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NEGATIVE RESISTANCE SEMICONDUCTIVE DEVICE

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FIG. 1

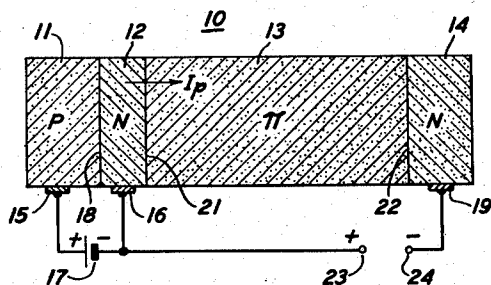


FIG. 2

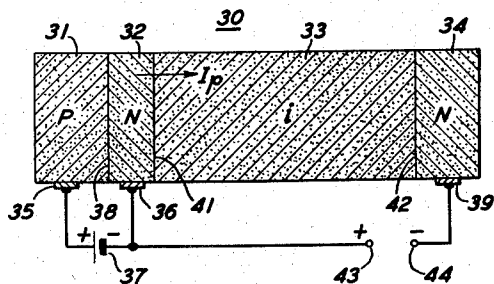


FIG. 3

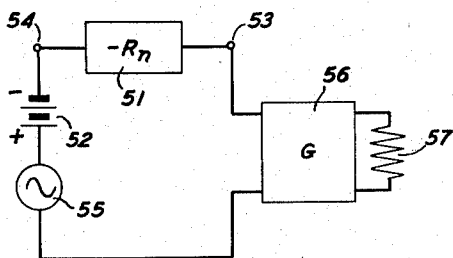
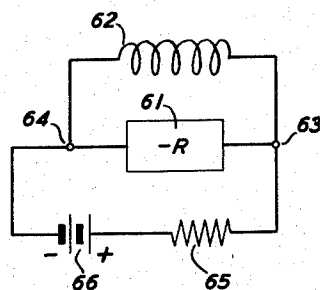


FIG. 4



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NEGATIVE RESISTANCE SEMICONDUCTIVE DEVICE

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8 Claims. (Cl. 333—80)

This invention relates to semiconductor devices and more particularly to semiconductor devices which provide a negative resistance across a pair of terminals.

Various applications are known to workers in the art for negative resistance elements as, for example, in combination with a tuned circuit to generate oscillations, or in a dissected amplifier to provide gain as is described in my copending application Serial No. 409,667, filed February 11, 1954, now Patent No. 2,772,360, issued November 27, 1956.

The present invention relates to a novel form of two-terminal negative resistance element which is particularly advantageous because of its broad frequency response and relative simplicity of associated circuitry.

The present invention is based upon having a constant current of one type of carrier flow from a region of a semiconductor body serving as a source of carriers of this type into an intermediate portion of the semiconductor body and using the space charge of this constant current to control a variable current of the carrier of opposite type into this intermediate portion from a region of the body serving as a source of carriers of this opposite type. This control may be exerted in two different ways in accordance with different forms of the invention.

In one form of the invention in which the active intermediate zone of the semiconductor body is characterized by an uncompensated chemical charge density, a constant current of carriers of the sign opposite to the sign of the chemical charge is made to control the flow of a variable current of carriers of the same sign as the chemical charge such that an increasing electric field gives rise to a decreasing total current through the active zone because of space charge limitations.

In the other form of the invention in which the active zone of the semiconductor body is characterized by a lack of a significant uncompensated chemical charge density, negative resistance is achieved by operation at such high electric fields in the active zone that the ratio of the velocities of the two types of carrier varies with increasing electric field.

In an embodiment illustrative of the first form of the invention, the semiconductor body comprises a $pn\pi n$ structure where p and n designate zones of the body which are strongly p-type and n-type, respectively, and π designates a zone which is weakly p-type. In operation, there is maintained a constant forward bias on the p - n junction and a reverse bias on the n - π junction while the signal is allowed to vary the forward bias on the π - n junction. As a consequence, the contiguous p- and n-type regions of the body provide a constant current of holes which is introduced into the active π -type zone and the n-type end zone provides a variable current of electrons. In operation, because of space charge limitations, the flow of electrons will decrease with increasing electric fields in the active zone and there will be provided a negative resistance between a pair of terminal connections to the pair of n-type zones.

