July 14, 1959 G. WEINREICH **2,895,109**

NEGATIVE RESISTANCE SEMICONDUCTIVE ELEMENT

Filed June 20, 1955 3 Sheets-Sheet 1

FIG. 1A

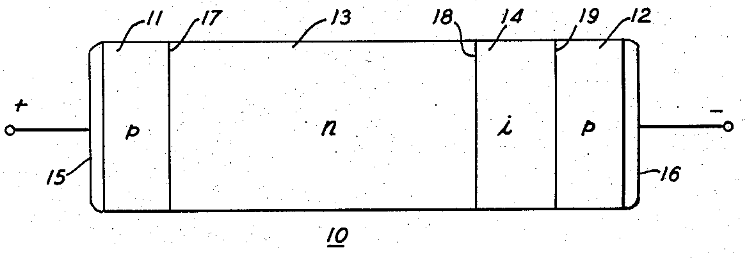


FIG. 1B

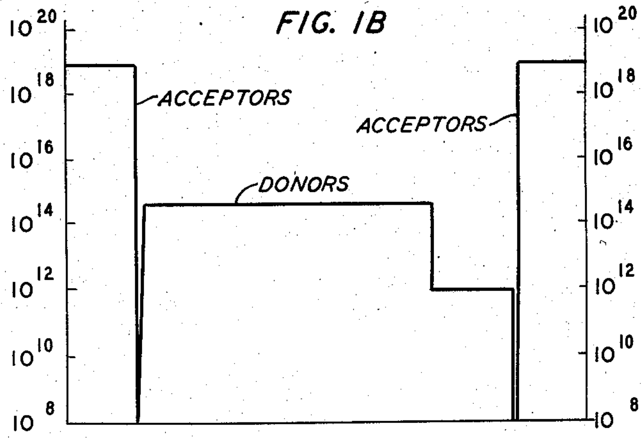
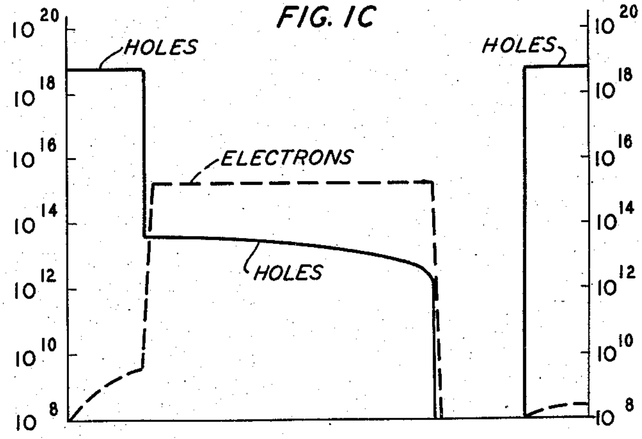


