Sept. 14, 1965 H. E. KALLMANN 3,206,618

NEGATIVE RESISTANCE DEVICES

Filed March 15, 1963 5 Sheets-Sheet 1

FIG. 1

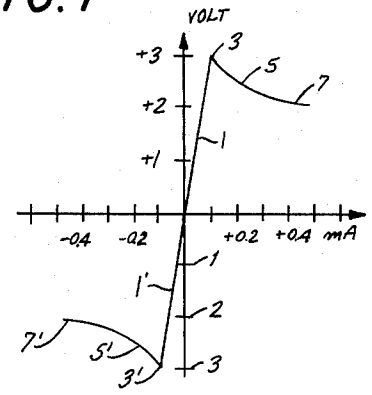
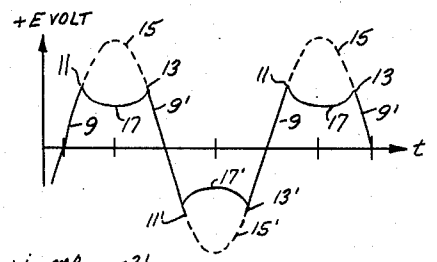



FIG. 2A



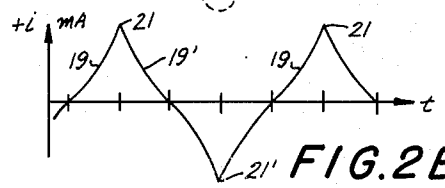




FIG. 2B

FIG. 3

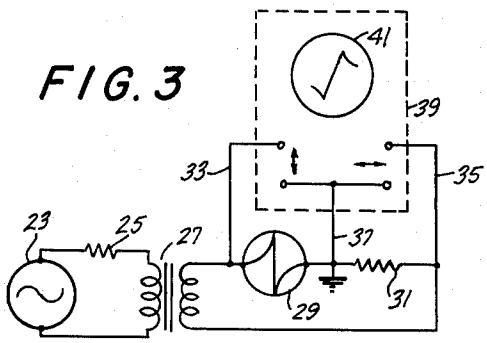



FIG. 4

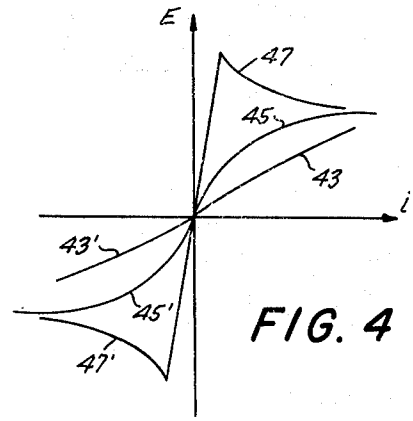



FIG. 6

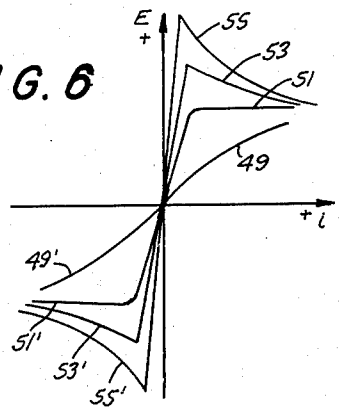
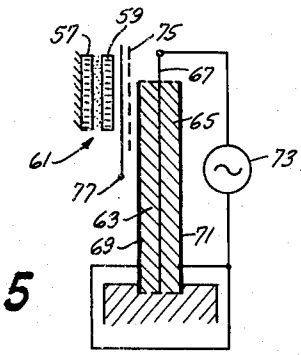



FIG. 5




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Sept. 14, 1965 H. E. KALLMANN 3,206,618

NEGATIVE RESISTANCE DEVICES

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FIG. 7A

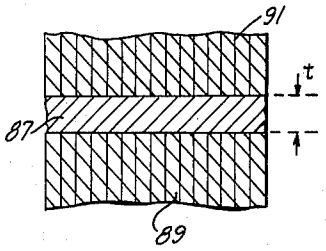



FIG. 8

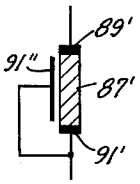



FIG. 7

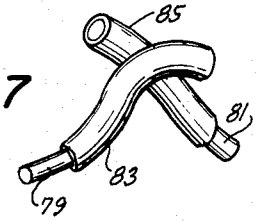



FIG. 9

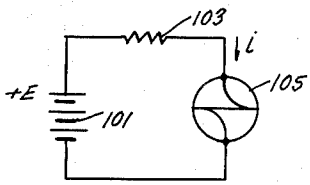
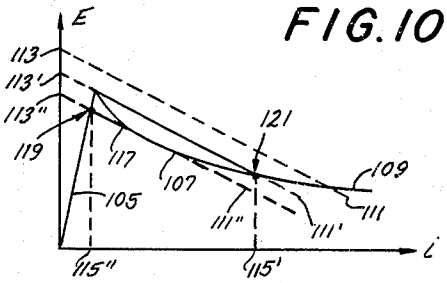