In an embodiment illustrative of the other form of the

invention, the semiconductor body comprises a $pnin$ structure where i designates a zone of substantially intrinsic material. Here, the operating biases are such that the contiguous p- and n-type regions provide a constant current of holes into the active intrinsic zone and the n-type end region provides a variable current of electrons into the intrinsic zone. In addition, the operating biases are chosen so that in the intrinsic zone the electric field is sufficiently high that the ratio of electron velocity to hole velocity decreases with increasing electric field. Under such circumstances, a negative resistance is developed across a pair of terminal connections to the pair of n-type zones.

In other embodiments to be discussed, other expedients are used for providing the constant current of holes and the variable current of electrons into the active zone.

The invention will be better understood from the following more detailed description taken in conjunction with the accompanying drawings in which:

Figs. 1 and 2 show negative resistance elements in accordance with different forms of the invention;

Fig. 3 shows schematically how a negative resistance element may be incorporated for use in a dissected amplifier; and

Fig. 4 illustrates schematically how a negative resistance element may be incorporated for use in an oscillator.

The negative resistance element shown in Fig. 1 comprises a semiconductor body 10, typically of monocrystalline germanium or silicon, which includes four zones arranged in succession for defining three rectifying junctions in the body. Terminal zone 11 is heavily p-type and is contiguous with an intermediate zone 12 which is heavily n-type. The latter zone, in turn, is contiguous with an intermediate zone 13 which is lightly p-type and, accordingly, has been designated as of π -type in the manner characteristic of the practice in the art. This zone 13, in turn, is contiguous with the terminal zone 14 which is heavily n-type. By means of electrode connections 15 and 16 to zones 11 and 12, respectively, and the D-C. voltage supply 17, the rectifying junction 18 therebetween is biased in the forward direction. Additionally there is provided an electrode connection 19 to zone 14. In operation the body is interconnected in its utilization circuit by means of terminals 23 and 24, which are connected to electrodes 16 and 19, such that there is maintained a potential difference between terminals 23 and 24 of the polarity shown, whereby the rectifying junction 21 is biased in the reverse direction and the rectifying junction 22 in the forward direction. Under operating conditions a negative resistance is developed across terminals 23 and 24.

For operation in the manner intended, it is important that there be supplied a constant current of holes into the active zone 13 which forms the high resistance part of the structure. The hole current is provided by the combination of zones 11 and 12 and the voltage supply 17 which maintains a constant forward bias on the junction 18. The thickness of zone 12 advantageously is less than a diffusion length to facilitate the diffusion therethrough of holes injected therein from the zone 11. Additionally, for constant hole current flow into the active zone 13, it is also important that there always be maintained a reverse bias on the rectifying junction 21 which is several times kT where K is Boltzmann's constant and T is the absolute temperature in degrees Kelvin. If this reverse bias is maintained sufficiently large, changes in its magnitude under the influence of applied signals will little affect the amount of hole current introduced from zones 11 and 12. Additionally, the width of zone 13 and the recombination rate therein are made such that electron-hole pairs which are generated are rapidly swept out of this zone and that this

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generation produces currents small compared to the constant hole current supplied from zones 11 and 12. Under such conditions, the hole current flowing through zone 13 may be viewed as essentially constant and corresponds to the constant current of holes introduced from zones 11 and 12.

The various voltages applied and the dimensions of the structure are chosen such that zone 13 is operated in essentially a condition of space charge neutrality. The condition for space charge neutrality in zone 13 is that

$$n = p - N_a \quad (1)$$

where n and p are the concentrations in the zone of conduction electrons and holes, respectively, and N_a is the concentration in the zone of the uncompensated acceptor centers. In operation, in order to maintain space charge neutrality, electrons are introduced into zone 13 from zone 14 to compensate for the constant current of holes introduced from zones 11 and 12.