FIG. 1C



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NEGATIVE RESISTANCE SEMICONDUCTIVE ELEMENT

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FIG. 2

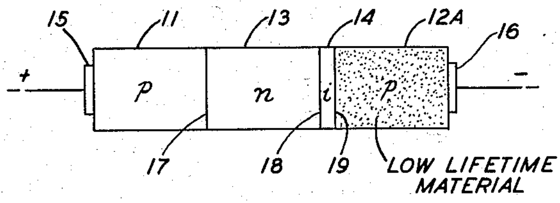

FIG. 3

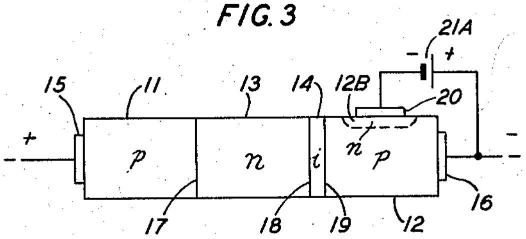

FIG. 4

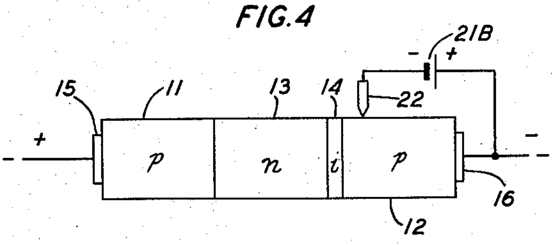

FIG. 5

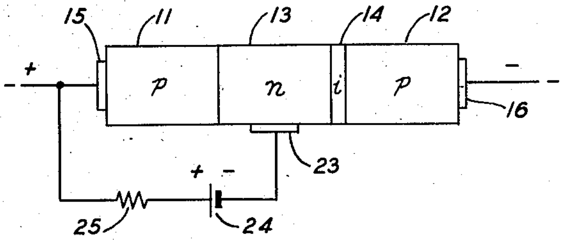

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FIG. 6

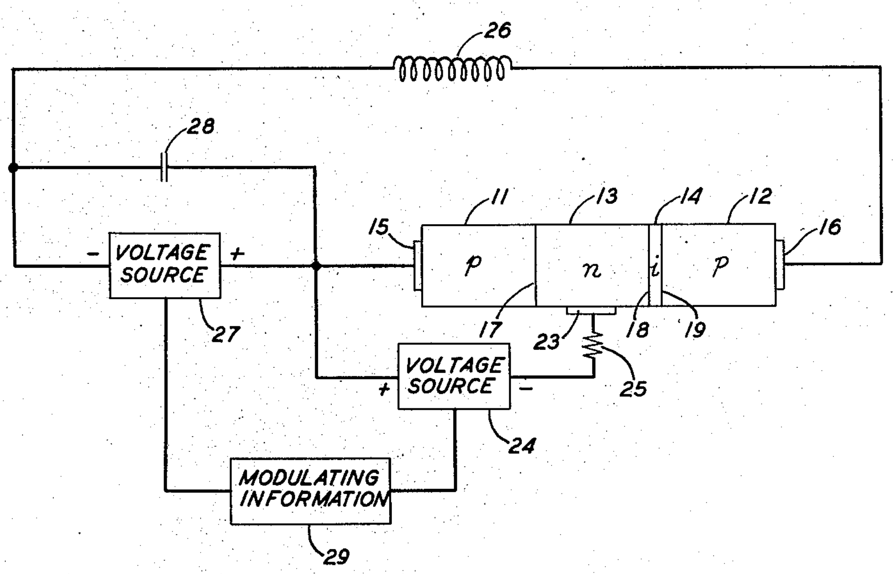
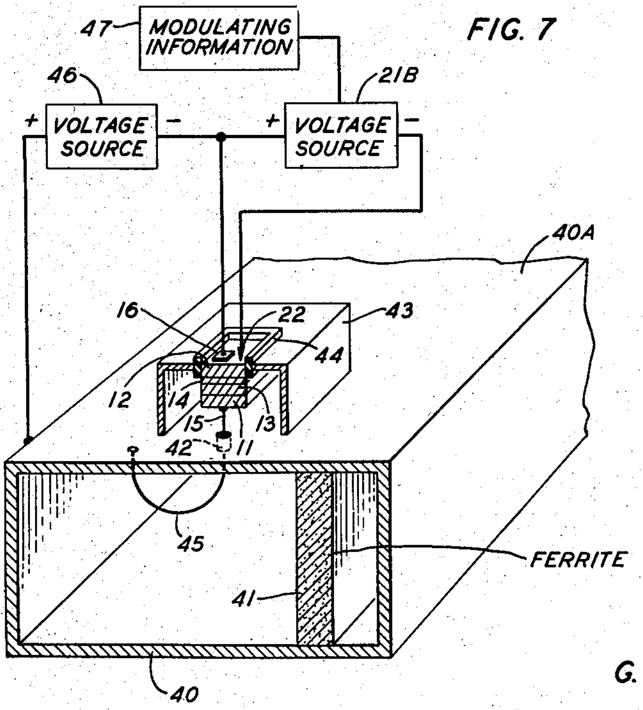


FIG. 7



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2,895,109

NEGATIVE RESISTANCE SEMICONDUCTIVE ELEMENT

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Application June 20, 1955, Serial No. 516,691

4 Claims. (Cl. 332—52)

This invention relates to semiconductive devices, and more particularly to such devices exhibiting negative power dissipation to alternating signals and to applications for devices having such negative power dissipation.

In an article published July 1954 in the Bell System Technical Journal, pages 799 through 826, and entitled "Negative Resistance Arising From Transit Time in Semiconductor Diodes," and in a copending application Serial No. 333,449, filed January 27, 1953 issued as Patent No. 2,794,917, there is described a device which includes a semiconductive element comprising a pair of terminal zones of like conductivity type contiguous with an intermediate zone of opposite conductivity type, and it is shown that by proper correlation of the structural and operating parameters of the device, negative resistance may be provided between a pair of electrode connections to the two terminal zones. The term "negative resistance" is employed in that article, as in the present application, to characterize a device which provides negative power dissipation to an alternating signal. Negative power dissipation is realized when the integrated product of the signal voltage and signal current over a cycle of operation is negative. A negative integrated product of current and voltage may be achieved by establishing a phase shift between the voltage and current of between 90 and 270 degrees. As set forth in the article, semiconductive devices wherein the transit time of charge carriers from the emitting terminal zone to the collecting terminal zone falls between one-half and three-halves the period of the applied signal may exhibit negative resistance to that signal. In the operation there described, a direct current potential difference is maintained between the pair of terminal zones to bias the emitting junction in the forward direction and the collecting junction in the reverse direction to establish the conditions necessary for negative resistance. Moreover, it has been further suggested in the above-identified publication that devices of this kind may be improved by the inclusion of means to increase the forward bias on the emitting junction to reduce its impedance to alternating voltages relative to the impedance of the collecting junction, and several expedients for accomplishing this end are described.

