

PATENT SPECIFICATION

DRAWINGS ATTACHED

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COMPLETE SPECIFICATION

High Frequency Oscillation Generators

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 high frequency energy generating devices and, more particularly, to those depending on transit time effects in a solid state element.

U.S. Patent No. 2,899,652 and U.S. Patent No. 2,794,917 referred to therein, disclose semiconductor negative resistance devices which utilize transit time effects.

In general, negative dynamic resistance can be developed in two terminal semiconductive elements by correlating the structural and operating parameters of the elements so that the period of the operating frequency and the transit time of charge carriers across a particular region are properly related. The negative power dissipation in these devices is the result of a shift in phase between an applied alternating voltage, which may arise internally, for example, as a result of noise, and the alternating current flowing through that portion of the device across which the principal voltage drop occurs.

An object of this invention is a transit time diode for mounting in a resonant cavity to produce high frequency power, which may be fabricated facilely.

According to the invention a high frequency oscillation generator includes a semiconductor diode mounted in a resonant cavity wherein

the diode comprises a semiconductor body having a pair of terminal zones of relatively high conductivity and of opposite conductivity type and an intermediate zone of relatively moderate conductivity, the intermediate zone and the terminal zone of opposite conductivity type thereto being included within an epitaxially grown layer on the other terminal zone and defining a P-N junction between them, the cavity being resonant at a frequency related to the transit time of electrons across the intermediate zone and means for applying a potential to the diode so that the junction is biased beyond its avalanche breakdown point so as to generate electrons in the intermediate zone.

One advantage of this device, in contrast to prior art transit time devices, is the use of zones of moderate conductivity instead of the intrinsic and near-intrinsic conductivity zones which characterize those previous structures. In particular, this simplifies the fabrication process.

In general, the minimum conductivity used for the intermediate region is determined by the present limitations on junction and surface technology. The aforementioned U.S. patent 2,899,652 shows that for minimum loss the intermediate region should be intrinsic. In accordance with this invention it is recognized that it is advantageous to depart from the use of intrinsic material for this region to material of moderate conductivity, thereby enabling a moderate direct current to flow, for at least two reasons. First, we have found that the existence of a moderate direct current tends to minimize the effects of microplasmas. Second, we have found that this current also minimizes surface effects in that a small number of charges do not vary the

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internal fields, on a percentage basis, to the previous extent.

In a preferred embodiment of the invention a silicon semiconductor diode is mounted in a suitable resonant cavity, for example, a waveguide portion and arranged for the application thereto of a steady bias voltage. In particular, the diode is of the P+NN+ configuration, in which the P+ and N zones are fabricated in the epitaxially grown region.

A direct voltage to reverse bias the junction to beyond avalanche breakdown is applied to the diode. In this condition a current flows within the device which gives rise to a negative dynamic resistance and, with appropriate circuitry, to continuous wave oscillations at frequencies related to the width of the space charge region induced principally within the N zone.

The invention will be more clearly understood from the following detailed description of an embodiment thereof when read with the accompanying drawings in which:

FIG. 1 is a perspective view illustrating the semiconductor diode structure of an embodiment of this invention;

FIG. 2 is a graphical representation of the diode of FIG. 1 showing the relation of space charge and field distribution within the device;

FIG. 3 is a graph of part of the current-voltage characteristic of the diode illustrating the bias level used;

FIG. 4 is a schematic cross-section of a waveguide section including a diode and connected for operation particularly as an oscillator;

FIG. 5 is a cross-section view of an encapsulated diode; and

FIG. 6 is similar to FIG. 4, showing a structure exhibiting the parametric effect.

FIG. 1 shows a silicon die including the several zones. It will be understood that the drawing is exaggerated in certain dimensions to facilitate description. The substrate terminal zone 11 is of N+ material, characterized as degenerate and having an impurity concentration of about 10^{20} atoms per c.c.. In functional terms, degenerate material is material which has a sufficiently heavy impurity concentration such that the resistance contribution of the material is small. The opposite terminal zone 12 is of degenerate P+ material having a similarly high impurity concentration in excess of about 10^{20} atoms per c.c.. Intermediate the terminal zones is an N-type zone 13 of moderate conductivity having an impurity level of about 10^{16} atoms per c.c.; a typical value being about 3×10^{16} atoms per c.c..