In operation the total current density in the zone 13 is given by

$$I = qp\mu_p E + qn\mu_n E \quad (2)$$

where q equals the charge of a hole and the minus charge of an electron, μ_n and μ_p are the mobilities of electrons and holes, respectively, and E is the electric field in the zone 13. In this last expression the first term corresponds to the hole current component and the second term the electron current component. It will be convenient to define the ratio

$$\frac{\mu_n}{\mu_p}$$

by the quantity b . This quantity will be greater than unity for many semiconductors, such as silicon, germanium, silicon-germanium alloys and various group III-group V intermetallic compounds and constant with changes in electric field for electric fields below a certain level. It is characteristic of this first form of the invention, in contradistinction to the second form to be described hereinafter, that the magnitude of the applied field is such that operation occurs in the region where b is constant with changes in electric field. It may now readily be shown by algebraic manipulation that

$$I = (1+b)I_p - qN_a\mu_n E \quad (3)$$

where I_p , the hole current component, is given by the product $q\mu_p pE$.

From Expression 3 it can be seen that increasing the electric field E will result in a decrease in the total current density I when the hole current component I_p is kept constant, as is characteristic of the structure described. Such a decrease in total current density for increasing values of electric field is the negative resistance effect desired.

The following physical interpretation of the negative resistance effect may be helpful to an understanding of the basic principles involved. It will be characteristic that as the electric field in the active zone 13 is increased, there will be a decrease in the density of holes present there if the hole current density remains constant, since the current density is proportional to the product of electric field and charge density. If space charge neutrality is to be maintained, this means that the density of electrons present also will decrease an equal amount. Because of the larger density of hole initially in the active zone 13, a decrease of the same absolute amount in the density of holes and electrons will result in a larger percentage decrease in the density of electrons present. Accordingly, although the hole current which is related to the product of the electric field and the density of holes remains constant with increasing electric field, the electron current density which is related to the product of the electric field and the density of electrons decreases. Restated, it will be characteristic that, with increasing

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electric field, the density of electrons will decrease proportionally faster than will the decrease in density of holes whereby the electron current will decrease relative to the hole current.

From the foregoing explanation, it should be clear that it is also possible to employ a constant current density of electrons to control a variable current density of holes through the active zone of a suitably modified semiconductive body. To compensate for this reversal in roles of holes and electrons, the conductivity types of the different zones of the body and the polarities of applied voltages should be reversed also. It is also clear that the principles of this form of the invention are independent of the specific choice of the semiconductor so that the body may be of any known semiconductive material, such as germanium, silicon, germanium-silicon alloys, and group III-group V intermetallic compounds.

It is also to be noted that the rectifying junction 18 serves merely a passive role from the negative resistance standpoint, being merely the preferred one of a variety of means for providing a constant hole current into the active zone 13. In particular, to achieve the desired constant hole current in the zone 13, it would be feasible to produce by photoelectric or thermal generation a constant number of hole-electron pairs in the contiguous zone 12. As a result of such generation, the n-type zone 12 will become a region rich in both holes and electrons and from the hole-electron pairs generated a constant number of holes could be drawn into the active zone to form the desired constant hole current. In such an embodiment, the p-type zone 11 and the potential source 17 in the structure depicted in Fig. 1 may be omitted as unessential.

It is also feasible to employ expedients other than the preferred one shown in the embodiment of Fig. 1 for providing the variable current of electrons. In particular, the basic structure illustrated may be modified by the elimination of the π -n rectifying junction 22 and by having instead the π -type zone widen abruptly into a region of low lifetime in which electron-hole pairs are generated. Such a region would then be rich both in holes and electrons and so could serve as the source of the variable electron current.

In the structure shown in Fig. 2, a semiconductive body 30 comprises in succession the p-type zone 31, the n-type zone 32, the substantially intrinsic zone 33 and the n-type zone 34. For purposes of this application, the term "substantially intrinsic" is used to denote material in which the density of conduction carriers resulting from impurity centers is less than 10 percent of the density of conduction carriers. Electrodes 35 and 36 make ohmic connections to zones 31 and 32, respectively, and a D.-C. voltage supply 37 is connected therebetween to bias the rectifying junction 38 in the forward direction. An electrode 39 makes ohmic connection to zone 34, and for utilization the body is interconnected so that a potential difference of the polarity shown is established between terminals 43 and 44 to bias the n-i junction 41 in the reverse direction and the i-n junction 42 in the forward direction.