The present invention relates more particularly to improvements in semiconductive devices of the kind described and to novel applications for such devices.

In one aspect, the present invention relates to improvements which increase the upper frequency limit at which negative resistance may be achieved in these devices.

In another aspect, the invention relates to the use of such devices in modulation arrangements in which an oscillator incorporating a negative resistance device of the kind described has either its amplitude or frequency modulated in accordance with modulating intelligence applied to the negative resistance device. In particular, it is found that modulation of the added forward bias on the emitting junction results in amplitude modulation of the oscillations while modulation of the voltage applied across the semiconductive body produces modulation of the oscillatory frequency.

In practice, in negative resistance devices of the kind described in the previously identified publication, it has been found difficult to operate at very high frequencies. It has now been discovered that the high frequency limitation is imposed when the impedance to alternating voltages of the collecting junction becomes insufficiently high relative to the impedance of the emitting junction. The inclusion of means to increase the forward bias on the emitting junction which has the effect of reducing the impedance to alternating voltages of the emitting junction is found to be inadequate alone to make feasible operation at very high frequencies. In one aspect, the present invention is based on the recognition and understanding of the deleterious factors imposing the high frequency limitations. In the light of such recognition and understanding, the invention provides modifications in the physical nature of the device to overcome such newly recognized factors.

In particular, it is in accordance with the invention to include as the semiconductive body in devices of the kind described one which includes two terminal zones of one conductivity type intermediate between which are interposed a zone of opposite conductivity type and an intrinsic region which is many Debye lengths long, where a Debye length is defined on page 441 of an article by W. Shockley entitled "The Theory of p–n Junctions in Semiconductors and p–n Junction Transistors," published in the July 1949 issue of the Bell System Technical Journal. The use of an element of this kind in the negative resistance device insures that the impedance to alternating voltages of the collecting junction will always be high relative to that of the emitting impedance. In conjunction with the use of an element of this kind, it is also generally advantageous to include means for increasing the forward bias on the emitting junction for keeping the impedance of the emitting junction low.

Various applications are feasible for negative resistance devices of the kind described generally. In particular, it has been suggested hitherto that such devices may be incorporated in a dissected amplifier in which a negative resistance device and a nonreciprocal element are inserted together in a signal path, the former to provide gain, the latter to furnish stability. The principles of the use of negative resistance devices in this fashion are described in copending applications Serial No. 364,291, filed June 26, 1953, issued as Patent No. 2,777,906 and Serial No. 409,667, filed February 11, 1954, issued as Patent No. 2,772,360.

Another application previously suggested for negative resistance devices of the kind described is in oscillators in which a reactive element is associated with the device and oscillations are set up at the frequency at which the reactive element and the negative resistance device resonate.

In another aspect, the present invention relates to the use as modulators of oscillators including negative resistance devices of the general kind described, in which there is included means for controlling the forward bias on the emitting junction. In a device of this kind, it has been discovered that the size of the negative resistance which can be realized may be controlled by the amount of forward bias. Accordingly, when the device is incorporated into an oscillator, amplitude modulation of the oscillations may be achieved by modulation of the forward bias on the emitting junction of the semiconductive element. However, it is further found in such an oscillator that appreciable modulation of the forward bias has the concomitant effect of modulating undesirably the reactive component of the impedance of the body as viewed between the two terminal connections to the semiconductive element which results in frequency modulation of the oscillations. To cancel out this effect and thereby insure pure amplitude modulation in arrangements of this kind, it is found advantageous to modulate the voltage applied across the two terminal zones concurrently with and in the same sense as the modulation of the forward bias on the emitting junction.

Alternatively, it is found that by incorporating a negative resistance device of the kind described in an oscillator and varying in accordance with modulating information the direct current voltage applied across the two electrodes associated with the terminal zones of the semiconductive element a frequency modulated oscillator may be provided.

In each of two illustrative embodiments of the present invention to be described in detail, a semiconductive element of PNIP configuration is used as a negative resistance element in a modulation arrangement.

