

PATENT SPECIFICATION

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(54) IMPROVEMENTS IN OR RELATING TO SEMICONDUCTOR DEVICES

(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 multilayer 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 r-f voltages at the diode terminals are out 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 d-c energy applied to the diode is converted to r-f energy in the resonator.

Improved microwave oscillator avalanche diodes now known as IMPATT diodes, are described in "The IMPATT Diode—A Solid State Microwave Generator", *Bell Labs. Record*, by K. D. Smith, Vol. 45, May 1967, page 144; "Microwave Si Avalanche Diode with Nearly Abrupt Type Junction", by T. Misawa, *IEEE Transactions on Electron Devices*, Vol. ED-14, September 1967, page 580; and United Kingdom Patent No.

1,142,585. Whereas the Read diode is a 4-layer device, the later IMPATT diode is typically a n+vn or n+np+ diode with only three layers. The newer IMPATT diodes are usually capable of higher efficiency than IMPATT diodes of the Read configuration.

United States patent no. 3,624,557 describes how even higher efficiencies can be achieved by using an IMPATT diode in a cavity resonator having a resonance at the normal IMPATT frequency f_i and also a high Q resonance at an output frequency f_i/n , where n is an integral number. This mode of oscillator operation is known as the TRAPATT mode (*trapped plasma avalanche triggered transit*).

U.K. patent no. 1,123,389 discloses a semiconductor device comprising a semiconductor wafer between an ohmic contact and a Schottky barrier contact.

Avalanche diode continuous-wave power output is limited mainly by the heat generated. As the frequency of operation is increased, wafer diameter must invariably decrease, the wafer becomes more susceptible to heating, and power capacities are reduced. Efficiency is also a prime consideration, and, to reduce series resistance, the contacts to the diode are usually ohmic contacts. To make an ohmic or non-rectifying contact, it is generally necessary to use a high conductivity semiconductor in a transition region between the metal contact and the lower conductivity active region of the diode.

According to this invention an avalanche diode comprises a wafer of semiconductor material between a pair of contacts each forming a Schottky barrier junction with said wafer, said diode being such that when reverse-biased to avalanche breakdown current passes from one to the other of said contacts.

A Schottky barrier contact is a contact of metal to semiconductor which forms a rectify-

ing barrier or junction, as opposed to an ohmic or non-rectifying contact. In the diode of the invention the entire semiconductor wafer between the contacts constitutes the active, or current transit, region. The diode may be used with virtually the same external circuitry as conventional diodes.

5 A direct-current bias across the diode reverse-biases one of the Schottky barrier junctions, called herein the front contact, and forward-biases the other, called the rear contact. In operation the front contact is reverse-biased beyond avalanche and a current pulse is formed which travels across the wafer transit region within a prescribed time period. The rear contact is, of course, a rectifying contact rather than an ohmic contact but both experiment and theory have shown that this does not appreciably increase the series resistance of the diode and thus the efficiency of the device is comparable to that of conventional negative resistance avalanche diodes. Studies indicate that the diode can be used in various circuits to give a number of desired modes of operation such as the TRAPATT mode.

20 The invention permits the use of bulk semiconductors of constant conductivity, rather than requiring epitaxial layers, or diffused or ion implanted p-n junctions. This ideally permits the use of semiconductors such as diamond which are desirably high in thermal conductivity but in which p-n junctions cannot readily be formed and to which it is difficult or impossible to form an ohmic contact. It also offers obvious advantages of convenience of fabrication and control of both the thickness and impurity density of the wafer. Also it permits heat to be extracted from both sides of the active semiconductor region, the thermal path to both metal contacts being reduced to a minimum.

The invention will now be described with reference to the accompanying drawing in which:

45 Fig. 1 is a schematic diagram of a negative resistance avalanche diode oscillator, and

Fig. 2 shows in cross-section the negative resistance avalanche diode used in the circuit of Fig. 1.