FIG. 10



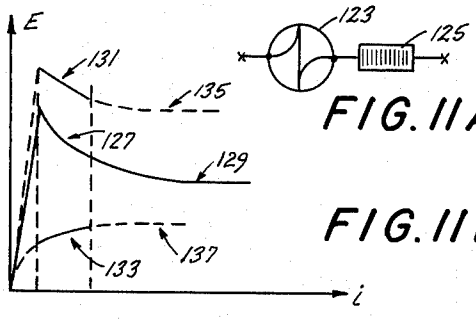




FIG. 11A

FIG. 11B

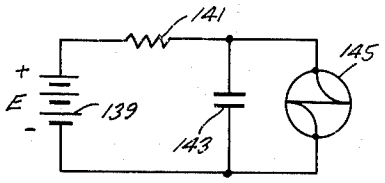



FIG. 12

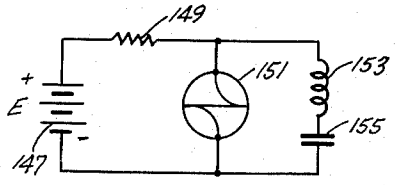



FIG. 13

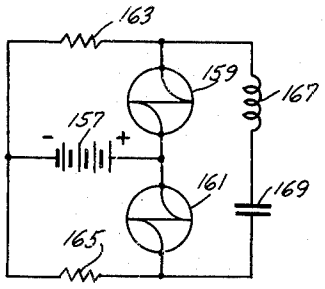



FIG. 14

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FIG. 15

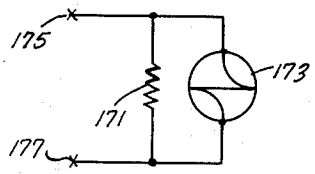



FIG. 16

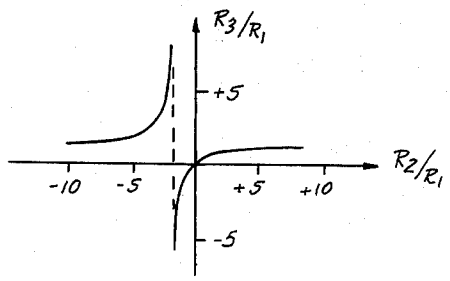



FIG. 17

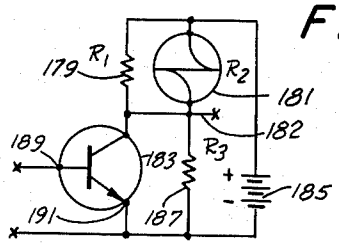



FIG. 18

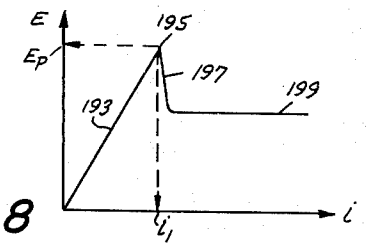



FIG. 19

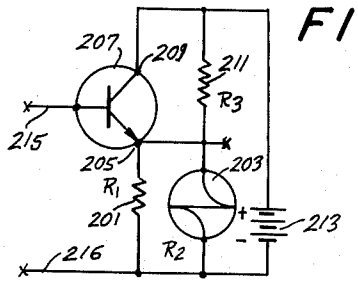



FIG. 20

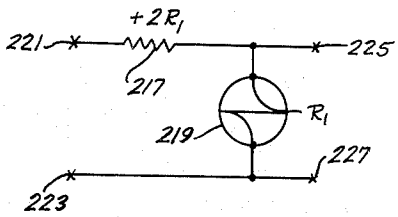



FIG. 21

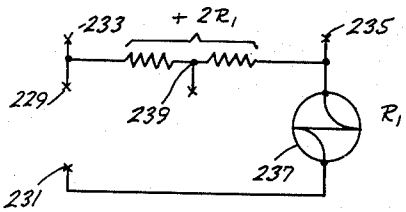
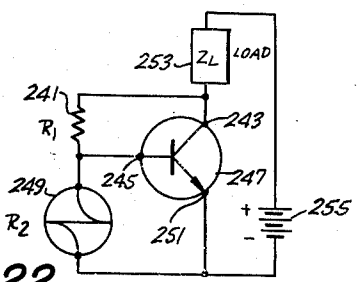



FIG. 22




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NEGATIVE RESISTANCE DEVICES

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FIG. 23

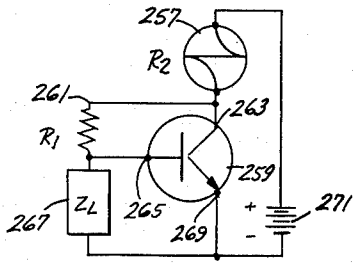
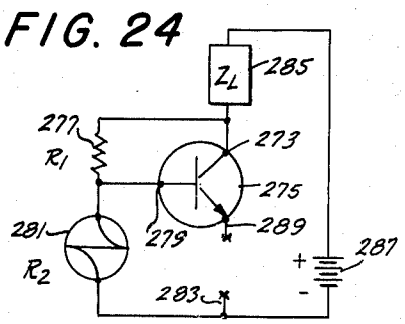