The die 10 typically is produced by first processing a slice of silicon material and cutting this slice into the individual dies as represented by the element 10. Although the following description will be given in terms

of the treatment steps as applied to the element 10 shown in FIG. 1, it will be understood that they are carried out on a large slice of about one-half to three-quarters of an inch in diameter.

The initial material is a uniformly doped substrate approximately three mils (75 microns) in thickness. This is N+ material having the high impurity concentration suggested above. On the face of this material a thinner layer, approximately 25 microns in thickness of N-type conductivity material, is grown by epitaxial deposition. By suitable control of the process the impurity concentration is kept substantially constant through this epitaxially grown layer and is typically about 3×10^{16} atoms per c.c..

The semiconductor element next is subjected to a diffusion heat treatment using a boron-containing compound which converts the upper face of the epitaxially grown layer to P+ conductivity-type to a depth of approximately eight to nine microns. As previously noted the impurity concentration in this zone is made about 10^{20} atoms per c.c.. The boundary of this diffused P+ terminal region 12 constitutes the P-N junction 14 of the device.

During this diffusion treatment donor impurity atoms also advance from the N+ substrate 11 across the original boundary 18 with the epitaxial layer. The extent of this penetration depends on the diffusion coefficient of the particular impurity. In this specific embodiment using an arsenic doper substrate the penetration is small. Thus, the NN+ boundary 15 is displaced about one to two microns into the epitaxial layer leaving a uniformly doped N zone 13 which is about fifteen microns in thickness. Although the thickness of this intermediate region is not critical, except to the extent discussed below, excessive thickness beyond that required to accommodate the space charge region is a source of loss.

In particular, as is well understood, because of the relationship between operating frequency and carrier transit time, high frequency operation of solid state devices requires very thin zones. Within the limits of the present technology an intermediate zone 13 ranging from 25 microns down to 2500 Å may be provided and is suitable for devices operating in the range of about one to two gigacycles to possibly one hundred gigacycles, respectively. Extension of the technology should permit the achievement of higher frequency responses.

Ohmic contacts 16 and 17 of plated metal are applied to the terminal zones 11 and 12, respectively, by techniques known in the art, such as nickel plating followed by gold plating. As previously noted, the foregoing processing is done on a slice of material which is diced into 125 micron square ele-

ments having a total thickness of approximately 75 microns. The individual die 10 then is mounted in a conventional cartridge-type encapsulation as illustrated in FIG. 5.

In the exemplary encapsulated device of FIG. 5 the semiconductor P-N junction diode 51 is mounted in electrical contact with a lead member 54 which in turn is held within the metal sleeve 57 which serves as one terminal of the device. Electrical contact is made to the opposite side of the diode by means of the metal C-spring member 52 mounted upon another lead 53 supported within the sleeve 56 comprising the opposite terminal of the device. Intermediate the sleeve members 56 and 57 and sealed thereto is a cylindrical insulating member 55, typically of ceramic.

The encapsulated diode 50 of FIG. 5 is mounted in a reduced height waveguide portion as shown in FIG. 4 to constitute an oscillator when the cavity is suitably tuned to resonance at an appropriate frequency related to the transit time characteristics of the diode as described more fully below. The encapsulated diode 33 is recessed in the walls of the guide so as to expose to the wave energy path only the semiconductor wafer and the connecting leads. Desirably the height of the waveguide portion 36 is selected so that the capacitance of the diode is series resonant with the inductance of the lead structure within the encapsulation at the operating frequency. In effect, by so adjusting the height, the device capacitance is tuned out.

One terminal of the diode 33 is mounted in a waveguide segment 34 which is insulated for direct current by a thin insulating layer 44, typically of Mylar (Registered Trade Mark). It is desirable that this insulation be thin to introduce as little radio frequency discontinuity as possible. The other terminal of the diode 33 is electrically connected to the waveguide proper. Accordingly, direct bias voltage is applied by connecting between the waveguide segment 34 and the waveguide 36, a voltage source 39 and means for adjusting the voltage comprising the variable resistor 40.

Between the full height portion 32 and the reduced height portion 36 is a tapered section 35 constituting an impedance transforming portion. At the end of the reduced height portion is an adjustable piston 37 for tuning the cavity and a series of adjusting screws 38 for impedance matching.