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

Fig. 1A shows a semiconductive body of the kind which forms the semiconductive element of a negative resistance device in accordance with one aspect of the invention, Fig. 1B is a plot of the impurity distribution in the body, and Fig. 1C is a plot of the carrier distribution desired for the body during operation;

Figs. 2 through 5 show different forms of negative resistance devices in accordance with one aspect of the invention, each including a semiconductive body of the kind shown in Fig. 1A but employing different expedients for achieving for the body the operating parameters shown in Fig. 1C; and

Figs. 6 and 7 illustrate applications of negative resistance devices of the kinds shown in Figs. 2 through 5 to modulation arrangements in accordance with another aspect of the invention.

With reference now more particularly to the drawings, in Fig. 1A there is shown a schematic side view of a semiconductive body **10** including a pair of terminal zones **11** and **12** of N-type conductivity between which are positioned an intermediate zone **13** of P-type conductivity and an intrinsic zone **14**. Typically, to provide such a body there is first prepared an NI body which is formed by growing from a melt of highly purified germanium a crystal which is substantially intrinsic and then adding a donor to the melt to convert to N-type material the remainder of the crystal grown. The NI body is then realized by carving out an appropriate piece of the crystal grown including the NI boundary. Then an aluminum film is evaporated on the body and alloyed in to form the terminal zones of P-type conductivity. In a unit that was built and tested experimentally, the body had a cross sectional area of 10^{-2} centimeter^2, the thicknesses of the P-type terminal zones **11**, **12** were estimated to be fractions of a mil, the N-type zone **13** was between five and six mils wide and the intrinsic zone **14** between one and two mils wide which represents a distance many Debye lengths long as distinguished from the length of the transition region associated with a PN junction.

In Fig. 1B, there is plotted the distribution of the predominant impurities with distance along the principal axis of the body of the unit that was built and tested. As depicted, the intrinsic zone **14** is characterized by a slight excess of donors. It is convenient to characterize as intrinsic semiconductive material in which the unbalance in conductivity type determining impurities is less than about 10^{13} atoms/centimeter^3.

In Fig. 1C, there is plotted the hole and electron distribution desired in the body for operation in the manner previously outlined and to be discussed in more detail hereinafter.

In particular, there is provided to the two terminal zones electrodes **15** and **16** between which is connected a voltage source not shown to bias electrode **15** positive with respect to electrode **16** as shown in Fig. 1A. This results in a forward bias across the PN junction **17** and a reverse bias across the NI junction **18** and the IP junction **19**. In operation of the kind to be described, the potential difference applied across electrodes **15** and **16** is sufficient to result in "punch through" of the intrinsic region **14**, and the entire intrinsic region **14** becomes one of high space charge fields.

Negative resistance to signals in a given band of frequencies is achieved by properly correlating the dimensions of the body, particularly the width of the intermediate zone **13** which acts as a delay space, and the impedances of the various junctions in the body with the operating range of frequencies.

In particular, the transit time of the minority carriers, in this case holes, across the intermediate delay space is adjusted to be approximately one-half the period of the alternating voltages in the operating band where the transit time across the intermediate delay space is given by the quantity

$$\frac{W^2}{4\pi D}$$

in which W is the width of the delay space and D is the diffusion constant of the minority carriers in the delay space. Additionally, the body is designed so that both the transit time of the minority carriers across the space charge region associated with the intrinsic region **14** is much shorter than their transit time across the delay space and the alternating voltage drop in the body occurs almost entirely across this space charge region. To this last end, it is found desirable to employ additional expedients to increase the forward bias across the junction **17** which serves as the emitting junction and in this way reduce the impedance to alternating currents of this junction. Various possible expedients to this end will be discussed subsequently in greater detail with reference to Figs. 2 through 5.

Briefly summarized, the operation to achieve negative resistance is essentially as follows: Under the influence of the alternating current signal applied across electrodes **15** and **16**, holes are injected from the terminal zone **11** past the emitting junction **17** into the intermediate zone **13**. They diffuse through this zone **13** at a relatively low rate and then enter the space charge region associated with the intrinsic zone **14** where the major voltage drop occurs. The high field in the space charge region carries the holes across this region into the terminal zone **12** at a high velocity so that the hole transit time across this region is short. The utilization of a relatively wide intermediate zone **13** in which there is little electric field and where the motion of the charge carriers occurs relatively slowly, to serve as a delay space, in conjunction with an intrinsic region **14** in which the electric field is high and where rapid motion of the charge carriers occurs, is characteristic of the mode of operation. In particular, the operation is such that the transit time of the holes across the delay space is so related to the frequency of the alternating voltage of the signal superimposed that there is introduced a phase shift of between 90 and 270 degrees between the voltage and current. The resulting negative resistance can be employed for use in an oscillator by associating with the semiconductive element an impedance which is resonant with the reactive component of the impedance of the element at a frequency at which the negative resistance effect is sufficiently pronounced.