FIG. 24



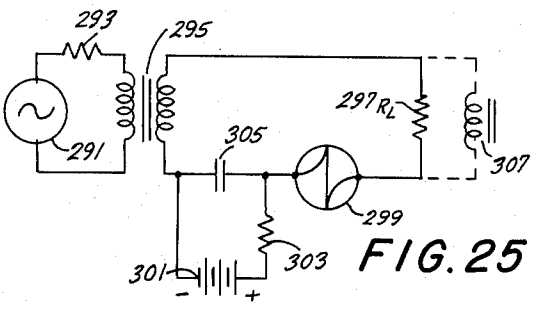




FIG. 25

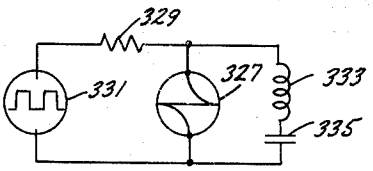



FIG. 26

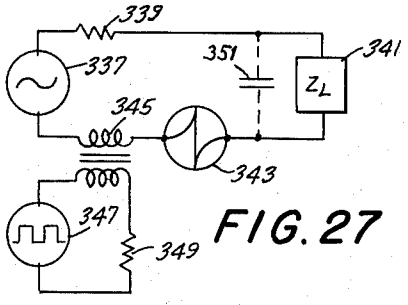



FIG. 27

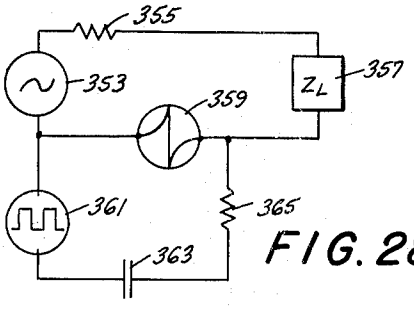



FIG. 28

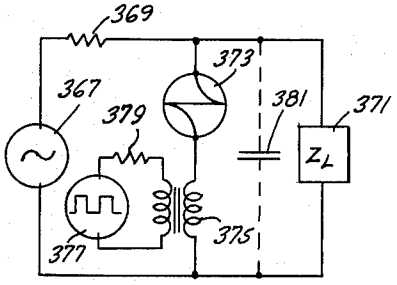



FIG. 29

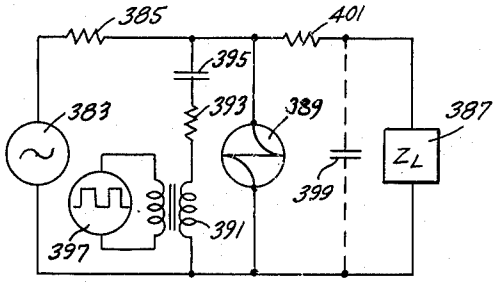



FIG. 30

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FIG. 31

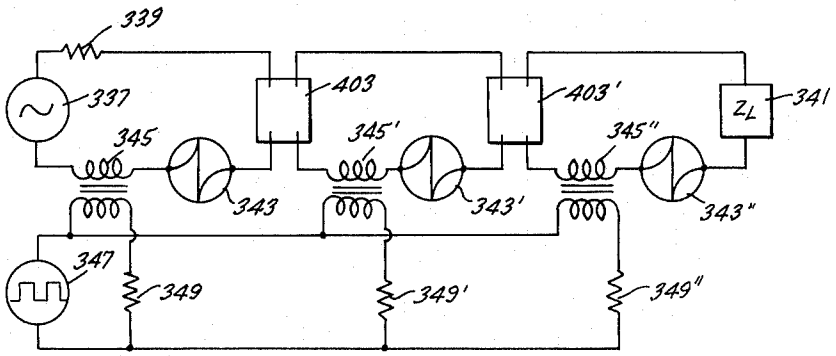



FIG. 32

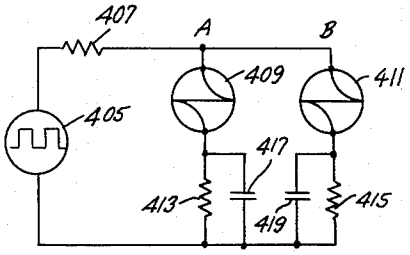
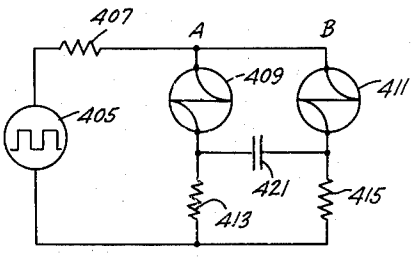



FIG. 33



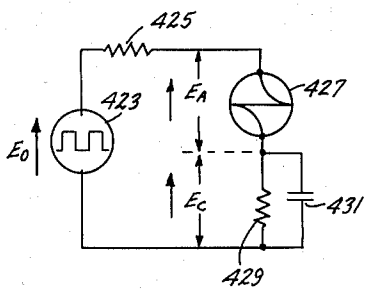




FIG. 34

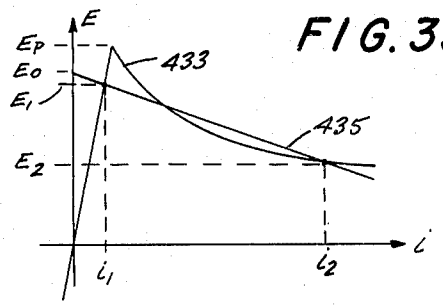



FIG. 35

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United States Patent Office 3,206,618 Patented Sept. 14, 1965



3,206,618

# NEGATIVE RESISTANCE DEVICES

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Filed Mar. 15, 1963, Ser. No. 265,387
15 Claims. (Cl. 307—88.5)

The objects of my invention are a new circuit element having negative resistance and circuits in which it may be used. Negative resistance is achieved by means of a "falling characteristic," i.e., a voltage vs. current characteristic having regions where an increase in current corresponds to a decrease in voltage. Such devices are useful in oscillator circuits, amplifiers, polarity reversing networks, impedance transformer networks, bi-stable switching and memory circuits, and they may be used as transducers. In particular, the object of my invention is a negative resistance device (NRD) having falling characteristics for either polarity, for both increasing and decreasing applied current, and over a wide frequency range, from D.C. to very high frequencies. The device is an N-type negative resistor having as much as three values of current for a given voltage, as distinct from an S type negative resistor having as much as three values of voltage for a given current. The disclosed devices are simple, very small, stable, and adaptable to both convenient currents and convenient voltages.

With the above objects in view, the invention includes a negative resistance device, comprising, in combination at least two electrodes of conductive material; and a thin layer of semiconductor material arranged between said two electrodes and in contact therewith in such a manner that a predetermined volume of said semiconductor material layer located between the contacting surfaces of said two electrodes, respectively, is fully penetrated by an electric field produced by at least one of said electrodes when operating potential is applied to said two electrodes, respectively.