50 Referring now to Fig. 1, the oscillator circuit comprises a negative resistance avalanche diode 11 connected to an inductance 12, a capacitance 13, a battery 14, and a load 15. The inductance 12 and capacitance 13 together constitute a resonant circuit which establishes an output frequency to be generated by the diode 11 and delivered to the load 15. A radio-frequency choke 16 isolates battery 14 from the high frequency output current.

60 The diode 11 operates as an IMPATT diode, that is, a rectifying junction in the diode is reverse-biased by battery 14 to avalanche breakdown, thus creating a current pulse which travels across a semiconductor transit region within a prescribed time period.

After the current pulse has completed its transit, the junction again is biased to avalanche breakdown, another current pulse is formed and the process repeats itself. The transit time is arranged with respect to the resonant frequency of the external resonator such that radio-frequency voltages at the diode terminals are out of phase with the current pulses in the diode. This establishes a negative resistance so that direct-current energy from battery 14 can be converted to radio-frequency energy, as is required in any oscillator.

70 As shown more clearly in Fig. 2, the diode 11 comprises a wafer 18 of bulk semiconductor material and two Schottky barrier contacts 19 and 20 which form rectifying junctions 21 and 22 with the wafer. In the circuit of Fig. 1, wafer 18 is of n-type conductivity and the battery 14 reverse-biases junction 21 and forward-biases junction 22. The reverse-bias is sufficient to cause periodic avalanching and a resultant transit time negative resistance as described before. The entire wafer 18 constitutes the active transit region of the diode; current pulses travel from front contact 19 to rear contact 20.

80 The primary advantage of the diode of Fig. 2 is that wafer 18 is a bulk semiconductor material of constant conductivity. As no p-n junction in the wafer is required, the invention permits new semiconductors, such as diamond and cadmium sulphide, to be used.

85 The manner in which the Schottky barrier contacts 19 and 20 are formed on the diode are well within the capabilities of those skilled in the art. The wafer may also be of the usual semiconductor materials such as silicon, germanium or gallium arsenide, and the contacts may be of a number of appropriate materials. The contacts should of course be uniform, not be "leaky", and otherwise conform to good engineering practice. Both experiment and practice show that the rear contact 20 will not constitute a large series resistance to the diode current and will not substantially degrade efficiency. The r-f resistance is small because the capacitance per unit area of a forward-biased Schottky barrier junction is large and almost completely shunts the junction resistance. The d-c resistance is small because the d-c voltage across a forward-biased Schottky barrier junction is small. Of course the diode may be used in circuits other than that shown in Fig. 1, and it is particularly well suited for use in a so-called TRAPATT oscillator.

90 An n-type silicon diode with platinum silicide Schottky barrier contacts may be made with the following parameters:

95 wafer thickness $\approx$ 7 microns;
wafer diameter $\approx$ 10 mils;
contact diameter $\approx$ 10 mils;

wafer doping level $\approx 3 \times 10^{15}$ carriers/cm³,
and
operating frequency ≈ 9 gigahertz.

5 Silicon carbide is also promising as a wafer material because of its high thermal conductivity and other factors.

WHAT WE CLAIM IS:—

10 1. An avalanche diode comprising a wafer of semiconductor material between a pair of contacts each forming a Schottky barrier junction with said wafer, said diode being such that when reverse-biased to avalanche breakdown current passes from one to the other of said contacts.

15 2. A diode as claimed in claim 1 wherein said wafer is of substantially constant conductivity.

3. A diode as claimed in claim 1 or 2 wherein said wafer is of diamond.

20 4. A diode as claimed in claim 1 or 2 wherein said wafer is of silicon carbide.

5. A diode as claimed in claim 1 or 2 wherein said wafer is of n-type silicon, and said contacts are of platinum silicide.

6. An avalanche diode substantially as 25 herein described with reference to fig. 2 of the accompanying drawing.

7. A microwave oscillator arrangement including a diode as claimed in any one preceding claim, 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 35 r.f. energy.

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