In the light of this mode of operation, several considerations are important in the design of the semiconductive body. The emitting junction **17** is considerably more heavily doped on the side of the terminal zone **11**, typically by a factor of 10,000, so that the terminal zone **11** will function as a good emitter. Moreover, throughout the intermediate zone **13** the concentration of holes everywhere during operation is advantageously arranged to be less than the electron concentration, typically by a factor of 50. The transit time of the holes across the intrinsic region **14** is made small compared to the total transit time for travel between terminal zones **11** and **12**, but the voltage drop across the intrinsic zone **14** is made the major portion of the voltage drop across the body.

It is to be noted that as depicted in Fig. 1C the product of free holes in electrons at the emitting junction is approximately 2 times 10^{28}. A product of this general order of magnitude was found advantageous in the unit built and tested for keeping the impedance of the emitting junction relatively low. However, at equilibrium the product of the concentration of free holes and electrons in germanium at room temperature is 10^{27}. Accordingly, in order to achieve the desired higher product at the emitting junction, it is necessary to add continuously to the supply of electrons and holes in the intermediate region. This is tantamount to applying a forward bias on the emitting junction sufficient to maintain the desired degree of unbalance from the equilibrium condition. It is necessary to increase both the electron and hole concentrations in the intermediate zone **13** if approximate space charge neutrality is to be maintained. Since the necessary supply of holes can be provided by injection from the terminal zones, it is necessary only to provide a supply of electrons to the intermediate zone. In each of Figs. 2 through 5 the basic unit shown in Fig. 1A is modified to provide the needed supply of electrons to the intermediate zone.

It will be convenient in a discussion of these modifications to employ the reference numerals used in Fig. 1A for corresponding elements. In Fig. 2 there is shown a body of the type shown in Fig. 1 in which the collecting terminal zone **12A** is made of material which is characterized by a low lifetime for minority carriers therein. Such low lifetime is the equivalent of a high rate both for the recombination of charge carriers present and for the thermal generation of new charge carriers. A low lifetime and a high rate of thermal generation of charge carriers may be achieved in this terminal zone **12A** by diffusion therein of a trace of copper or nickel. However, it is important to keep the life-time of the material in the intermediate zone **13** and the intrinsic zone **14** high to keep the efficiency of the unit high. The thermal generation of hole electron pairs in the terminal zone **12A** may be accelerated, if found necessary, by heating. However, ordinarily it should be possible to adjust the lifetime of the material in the terminal zone to provide the desired amount of thermal generation of carriers at normal operating temperatures. As a result of the large reverse bias across the junctions **18** and **19**, many of the electrons which are thermally generated in the terminal zone **12A** will be drawn into the intermediate zone **13**. These electrons will, in turn, effect a complementary flow of holes from terminal zone **11** into the intermediate zone **13**, and as a consequence, the increase in concentration of holes and electrons at the emitting junction provides the desired increment on the forward bias thereacross.

In Fig. 3 there is shown a negative resistance element which employs a different expedient to increase the electron flow into the intermediate zone **13** for reducing the impedance of the emitting junction **17**. To this end, the basic structure shown in Fig. 1A is modified to provide means for the injection of electrons into the collector terminal zone **12** for diffusion across the intrinsic region **14** into the intermediate zone **13**. To this end, a portion of terminal zone **12** is converted to N-type conductivity to form an N-type zone **12B** and the junction therebetween is biased in a forward direction by the application of a voltage supplied by voltage source **21A** across electrodes **16** and **20**.

Alternatively, electrons may be injected into the collector terminal zone **12** in the manner shown in Fig. 4, in which a point electrode **22** makes rectifying connection to the terminal zone **12**. Electrode **22** is maintained at a negative potential with respect to the terminal zone **12** by voltage source **21B**.

In each of the embodiments shown in Fig. 5 the electrons injected into the collector zone are drawn across the intrinsic region **14** under the influence of the strong space charge fields therein for transfer to the intermediate zone **13** where they constitute the desired extra electron flow desired.

In the arrangement shown in Fig. 5, the basic arrangement shown in Fig. 1A is modified to include an electrode **23** which makes a nonrectifying or ohmic connection to the intermediate zone **13** and the voltage source **24** is connected between electrodes **15** and **23** to increase directly the forward bias on the emitting junction, as desired. In this arrangement, the only useful function intended for the electrode **23** is to aid in the control of the direct current forward bias on the emitting junction. It is undesirable that any signal current be shunted into this direct current biasing circuit. To minimize any signal shunting effect which the circuit associated with the electrode **23** may have, it is desirable to keep the impedance of this circuit high. To this end, the resistance **25** is inserted in this circuit to insure that the impedance offered the signal currents by this circuit is appreciably higher than that offered by the circuit through the emitting junction.