By an analysis similar to that set forth for the structure shown in Fig. 1, where now the density of holes equals the density of electrons because of the intrinsic nature of the zone 33, it can be shown that therein the total current density is given by

$$I_p \left(1 + \frac{v_n}{v_p} \right)$$

where v_n and v_p are the absolute values of the velocities of the electrons and holes respectively, in the zone 33. As is now well known, at high enough electric fields both holes and electrons become "hot," i. e., their velocity no longer increases linearly with increasing electric

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field. In the better known semiconductors the velocity dependence on electric field is such that the ratio

$$\frac{v_n}{v_p}$$

decreases with increasing field over a range of electric fields in excess of a certain minimum electric field. Operation of the active zone 33 of the structure shown in Fig. 2 in such a range will result in a negative resistance being developed across the output terminals 43, 44 since the total current density will decrease with increasing electric field. Operation in the desired range is realized by properly relating the potential difference maintained between electrodes 36 and 39 and the width of the intrinsic zone 33. Typical operating ranges for the desired effect are field strengths between 1000 and 2000 volts/centimeter for germanium and between 2000 and 3000 volts/centimeter for silicon. Various group III-group V intermetallic semi-conductive compounds, such as indium antimonide, may be employed advantageously in permitting such operation at even lower electric field strengths.

The various alternative expedients previously described in connection with the structure of Fig. 1 for providing a constant current of one type and a variable current of opposite type can similarly be employed here.

However, in such a form of the invention, use of a constant current of electrons to control a variable current of holes would require not only a reversal in conductivity type of the various extrinsic regions of the semiconductive body and the polarities of applied potentials, but also use of a semiconductor in which the ratio

$$\frac{v_n}{v_p}$$

increased and the ratio

$$\frac{v_p}{v_n}$$

decreased with increasing electric field over the operating range.

Semiconductive bodies having the distribution of chemical charge impurities characteristic of the structures shown in Figs. 1 and 2 may be fabricated in various ways. Advantageously, suitable semiconductive bodies may be fabricated by the use of vapor-solid diffusion techniques of the kind described in copending application Serial No. 516,674, filed June 20, 1955, by C. S. Fuller and M. Tanenbaum and copending application Serial No. 550,622, filed December 2, 1955, by L. Derick and C. J. Frosch, now Patent No. 2,802,760, issued August 13, 1957. Typically, for the fabrication of a $pn\pi n$ structure, a π -type monocrystalline wafer is heated in the presence of the vapor of a donor impurity for forming a pair of n-type layers in opposite faces of the wafer. Subsequently, by heating the wafer in the presence of the vapor of an acceptor impurity after appropriate masking of one of the two faces, a p-type layer may be formed on the unmasked of the previously formed n-type layers. By starting with a wafer which is substantially intrinsic in conductivity type, the same technique may be used to form a p-n-i-n structure.

It is evident that negative resistance structures of the kind shown in Figs. 1 and 2 may be viewed as simple two-terminal elements for alternating currents for circuit applications.

In the dissected amplifier shown in Fig. 3, a negative resistance element of the kind previously described is designated schematically as the block element 51. By means of its two terminals 53 and 54, which correspond to terminals 23 and 24 of the structure shown in Fig. 1 and to terminals 43 and 44 of the structure shown in Fig. 2, the element 51 is connected in series with a D-C. voltage supply 52 and a signal source 55 and the input terminals of the nonreciprocal element 56. The

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load, shown schematically as the resistor 57, is connected across the output terminals of the nonreciprocal element 56. This nonreciprocal element may be a Hall effect plate or a gyrator of the kind described in application Serial No. 219,342, filed April 5, 1951, of W. P. Mason and is used to provide low attenuation to signal transmission from its input branch to its output branch but very high attenuation to transmission from its output branch to its input branch. The voltage supply 52 is poled to provide the proper polarity on the two terminals of the negative resistance structure. Additionally, the magnitude of the voltage supply is chosen to provide electric fields suitable for the intended mode of operation. In particular, where the negative resistance structure is of the kind shown in Fig. 1 the voltage supply 52 and the signal level provided by the signal source 55 are adjusted so that the electric field in the active portion is in the range where the ratio

$$\frac{\mu_n}{\mu_p}$$

is independent of the electric field. On the other hand, where the negative resistance structure is of the kind shown in Fig. 2, the voltage supply 52 and signal source 55 are adjusted so that the electric field in the active portion of the semiconductive body is in the range where the ratio

$$\frac{v_n}{v_p}$$

varies with electric field in the manner desired.