In other aspects the invention also includes various circuit arrangements comprising my novel negative resistance device, namely e.g. resistor combinations, voltage dividers and amplifiers.

The novel features which are considered as characteristic for the invention are set forth in particular in the appended claims. The invention itself, however, both as to its construction and its method of operation, together with additional objects and advantages thereof, will be best understood from the following description of specific embodiments when read in connection with the accompanying drawings, in which:

FIG. 1 shows a typical voltage vs. current characteristic of the negative resistance device according to the invention;

FIGS. 2A, B show typical voltage and current plots vs. time applying to the case when a sinewave generator is connected to the NRD via a series resistor;

FIG. 3 shows a circuit for tracing the characteristic of FIG. 1 on an oscilloscope;

FIG. 4 shows other voltage vs. current characteristics, ohmic and non-ohmic, for comparison with that of the negative resistance device according to the invention;

FIG. 5 shows a transducer controlling the characteristic of a negative resistance device by deflection of a piezoelectric device;

FIG. 6 shows variations of the characteristic observable with varying electrode pressure or spacing;

FIG. 7 shows an experimental device comprising semiconductive oxide film on metal wire electrodes;

FIG. 7A represents the section through a semiconductor layer between conducting electrodes;

FIG. 8 is a modified semiconductor arrangement;



FIG. 9 shows a circuit with an NRD in series with a positive resistance;

FIG. 10 is a plot of the bistable characteristic of the circuit of FIG. 9;

FIGS. 11A, B show the linearizing of a nonlinear negative resistance by a suitable nonlinear positive resistance in series;

FIG. 12 shows a relaxation oscillator using an NRD;

FIG. 13 shows a sinewave oscillator using an NRD;

FIG. 14 shows a D.C. fed pushpull sinewave oscillator using two NRD's;

FIG. 15 shows a circuit of an NRD in parallel with a positive resistance;

FIG. 16 is a diagram of the resulting resistance of the combination of FIG. 15;

FIG. 17 shows the combination of FIG. 15 as collector load to a transistor amplifier stage;

FIG. 18 illustrates the voltage vs. current characteristic of combination of FIG. 17;

FIG. 19 shows combination of FIG. 15 as the emitter load of a transistor;

FIG. 20 shows a polarity reversing voltage divider circuit using an NRD;

FIG. 21 shows a phase-splitting voltage divider using an NRD;

FIG. 22 shows a polarity reversing feedback from collector to base of a transistor stage, using an NRD;

FIG. 23 shows a variant of circuit FIG. 22;

FIG. 24 shows circuit of FIG. 23 in a negative impedance converter;

FIG. 25 shows a D.C. fed amplifier stage using an NRD;

FIG. 26 shows a squarewave fed pushpull sinewave oscillator using one NRD;

FIGS. 27, 28, 29, 30 show different squarewave fed amplifier stages, each using an NRD;

FIG. 31 shows a squarewave fed cascade of amplifier stages using NRD's;

FIGS. 32 and 33 show squarewave fed bistable circuits using two NRD's;

FIG. 34 shows a squarewave fed bistable circuit using one NRD;

FIG. 35 is a plot of the voltages and currents for the circuit of FIG. 34.

A simple, convenient, and stable circuit element having bipolar negative resistance has very many uses in electrical circuitry. There exist a few two-terminal components whose voltage vs. current characteristics have falling regions indicating negative resistance. Among them is the carbon arc, for heavy current and too inert for high frequencies, having negative resistance mainly for rising, almost none for falling, current. Some gas discharges such as in Neon lamps offer negative resistance at low current but high voltage, suitable for switching at moderate frequencies. Another device is the tunnel diode, having (S type) negative resistance for one polarity only and at such very low voltage levels as to render it inconvenient for many purposes.

My new negative resistance device (NRD) differs from any known; and it exhibits typically a characteristic as shown in FIG. 1. The plot is symmetrical about its origin. The device offers very high, nearly linear positive resistance to the lowest current as is indicated by the straight regions **1** and **1'** for currents below ±0.1 milliampere. But at this value the curve turns over, at **3** and **3'**, more or less sharply, into a smoothly curved falling region, **5** and **5'**, finally to level out, at and **7'**. As a rule, forward and return trace (with current varied) are identical. This can be confirmed by applying a sine wave via a fixed ohmic resistance to the device and observing the voltage across it as a function of time, which is illus-

trated by FIG. 2A. If the device had ohmic resistance throughout the swing of the applied sine wave, one would observe a sine wave voltage comprising the solid line sections 9 and 9' and the broken-line peaks 15 and 15'. Actually, the voltage breaks down at the peaks 11 and 11', corresponding to points 3 and 3' in FIG. 1, and smoothly drops to a valley 17 and 17'. But then with decreasing current, unlike a carbon arc, the voltage rises again to peaks 13 and 13' generally of the same shape and height as peaks 11 and 11'. Unless the series resistance is very large the sine wave current will be distorted as shown in FIG. 2B. Rising and falling portions 19 and 19' correspond to the ohmic regions 1 and 1' of FIG. 1 and to 9 and 9' in FIG. 2A; but the lowered voltage drop in valleys 17 and 17' causes the current to rise above its usual round peaks to sharper peaks as shown at 21 and 21' in FIG. 2B.