It seems desirable at this point before describing specific applications or devices of the kind described to differentiate more specifically such devices from PNIP junction transistors of the prior art which they superficially resemble.

First, in devices in accordance with the invention the semiconductive body is designed so that the transit time of minority carriers through the intermediate zone **13** which serves as the delay space is a large fraction, advantageously approximately one-half of the period of the operating alternating signal superimposed on the direct current bias applied between electrodes **15** and **16**. In contradistinction, in prior art devices bearing resemblance to those described, operation is generally such that the transit time of minority carriers across the intermediate zone which serves as the base is a much smaller fraction of the signal period. Stated somewhat differently, in prior art devices there is defined a parameter f_α, designated the alpha cutoff frequency, which is related to the transit time of minority carriers across the base, and operation is generally at frequencies below the alpha cutoff frequency. In contradistinction, in the practice of the present invention operation is at a frequency necessarily at least ten and advantageously about twenty times the alpha cutoff frequency.

Additionally, in the usual junction transistor which is used for the amplification of input signals it is customary to operate such that a real positive value close to unity is had by the parameter alpha which is defined as equal to the ratio

$$\left.\frac{i_e}{i_c}\right|_{E_c} \text{ constant}$$

where i_e and i_c represent the signal currents flowing across the emitting and collecting junctions, respectively, and E_c is the direct current collector bias. In the practice of the present invention, the frequency of operation is such that α is a complex number having an absolute value which is a small fraction of unity and having a positive imaginary part in contradistinction to the case of conventional transistor operation in which such complex imaginary part is either zero or negative. The small fractional absolute value of alpha characteristic of operation in the manner described can be explained by the fact that many of the carriers which cross the emitting junction in one portion of the operating cycle flow back across it in a succeeding portion of the cycle.

Moreover, whereas junction transistors require three electrode connections to the semiconductive element, each of which is effectively part of the circuit for alternating voltages, in the practice of the invention only two electrodes actively serve as part of the circuit for alternating currents, even though in some embodiments three connections may be provided to the semiconductive element. As a corollary, whereas in the usual junction transistor it is important to minimize the lateral base resistance, in the practice of the present invention the resistance of the path provided by any electrode connection to the delay space should be high. Accordingly, when a semiconductive device in accordance with the invention is employed in an amplifier, the input signal source and the output load are both effectively connected across the two active electrodes of the semiconductive element. Similarly, when a semiconductive device in accordance with the invention is employed in an oscillator, it is unnecessary to provide any external feedback between branch paths of the external circuitry of the device, but rather internal feedback of the kind which gives rise to the negative resistance effect is sufficient.

As illustrative of an application of the devices described, in Fig. 6 there is shown an oscillator which by way of example incorporates as the negative resistance element the semiconductive device shown in Fig. 5. In the interest of simplicity the same reference numerals have been used in the two figures to designate like elements. In addition, as a separate aspect of the invention, provision is made for modulating the amplitude or the frequency of oscillations under the influence of modulating intelligence.

It will be convenient to discuss first the basic oscillator arrangement and then indicate how modulation in accordance with this feature of the invention is affected. To the basic arrangement shown in Fig. 5, an inductor **26** is connected in series with the biasing voltage source **27** between electrodes **15** and **16** associated with zones **11** and **12** of the semiconductive body. The frequency of oscillation essentially is the frequency at which the inductance of element **26** resonates with the capacitance of the semiconductive body. The size of voltage source **27** and the design of the semiconductive element are correlated so that at the resonant frequency the transit time of holes from the terminal zone **11** to the intrinsic zone **14** is approximately one-half the period of this resonant frequency. The capacitor **28** is inserted advantageously to provide a bypass for the oscillatory signal around the voltage source **27**. Typically, its capacitance will be large compared to that of the semiconductive element. To provide added forward bias on the emitting junction **17** of the body the voltage source **24** and the current limiting resistor **25** are connected between electrode **23** associated with the intermediate zone **13** and electrode **15** associated with the emitting zone **11** in the manner shown in Fig. 5. There has now been described the basic oscillator circuitry. Oscillatory wave energy may be abstracted either by shunting a load across inductor **26** or by inserting a load serially in the circuit path between electrodes **15** and **16**.