In Fig. 4, there is shown schematically the use, in an oscillator circuit, of a negative resistance structure 61 of the kind described. The impedance of the negative resistance structure includes a reactive component which is capacitive in nature and this capacitance is made to resonate with an inductance element 62 which is connected in shunt across the two terminals 63 and 64 of the negative resistance structure. A resistive load 65 is connected in series with the negative resistance element. The necessary operating potentials are supplied by the voltage supply 66. The considerations previously discussed are applicable to the polarity and magnitude of the voltage supply 66.

It should be evident that various other applications may be made of negative resistance structures of the kind described. Accordingly, it is further to be understood that the various arrangements described are merely illustrative of the general principles of the invention. Various modifications may be provided therein by one skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In combination, a semiconductive body having an active portion intermediate between two end regions, a pair of electrode connections, a different one to each of the end regions, across which there is applied an alternating voltage, means associated with one of the end regions for introducing therefrom into the active portion of the body a current primarily only of charge carriers of one sign and of amplitude which remains constant despite variations in the voltage across said pair of electrode connections, means associated with the other of the end regions for introducing therefrom into the active portion of the body a current of charge carriers primarily only of the sign opposite that of the first-mentioned charge carriers and of amplitude which varies inversely with variations in the voltage across said pair of electrodes whereby a negative resistance is developed across said pair of electrodes.

2. The combination of claim 1 further characterized in that said one end region includes a pair of zones of opposite conductivity type having a first rectifying junction therebetween and forms a second rectifying junction with said active portion and the means associated

with the end region for introducing into the active portion the constant current of charge carriers of one sign includes means for providing a constant forward bias on said first rectifying junction and a reverse bias on said second rectifying junction.

3. The combination of claim 1 further characterized in that said other of the end regions comprises a zone which forms a rectifying junction with the active portion and the means associated with said last-mentioned end region for introducing into the active portion the current of charge carriers of variable amplitude comprises means for maintaining a forward bias on said last-mentioned rectifying junction.

4. In combination, a semiconductive body having four zones in succession for defining three rectifying junctions, a separate electrode connection to each of the first, second and fourth zones of the succession, means for introducing into the third zone of the body by way of the second zone a constant current of charge carriers primarily only of the type predominant in the first zone and by way of the fourth zone a variable current of charge carriers of the type predominant in the fourth zone comprising voltage supply means connected between the electrode connections to the first and second zones for maintaining during operation a constant forward bias on the rectifying junction between the first and second zones and variable voltage supply means connected between the electrode connections to the second and fourth zones for establishing during operation a reverse bias on the rectifying junction between the second and third zones and a forward bias on the rectifying junction between the third and fourth zones, whereby a negative resistance is developed across the electrode connections to the second and fourth zones.

5. The combination of claim 4 further characterized in that the first and third zones of the body are of one

conductivity type and the second and fourth zones of the opposite conductivity type and the amplitude of the voltage applied between the electrode connections to the second and fourth zones is such that for the resulting electric field in the third zone that the ratio of the mobilities of the two types of charge carriers in the third zone is substantially constant.

6. The combination of claim 4 further characterized in that the first zone is p-type, the second and fourth zones n-type, and the third zone substantially intrinsic and the voltage applied across the electrode connections to the second and fourth zones establishes in the third zone an electric field such that the ratio of electron velocity to hole velocity in the third zone decreases with increasing electric field.

7. The combination of claim 4 further characterized in that said variable voltage supply means connected between the electrode connections to the second and fourth zones comprises a steady voltage supply in series both with a source of input signals to be amplified and a load.

8. The combination of claim 4 further characterized in that said variable voltage supply means connected between the electrode connections to the second and fourth source comprises a steady voltage supply and inductive means resonant with the capacitance of the third zone for establishing an alternating component on the voltage applied between the electrode connections to the second and fourth zones.

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