The dynamic voltage vs. current characteristic of such devices is conveniently observed on an oscilloscope screen as in the circuit of FIG. 3. Here a source 23 of alternating current, with a source impedance 25, is fed via transformer 27 to a circuit comprising the new device represented (here and hereafter due to the lack of a standard symbol) by the symbol 29 and an ohmic resistor 31 in series. The junction between them is connected to the common ground terminal 37 of an oscilloscope 39; the voltage across the new device 29 is applied to vertical deflection terminal 33 of the oscilloscope, the voltage across resistor 31 is applied to the horizontal deflection terminal 35. Since the later voltage is proportional to the current, namely the same through resistor 31 and device 29, horizontal deflection thus represents current; hence the alternating current from source 23 will trace the dynamic characteristic, such as of FIG. 1, on the screen 41 of the oscilloscope 39.

The large variety of symmetrical voltage vs. current characteristics observable with various resistive devices may be reduced to the three basic curves of FIG. 4 and their many combinations. Exactly (nor nearly) ohmic resistors (such as of metal) have a characteristic 43 and 43', of constant slope $R=E/i$. Many semiconductor devices have characteristics where the resistance decreases with increasing current, to very low if still positive values, as in curve 45 and 45'. But the plot for the new NRD, curve 47 and 47', comprises a region of very high positive resistance about the origin and, for both positive and negative currents, a region of first moderately high, then decreasing negative resistance. Parallel combinations of different resistances yield characteristics where the two currents for each voltage are added; series combinations yield characteristics where the two voltages for each current are added.

In its earliest form, the new device consisted of a small quantity of solid semiconductor pressed between conducting electrodes of e.g. metal. These electrodes may, for instance, consist of a pair of round steel wires crossing at right angle, with a semiconductor such as zinc oxide ZnO in the form of a fine powder between them. I find it important that the layer of such powder grains is not substantially thicker than $10^{-4}$ centimeters=one micron, e.g. a layer of single grains powdered to $10^{-4}$ cm. grain size. I then observe peak voltages (3 and 3' in FIG. 1) of the order of 2 to 10 volts, with currents of the order of 100 microampere in the region of largest negative resistance. The overall field strength at 2 volts per 1 micron amounts to 20 kv./cm.; the steeper parts of the negative-resistance regions usually correspond to −5 kohm to −10 kohm or even higher.

The effect is believed to occur in a semiconductor bulk of substantially homogenous conductivity, as distinct from a PN junction. Present theory seems to permit, but has not developed, an explanation for this easily demonstrated effect. Field emission from metal to vacuum would require a field strength many orders of magnitude larger.



The following is therefore offered not as an explanation but as a possible clue to an explanation. (1) Semiconductors, unlike metals, do not provide an electric shield of their interior against external fields. Thus the conductivity of a semiconductor may be vastly increased, or decreased, according to whether it has electron or hole conduction and according to the metal used in the region of close proximity to the metal (A. V. Joffe, J. of Physics, Moskow 10, pp. 49–60, 1946). Such altered conductivity in a conductor-proximity modified region may extend about 1 micron from the metal surface; and for instance the conductivity of zinc oxide with the metals I use is in this region very much increased. Present theory seems to indicate that the depth L is centimeters of the conductor-proximity modified layer is

$$L=\sqrt{\frac{\epsilon V_0}{2\pi\delta}}$$

where $\epsilon$ is the dielectric constant, $\delta$ is the specific charge density of the bulk material, and $V_0$ the voltage across the layer in e.s.u. My observations to date are in plausible agreement with values expected from this equation. (2) The potential to free a charge (corresponding to the ionization potential of a gas) inside a semiconductor can be very small, a fraction of one volt. Present theory suggests that it is $\epsilon^2$ smaller than the ionization potential in free space. (3) Applying the analog of a gas discharge requiring perhaps three times the ionization potential for an avalanche, one may then expect that in a suitable semiconductor such as conductor-proximity modified zinc oxide a total potential of perhaps two volts suffices for an avalanche, with increase of current and decrease in voltage, similar to that in a gas discharge just beyond the Townsend current.

I find that zinc oxide single crystals of perhaps 0.1 cm. size are not suitable for my new device, neither when they are powdered to about $10^{-3}$ cms. grain size; but they behave substantially like the 1 micron grain size powder when they are further crushed to near that size of grain.

In my tests I have used as electrodes a large variety of conductors including aluminum, brass, copper, gold, mercury, silver, steel, tin alloy, zinc, graphite; most of these with success though not all equally suited and not each with each semiconductor. Among the semiconductors tested with success are zinc oxide ZnO, cupric oxide CuO, ferric oxide $Fe_2O_3$, an oxide of titanium, cadmium sulfide CdS, lead sulfide PbS, pure or doped, usually as thin layer of powder, e.g. settled on one electrode from a weak suspension in a drop of water. Required conditions for success in a suitable combination such as zinc oxide and silver are that the grains are fine enough, that they are pressed on at least one electrode for good electrical and thermal (cooling) contact. Not all grains will yield the desired result. In some semiconductors certain alignment of crystal axes may be unsuitable. For consistent success, good heat dissipation and larger currents, thin films, perhaps one micron or less thick, of semiconductor deposited on one electrode and touched by, or coated with, a second electrode should be used.

I have made and tested such devices. For instance, an iron wire of 0.25 mm. diameter and approximately 10 inches long was slowly oxidized by heating it with approximately 3 amp. A.C. from a 7 volt source for nearly 30 minutes freely suspended in air; temperature (below visible glow) estimated at 400° C. As a result, the surface changed from bright gloss to dull, but not dark; and under 300 magnification to barely noticeable yellow tinge on metallic base.