Amplitude modulation in accordance with this aspect of the invention is achieved by varying the amount of forward bias added across the emitting junction **17**. In the embodiment depicted, amplitude modulation of the oscillatory signal is effected by modulating the voltage provided by the voltage source **24**. To this end, a source of modulating information **29** controls the voltage of the voltage source **24**. In a typical arrangement the output voltage developed across the load of an amplifier is inserted between electrodes **15** and **23** in serial connection with the voltage provided by source **24**, and the source of modulating information **29** is used to develop a voltage which is applied to the amplifier to control the output voltage developed across its load. Alternatively, it is feasible to have the source of modulating information control the resistance of the current limiting resistance **25** in accordance with modulating intelligence to vary the direct current flowing through the auxiliary control path.

It is characteristic, however, that variations of the forward bias on the emitting junction will have the concomitant effect of modulating the oscillatory frequency. If such modulation is found undesirably large, compensation may be provided by varying correspondingly the voltage applied by the voltage source **27** which controls the reactive component of the impedance of the semiconductive element. To this end, the source of modulating information **29** may be used to control the voltage source **27** typically in the manner previously described for control of the voltage source **24**, the variations applied to sources **24** and **27** being in the same sense. This means that when the magnitude of the voltage provided by source **24** is increased to augment the number of electrons injected into the intermediate layer, the magnitude of the voltage provided by source **27** is increased to increase the bias applied across terminal electrodes **15** and **16** to lower the capacitance associated with the semiconductive body.

In amplitude modulation operation in accordance with this aspect of the present invention, it may be advantageous for operation at lower frequencies to substitute for a semiconductive body which includes an intrinsic region associated with the collecting junction, as is characteristic of the negative resistance devices which form another aspect of the present invention as discussed hereinbefore, a semiconductive body in which this intrinsic region is omitted as is characteristic of the negative resistance devices of the type described in the previously identified Bell System Technical Journal article. In negative resistance devices of this latter kind, compensation for changes in the negative component of the impedance of the semiconductive body resulting from changes in the forward bias on the emitting junction is readily achieved by corresponding changes in the voltage applied across the connections to the two terminal zones as discussed.

However, in negative resistance devices of the kind which form a feature of the present invention, changes in the voltage applied across the two electrodes associated with the teminal zones will little affect the reactive component of the impedance of the semiconductive body if the steady voltage applied is already adequate to insure complete punch through of the intrinsic region **14** by the space charge so that control of the depth of penetration into the intrinsic region of the space charge region is effectively lost.

To permit control of the depth of penetration of the space charge region for modulator applications it becomes advantageous to operate with a voltage applied across the two electrodes associated with the terminal zones which is insufficient to punch completely through the intrinsic region **14**, so that variations in the voltage applied by the voltage source **27** under the influence of the source of modulating information **29** will serve to vary the depth of penetration and thereby compensate for the changes in the reactive component of the impedance of the body resulting from changes in the forward bias on the emitting junction **17**.

It is feasible to provide amplitude modulation in the manner discussed by changing the forward bias on the emitting junction of the body by any of the expedients illustrated in Figs. 3 through 5.

Alternatively, the arrangement may be employed to provide frequency modulation, the modulating intelligence being used to vary the voltage of source **27** to vary the reactive component of the impedance of the body for varying the resonant frequency of the tuned circuit which fixes the oscillatory frequency.

In Fig. 7 there is shown, as a high frequency application of a negative resistance device of the kind which forms one aspect of the invention, a dissected amplifier of the kind described in copending application Serial No. 364,291, filed June 26, 1953. Moreover, provision is made for having the arrangement shown serve additionally as a modulator. A hollow rectangular wave guide **40** is arranged to have nonreciprocal transmission properties by the insertion therein of a ferrite element **41** which is magnetized (by means not shown) in a direction parallel to the electric vector of the dominant mode of the wave guide **40**. The general principles of nonreciprocal arrangements of this kind are described in copending application Serial No. 362,193, filed June 17, 1953, by S. E. Miller. By choice in the direction of the magnetic field applied to the ferrite element the wave guide may be made to offer much higher attenuation to wave energy propagating therethrough in an undesired direction.

Amplification sufficient to overcome the attenuation in the low loss direction of travel but insufficient to overcome the attenuation in the high loss direction of travel may be provided by inserting a negative resistance device of the kind previously described along the wave path. In wave guide operations of this kind it is advantageous to avoid having to provide electrode connections to the middle zone of the body so that devices of the kind shown in Figs. 2, 3 and 4 are preferable for use in providing the negative resistance. By way of example, there is employed in the arrangement shown a negative resistance device of the kind shown in Fig. 4. In the interest of simplicity, similar reference numerals are used to designate like elements.