In a specific embodiment the full height waveguide portion 32 was 900 mils wide and 400 mils high. The reduced height portion 36 was the same width but only 50 mils high and the transformation section was a three wavelength raised cosine taper. Using a P+NN+ diode of the configuration and dimensions described above and an

applied direct bias of about 50 volts providing a current of about 50 milliamperes, with the cavity tuned to 8.9 gigacycles an output of 1.7 milliwatts was observed.

The operation of the device as described above appears to be consistent with the theory propounded in U.S. Patent No. 2,899,652 noted hereinabove, although there are the important distinctions in diode configuration and degree of direct current biasing. In particular, referring to the graph of FIG. 3 there is depicted part of the direct current-voltage characteristic curve of the P-N junction semiconductor diode. In the reverse direction the avalanche breakdown point is noted as the point where, with small increases in voltage in the reverse direction, say from V_1 — V_2 , there is a large increase in the current flowing through the diode. The phenomena of avalanche breakdown is explained more fully in the article by K. G. McKay in the *Physical Review*, Volume 94, pages 879 to 884, May 15th, 1954, entitled "Avalanche Breakdown in Silicon".

FIG. 2 shows in diagrammatic form the depletion layer and field distribution within the semiconductor diode. The P+, N and N+ zones are labelled 20, 21 and 22, respectively. The direct current source 25 and variable resistor 26 are shown serially connected by way of ohmic contacts 23 and 24 to the terminal zone 21, which has the lower carrier concentration, to the boundary line 28. The other boundary line 27 depicts the very slight extension of the space charge region into the heavily-doped P+ zone 20.

The magnitude of the electric field plotted against distance across the zones of the diode is shown by the broken line 29. For graphic purposes the top line of the device outline is the field magnitude corresponding to avalanche breakdown, hence the line 29 depicts the field level for the bias voltage V_1 and the space charge region D depicted. Typically, for the conditions described hereinabove, namely a reverse bias of about 50 volts, the space charge width is about two microns.

As can be seen the field drops from the level corresponding to avalanche breakdown near the P-N junction to a lower value at the edge 28 of the swept out layer. Under these conditions a continuous current flows giving rise to a negative dynamic resistance and to a transit time effect. As a consequence the device goes into oscillation at a basic frequency related to the width of the space charge region D. Specifically, it appears that

for optimum operation the carrier transit time across D is substantially equal to $\frac{t}{2}$ where t is the period of the oscillation frequency.

5 Although the foregoing description is in terms of an oscillator suitable as a primary source of high frequency energy the device also exhibits a parametric effect useful for
10 parametric amplification and conversion in an appropriate structure. The structure of FIG. 6 again is a reduced height waveguide similar in dimensions to that described in connection with FIG. 4. However, the closed end
15 61 of the cavity is of full height which enables positioning of a tuning piston 67 at a greater distance from the diode 63. Additionally, a slide screw tuning element 62 is placed in the output portion 64 of the waveguide at a distance of several wavelengths from the
20 diode 63. In a specific embodiment, using a 900×400 mil waveguide with a reduced height portion of 50 mils the distance from the diode 63 to the end of each tapered section was four and one-half inches. The tuning
25 piston 67 had an adjustment range of from 5.75 inches to 7.25 inches from the diode and the slide screw tuner 62 an adjustment from 7.5 inches to 8.5 inches from the diode. The diode 63 is mounted in sockets 70 and
30 71 as shown, the upper socket 71 being insulated by a dielectric layer 72 of Mylar. A direct current source 73 and variable resistor 74 are shown connected across the diode terminals. For a particular tuning of
35 this apparatus, and using a semiconductor diode of the type described above, biased beyond avalanche breakdown at a value of 50 volts direct current a simple three frequency parametric effect was observed.
40 Specifically, output observed from the open end of the waveguide was detected at frequencies f_1 , f_2 and f_p where, in accordance with known principles $f_1 + f_2 = f_p$. In a particular instance $f_p = 17.49$ gigacycles,
45 $f_1 = 8.982$ gigacycles and $f_2 = 8.512$ gigacycles. These frequencies always maintained the additive relationship stated above as the tuning elements were varied until, at a critical tuning, oscillation at f_1 and f_2 disappeared
50 leaving amplification bands. In other instances, f_1 and f_2 merge to yield an amplified signal at one-half the basic frequency, the degenerate parametric case. Thus, it appears that there results a parametric device in which
55 the pumping energy at frequency f_p is provided by transit time oscillations of the kind described hereinabove necessitating only the application of a direct current bias whereupon this oscillation in turn pumps the non-linear reactance of the diode giving rise to
60 parametric oscillation or amplification depending on the circuit configuration.