I find that two pieces of such wire as shown at 79 and 81 in FIG. 7, with oxide films indicated at 83 and 85, lightly touching each other exhibit an excellent, polarity and time symmetrical, negative-resistance characteristic as in FIG. 1, with sharp peaks at ±2.5 to 10 volts, with good stability for peak currents up to 1.0 milliampere and with initial (maximum) negative resistances well

above —5 kohm, perhaps —20 kohm, at frequencies to at least 10 kilocycles.

I also find that I may use with good result one such piece of oxidized iron wire as one electrode plus semiconductor, and as the other electrode bare metal such as solid copper, solid silver, cadmium plated steel, or thin deposits of metal on 0.25 mil Mylar film, such as gold 1000 A. thick, or similarly thin films of aluminum or silver. I also have formed useful oxide films on plates of titanium and applied a second electrode to these films, again in the general configuration of FIG. 7A where 87 represents a suitable semiconductor layer of thickness $t$ between conducting electrodes 89 and 91. I also propose a semiconductor 87' mounted or held as shown by FIG. 8 between two electrodes 89' and 91' with an auxiliary electrode 91'' not contacting the semiconductor 87' but connected with electrode 91' for influencing the semiconductor by its field.

I find that as useful an electrode as a metal foil is a deposit, 0.1 micron thick, of gold on a Mylar film 6 microns thick, the gold facing the semiconductor. Indeed, in other arrangements both electrodes may consist of such thin metal deposit on a plastic film and the experimental success proves them thick enough to modify the semiconductor. This suggests that for higher operating voltages one may use a device having several layers of semiconductor separated and modified by thin conductor layers between them, with terminals as now connected to the two outer conductors, and perhaps, e.g. for control purposes, also terminals connected to one or more intermediate conductor layers.

When operating an assembly with one movable electrode I find very often—when perhaps elastic deformation of electrodes and/or powder grains play a role—that between open and short circuit I can traverse repeatedly a family of characteristic curves as shown in FIG. 6. For tightest contact and relatively maximum pressure I find nearly ohmic low resistance, curve 49 and 49'; with reduced pressure the characteristic gradually changes to curve 51 and 51' which exhibits shoulders though no negative resistance. With still less pressure the shoulders grow into modest peaks, curve 53 and 53', and finally to the sharp peaks of curve 55 and 55'. Since it was noted that the whole range of motion is of the order of $10^{-4}$ cm., such arrangement may be used in a transducer to control an electrical circuit with very small motion (or pressure) of an actuator, as exemplified in FIG. 5. There the NRD comprises stationary electrode 57, movable electrode 59, and semiconductor 61 between them. As a source of minute motion I have shown a piezoelectric bender, comprising a pair of strips of e.g. barium titanate, 63 and 65, bonded to a common electrode 67 and each carrying an outer electrode 69 and 71. One end of the bender is held stationary as shown; when an electrical signal from source 73 is applied between the common electrode 67 and the tied outer electrodes 69 and 71 the free end will be deflected in well known manner, e.g. in the direction toward the NRD, from which it is separated only by the insulating layer 75 and electrostatic shield 77. The members 59, 77, 75 and 69 are shown in the diagram spaced from one another only for the sake of clarity, in fact they are in solid engagement for transmitting pressure. Thus the slight bending due to a signal will result in change of the pressure between the parts of the NRD and therefore of the positive or negative resistance between electrodes 57 and 59 and so control an electrical circuit, not shown.

The uses of NRD's as circuit elements are of considerable variety. They comprise (1) known circuits but in a more compact or convenient form than with other components; (2) new circuits for which, however, other components with unilateral negative resistance could also be used; and (3) new circuits made possible by a bipolar NRD.

The simple series connection (shown by FIG. 9) of a battery 101, an ohmic resistor 103 and an NRD105 is bistable as is the same circuit using a Neon glow lamp; but it requires much lower voltages, at most a 10 volt battery. The circuit is bistable if the positive resistance of 103 is less than the largest negative resistance of the NRD. FIG. 10 shows the positive half of the NRD characteristic, 105, 107, 109; and the slope of the broken lines 111, 111', 111'' corresponds to the resistance of 103. Their intercept, defining the operating point, depends on the source voltage 113, 113', or 113''. For voltages larger than 113' the current is large, above that marked 115'; for voltage lowered below 113' the operating point follows the curve 109 until for 113'' the line 111'' is tangential, and then jumps via 117 to point 119 on the ascending branch 105, then follows that for even lower voltages. With increasing source voltage the operating point follows the ascending branch to the peak, and for voltage marked 113' jumps along 111' to point 121. Thus for source voltages between 113'' and 113' the current may have values either near 115'' or near 115' depending on the previous state such as higher or lower voltage during a triggering voltage pulse.

In other applications the curvature of the NRD characteristic may be troublesome, representing a negative resistance whose value varies from point to point proportionally to the slope of the curve. To achieve a constant negative resistance, corresponding to a linear down slope, I may, as shown in FIG. 11A, add in series with the NRD123 a suitable nonlinear positive resistance 125 of familiar type, such as a silicon carbide varistor. Its proper characteristic is found as plotted in FIG. 11B where 127 is curved down slope of the NRD and where the desired series combination may have the linear down slope 131. The required correction is then the difference at each current between the voltages of 131 and 127, plotted as the curve 133 for the resistor 125. Its continuation, broken line 137 and the continuation 129 for the NRD add to the arbitrarily shaped continuation for the combination, broken line 135, in a region not to be used.

A relaxation oscillator circuit, familiar with Neon glow lamps, is shown in FIG. 12 adapted to the use of an NRD. A battery 139 of maybe 10 volts charges capacitor 143 via large resistor 141 until the peak voltage of shunting NRD145 is reached and it fires. The then heavy current through the NRD at lower voltage is supplied by the charge on capacitor 143 until the circuit falls back to low current and the cycle repeats.