Coupled to the main guide **40** through an aperture **42** in a broad wall **40A** of the main guide **40** is a conductive chamber **43** of dimensions small relative to the operating wavelengths and to be non-resonant in the operating range. The semiconductive body is positioned in the chamber so that its collecting zone **12** forms for radio frequency currents a portion of the upper wall of the chamber **43**. The semiconductive body is insulated from the walls of the chamber **43** by the insertion of a thin dielectric spacer **44** between the body and the chamber wall. The coupling loop **45** is used to apply the radio frequency energy in the main guide to the body. For this purpose, the coupling loop **45** has one end fastened to the broad wall **40A** of the main guide and its other end is connected to the emitter electrode **15** of the semiconductive body. The intermediate portion of the loop is positioned to couple inductively to the magnetic vector of the radio frequency energy in the wave guide and passes through the aperture **42** in the wave guide wall **40A**. To provide the direct current bias necessary for negative resistance operation, the positive terminal of voltage source **46** is connected to the emitter electrode **15** by way of the coupling loop **42** and its negative terminal is connected to the collector electrode **16**. The voltage source **21B** has its negative terminal connected to the rectifying point electrode connection **22** and its positive terminal to electrode **16**.

For amplitude modulation of the wave passing through the wave guide **40** in the low loss direction of transmission, provision is made to vary the potential applied by voltage source **21B** for varying the amount of negative resistance inserted in the wave path. To this end, a source of modulating information **47** is shown connected to the voltage source **21B**. In operation, the modulating information changes the voltage supplied by voltage source **21B** which varies the amount of electron current injected from the collecting zone past the intrinsic region **14** into the intermediate region **13**. This variation in electron current to the intermediate region **13**, in turn, varies the forward bias on the emitting junction of the semiconductive element, and, as a consequence, the amount of negative resistance and amplification provided by the device. From the various applications which have been illustrated, it can be appreciated that negative resistance devices in accordance with the invention have a wide variety of uses. It is also be understood that the specific embodiments described are illustrative of the general principles of the invention. For example, while the first aspect of the invention has been described with reference to the use of a PNIP body it is equally feasible to employ NPIN bodies so long as the polarities of the various voltage sources are suitably reversed. Moreover, the semiconductive body may be formed of any suitable semiconductive material, such as silicon, silicon-germaniumalloys or any of the group III–group V compounds known to exhibit semiconductive properties.

Moreover, various other design modifications may be devised without departing from the spirit and scope of the present invention. For example, the semiconductive bodies may be designed to have in the intermediate zone which serves as a delay space, a gradient in the charge impurity concentration which provides a built-in electrostatic field which superimposes a drift velocity on the diffusion velocity of carriers through the delay space. As a consequence, a body of this type having an intermediate zone of given dimensions may be used in operation at higher frequencies than would otherwise be the case since the transit time of the minority carriers across such zone would be reduced.

What is claimed is:

1. In an oscillator, a semiconductive body having a pair of terminal zones of like conductivity type and intermediate therebetween a zone of opposite conductivity type and an intrinsic zone, a pair of electrode connections to the terminal zones, circuit means connected between the pair of electrode connections including a voltage source for applying a direct current voltage across the electrode connections to the terminal zones for establishing a flow of minority carriers through the intermediate zone of opposite conductivity type and an inductive element for providing a reactance which is resonant with the reactive component of the semiconductive element, the thickness of the intermediate zone of opposite conductivity type being such that the transit time of the minority carriers therethrough is approximately one-half the period of the resonant frequency, and means for providing a flow of majority carriers into said intermediate zone for reducing the impedance of the junction between said intermediate zone and its contiguous terminal zone.

2. A modulation arrangement comprising an oscillator in accordance with claim 1 and means for varying the flow of majority carriers into said intermediate zone in accordance with signal intelligence.

3. A modulation arrangement comprising an oscillator in accordance with claim 1 and means varying in the same sense the flow of majority carriers into said intermediate zone and the direct current voltage applied across the pair of electrode connections to the terminal zones.

4. In a modulation arrangement, an oscillator comprising a semiconductive body having a pair of terminal zones of like conductivity type and intermediate therebetween a zone of opposite conductivity type, a pair of electrode connections to the terminal zones including a voltage source for applying a direct current voltage across the electrode connections for establishing a flow of minority carriers through the intermediate zone and an inductive element providing a reactance which is resonant with the reactive component of the semiconductive element, the thickness of the intermediate zone being such that the transit time of the minority carriers therethrough is approximately one-half the period of the resonant frequency, a third electrode connection to the body, circuit means connected between one of the pair of electrodes connected to the terminal zones and said third electrode and including a voltage source for injecting a flow of majority carriers into the intermediate zone, and means

under the control of signal intelligence for varying in the same sense the flow of majority carriers in the intermediate zone and the direct current voltage applied to the pair of electrode connections to the terminal zone.

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