energy from said source is converted to r.f. energy.

C. S. T. BUCKLEY,
Chartered Patent Agent,
5 Mornington Road,
Woodford Green,
Essex.
Agent for the Applicants.

Printed for Her Majesty's Stationery Office, by the Courier Press, Leamington Spa, 1973.
Published by The Patent Office, 25 Southampton Buildings, London, WC2A 1AY, from which copies may be obtained.