A simple sine wave oscillator is shown in FIG. 13. It comprises a battery 147 feeding via resistor 149 an NRD 151 and maintaining it in its range of negative resistance. The NRD151 is shunted by the series combination of inductor 153 and capacitor 155 tuned to the desired frequency. NRD151 completes the resonance circuit and if its negative resistance is equal to, or larger than, the positive series resistance, e.g. that in the inductor winding, oscillations are maintained, with the less harmonic distortion the more linear the traversed negative resistance region of the NRD. Present NRD's readily oscillate at any frequency from below audio range to several megacycles.

As any other device, the new NRD's may be connected in push-pull pairs so as to increase power, to cancel nonlinearity, and to decouple signal circuits from supply voltage changes such as ripple. In FIG. 14 is shown a push-pull sine wave oscillator circuit corresponding to that of FIG. 13. A battery 157 feeds two NRD's 159 and 161 in parallel, via series resistances 163 and 165, respectively. However to the series tuned resonance circuit of inductor 167 and capacitor 169 the two devices are connected in series, and their two negative resistances are added. Since the sine wave excursions at any given moment add to the current through the one NRD while simultaneously subtracting from that through the other NRD, all even harmonics due to curvature are cancelled as in any other push-pull circuit. Substantially no D.C. or its ripple are

coupled into the load circuit 167, 169 since both its ends are at substantially the same D.C. potential.

FIG. 15 shows the simple but interesting combination of an ohmic resistor 171 of resistance $R_1$ (positive) in parallel with an NRD173 of resistance $R_2$ (negative). The resulting resistance between terminals 175 and 177 is $R_3=R_1R_2/(R_1+R_2)$; and since $R_2$ is negative the denominator becomes zero for $R_1=-R_2$, thus $R_3$ becomes infinite. In FIG. 16 the value of $R_3$ is plotted for $R_2$ varied, both in units of $R_1$. For $R_2/R_1$ near minus one the resultant $R_3$ steeply rises to $+\infty$, jumps to $-\infty$ and rises back to near $+1$, for large $\pm R_2$. The circuit thus offers very sensitive discrimination for small changes of $R_1$ near $-R_2$.

The parallel combination of nearly equal positive resistance and negative resistance, discussed in connection with FIGS. 15 and 16, is suited to serve in amplifiers as a large all-frequency load impedance yet has only a small supply voltage drop. FIG. 17 shows it, consisting of positive resistance $R_1$, 179, and negative resistance $R_2$, 181, in parallel as the collector load of transistor 183. The transistor is supplied from suitable battery 185, from which the negative resistance device 181 is also fed with suitable current via series resistance $R_3$, 187. If now, for given values $R_2$ and $R_3$, $R_1$ is chosen to satisfy $R_2=-R_1R_3/(R_1+R_3)$, then the load impedance to the transistor, for signals fed to the base 189 and emitter 191, is very high. Voltage and currents when using my negative resistance device in this manner are diagrammed in FIG. 18. After the straight rise 193 the peak voltage 195 is the same as 3 in FIG. 1. For the proper parallel combination, the voltage drop is nearly vertical, as at 197, with very high impedance, then levels out at 199, corresponding to 7 in FIG. 1. By adjustment of the total supply current to $i_1$, the circuit is constrained to operate in the region 197; but in spite of the high signal impedance, the voltage drop on the load is less than $E_p$.

FIG. 19 applies the same idea to an emitter follower circuit. The positive resistor $R_1$, 201 and negative resistor $R_2$, 203 in parallel are connected to emitter 205 of transistor 207 whose collector 209 and (via $R_3$, 211) negative resistor $R_2$, 203 are fed from battery 213. When adjusted as above the combination offers a high load impedance to the emitter for signals fed to base 215, yet has a small supply voltage drop.

In FIG. 20 is shown a voltage divider comprising a positive resistance 217 of value $+2R_1$ in series with a negative resistance 219 of value $-R_1$. If a voltage $E_1$ is applied to the input terminals 221 and 223, a current $+i_1=E_1/R_1$ will flow through the divider since its total resistance will be $R_1=+2R_1-R_1$. The voltage across the negative resistance 219 will be $-i_1R_1=-E_1$, equal to input $E_1$ but of opposite polarity. With output taken from terminals 225 and 227, the circuit thus serves as a phase-inverting circuit that may take the place of a transformer or a polarity-inverting amplifier stage of unity gain.

Further, as shown in FIG. 21 for the same components, the circuit may serve as a phase splitter, in place of a transformer with center-tapped secondary winding, e.g. to drive from a single-ended input signal $E_1$ applied to terminals 229 and 231 a push-pull output connected to terminals 233 and 235. Since the voltage at terminal 233 equals that of terminal 229, $+E_1$, and since the voltage across the NRD237, at 235, is $-E_1$, the voltage between 233 and 235 is $2E_1$ and is balanced to ground. The center 239 of resistor $2R_1$ is at zero signal potential and the resistor $2R_1$ may thus be replaced by a pair of loads $R_1$ in series and with their common terminal at signal ground.

Another application of the polarity-reversing voltage divider is shown in FIG. 22. There its positive resistor $R_1$, 241, is connected between collector 243 and base 245 of a transistor 247, and the negative resistance $R_2$, 249, is connected between base 245 and grounded emitter 251. Any signal potential on the collector 243, due to load $Z_L$, 253 is thus, suitably attenuated, fed back to the base 245 with reversed polarity. If the load $Z_L$ is a parallel resonance circuit and battery 255 of suitable voltage and polarity, the circuit oscillates, virtually presenting to the load $Z_L$ a negative resistance of high source resistance.