It will be apparent to those skilled in the

art that other parametric effects may be realized using the structures in accordance with this invention, simply by providing appropriate resonances and abstracting power at appropriate frequencies in accordance with known parametric device principles. Descriptions of these principles are set forth in
65 "Some Energy Properties of Nonlinear Elements. Part I. General Energy Relations" by J. M. Manley and H. E. Rowe, published in *Proceedings of the IRE*, Volume 44, July 1956, pages 904—913 and "Some General
70 Properties of Nonlinear Elements. Part II. Small Signal Theory" by H. E. Rowe, published in *Proceedings of the IRE*, Volume 46, May 1958, pages 850—860. Thus to summarize, the following types of operation
75 have been observed. First, the device has been operated as a free frequency inverter-type (negative resistance) in which gain or oscillations are obtained at two frequencies
80 f_1 and f_2 , such that $f_1 + f_2 = f_p$ and both f_1 and f_2 are less than f_p . The device is capable also of operation as a three frequency non-inverting (positive resistance) device in which
85 upconversion gain is obtained from f_1 to f_2 where $f_1 + f_p = f_2$ and f_2 is greater than f_p , which, in turn, is greater than f_1 . As noted above, the degenerate inverter-type operation in which f_1 and f_2 merge at one-half of f_p
90 also has been observed. In addition, harmonic generator types of operation have been achieved in which gain has been observed at harmonics of the frequency f_p .

Although the specific embodiment is of silicon semiconductor material, other elemental and compound semiconductors may be used. Similarly, complementary P+PN+ structures can be used with appropriate reversal in polarity of the applied voltages. Moreover, although the cavity for mounting the diode is specifically described as a section of rectangular waveguide, other suitable resonant cavities including coaxial lines may be used.

WHAT WE CLAIM IS:—

1. A high frequency oscillation generator including a semiconductor diode mounted in a resonant cavity wherein the diode comprises a semiconductor body having a pair of terminal zones of relatively high conductivity and of opposite conductivity type and an intermediate zone of relatively moderate conductivity, the intermediate zone and the terminal zone of opposite conductivity type thereto being included within an epitaxially grown layer on the other terminal zone and defining a P-N junction between them, the cavity being resonant at a frequency related to the transit time of electrons across the intermediate zone and means for applying a potential to the diode so that the junction is biased beyond its avalanche breakdown point so as to generate electrons in the intermediate zone.

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110
115
120
125 electrons in the intermediate zone.



2. A generator according to claim 1 wherein the diode is of P+NN+ configuration and is biased for the generation of electrons at the P+ edge of the N zone for transit to the N+ zone. 30
3. A generator according to claim 2 wherein the P+ zone and the N+ zone have impurity concentrations of about 10^{20} atoms per c.c. and the N zone has an impurity concentration of about 10^{18} atoms per c.c. 35
4. A generator according to claim 2 or 3 wherein the thickness of the N zone of the diode is less than 15 microns. 40
5. A generator according to claim 2, 3 or 4 wherein the semiconductor material is silicon. 45
6. A generator according to any preceding claim wherein the cavity is resonant at a first frequency and at one or more other frequencies parametrically related to said first frequency.
7. A generator according to claim 6 wherein the cavity is resonant at two other frequencies the sum of which is substantially equal to the first frequency.
8. A generator according to claim 6 wherein the cavity is also resonant at a frequency of half the first frequency.
9. A generator according to claim 6 wherein the one or more other frequencies are integral multiples of the first frequency.
10. A generator according to claim 6 wherein the cavity is resonant at two other frequencies f_1 and f_2 such that the sum of f_1 and the first frequency is substantially equal to f_2 and that f_2 is greater than the first frequency which is itself greater than f_1 .
11. A generator according to claim 1 wherein the diode is of P+PN+ configuration.
12. A generator according to any preceding claim wherein the resonant cavity comprises a rectangular section waveguide.
13. A generator according to any one of claims 1 to 11 wherein the resonant cavity comprises a coaxial line.
14. A high frequency generator arranged and adapted to operate substantially as herein described with reference to and as shown in FIGS. 1, 2, 3, 4 and 5, or FIGS. 1, 2, 3, 5 and 6 of the accompanying drawings.

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