A variant of this circuit is shown in FIG. 23. There the load 257 in the collector circuit of transistor 259 is a negative resistance $R_2$. The feedback path compreses the positive resistance $R_1$, 261, between collector 263 and base 265, and the parallel resonance circuit $Z_L$, 267, of positive impedance, between base 265 and grounded emitter 269. With suitable supply 271 connected, the transistor will yield a signal on load 267 in phase with that on its base; thus the in-phase feedback will be regenerative and maintain oscillations.

FIG. 24 shows application of the circuit of FIG. 23 to a negative impedance converter. As before, signals from collector 273 of transistor 275 are fed via positive resistance $R_1$, 277 to base 279 and to negative resistance $R_2$, 281, between base and ground 283. A load $Z_L$, 285, and a suitable battery 287 are connected in series between collector 273 and ground 283. As has been proved by J. G. Linvill for more complicated circuits, the emitter impedance $Z_i$ between emitter 289 and ground 283 of this circuit is then $Z_i=-Z_L$ for any load impedance.

Use of an NRD in an A.C. signal amplifier is shown in FIG. 25. There a signal from A.C. source 291 with source impedance 293 is fed via transformer 295 to the load resistance $R_L$, 297. The NRD299 is connected in series with source and load, and by nearly cancelling out the sum of source resistance and load resistance permits a very large signal current to flow through the latter. The NRD is fed with D.C. from battery 301 via large resistance 303, both shunted for signal A.C. by the bypass capacitor 305. In this circuit the D.C. also flows through the transformer winding and the load; if the D.C. resistance of either, e.g. of $R_L$, is very large it may be bypassed by a choke 307.

All the negative resistance circuits described above are based on the assumption that the NRD is supplied with D.C., e.g. from a battery. Thus, once the NRD is connected, only one of the two negative resistance regions of its bipolar characteristic is actually utilized. Yet by the use of its bipolar symmetry many advantageous and novel circuits become possible. It is particularly advantageous to replace the D.C. of the battery by a square wave of a frequency above the range of interest and of a peak-to-peak amplitude twice that of the battery voltage. Except for the brief transition periods after each half cycle, the NRD is then operated at the same region of its characteristic as before and with the same negative resistance, but—as it were—alternatingly supplied with positive and negative D.C.

For instance, the circuit of FIG. 26 offers most of the advantages of a push-pull oscillator circuit, but it uses only a single NRD while replacing the D.C. fed push-pull circuit of FIG. 14. Squarewave generator 331 of a frequency well above that of the output sine wave feeds via large resistor 329 the NRD327 which is shunted by the series tuned resonance circuit of inductor 333 and capacitor 335, while for the output sine wave the resonance circuit is connected in series with the NRD327. The circuit oscillates unless 333 and 335 present such low impedance to the square wave as to bypass the NRD. As in a push-pull circuit, all even harmonics of the output sine wave due to nonlinearity of the NRD are cancelled. It should be noted that the supply square waves need not be perfectly flat-topped. If the tops droop or show wriggles, the effective negative resistance of the device is averaged over the corresponding range, and no harm is done as long as all the distortions are symmetrical for positive and negtaive squarewave half cycles.

FIGS. 27 and 30 show the advantages of supplying an NRD amplifier stage with square waves instead of D.C.,

particularly if the signal frequencies go down to and include D.C. FIG. 27 shows a D.C. and A.C. signal source 337 with source impedance 339 connected to a load $Z_L$, 341, via NRD343 acting as 299 of FIG. 25 described above. The NRD is fed with square waves from source 347 via series resistor 349, coupled into the signal circuit via small squarewave transformer 345. If source or load present a very high impedance to the square waves, they may be suitably bypassed as instanced by capacitor 351. Again, the nonlinearity of the NRD is reduced as in a push-pull pair. Since no D.C. is supplied to the circuit problems of separating it from signal D.C., and of D.C. supply drift do not arise with a strictly symmetrical, nonrectifying NRD. The circuit shown in FIG. 28 does much the same as that of FIG. 27 but saves the squarewave transformer if the signal and the squarewave sources are permitted a common terminal, e.g. ground. D.C. and A.C. signal source 353 of source impedance 355 is connected to load $Z_L$, 357, via NRD359. The latter is fed with squarewaves from generator 361 via series resistor 365. Low impedance of source or load to square wave frequencies is neither needed nor desirable; the bypass for D.C. and signal A.C. around the NRD is blocked by capacitor 363 in series with resistor 365.

Depending on the given source and load impedances, other NRD amplifier stages may be advantageous; the circuit of FIG. 29 is suited to extremely high impedance 369 of D.C. and A.C. signal source 367. This source is connected to a load 371 of much lower impedance $Z_L$. The impedance presented to the source is made very high by shunting the load with the approximately equal negative resistance (as explained in reference to FIGS. 15, 16) of NRD373. The latter is supplied from squarewave source 377 via series resistance 379 and small transformer 375. Any high resistance presented to the square waves by the load 371 may be bypassed by a capacitor 381. The circuit amplifies since the voltage across the very high impedance of 373 and 371 in parallel nearly equals the open-load voltage generated by source 367; yet the current through the modest load impedance is as large as if came from a source of negligible impedance. The circuit of FIG. 30 is a variant of this circuit. D.C. and A.C. signal source 383 of impedance 385 is connected to load 387 of impedance $Z_L$, if desired via a lowpass R.C. filter consisting of resistor 401 and capacitor 399. The NRD389 in parallel with the load is supplied by a parallel branch comprising the secondary winding of small transformer 391 in series with resistor 393 and signal blocking capacitor 395. Squarewave source 397 feeds the primary of transformer 391. As in the stages of FIGS. 27, 28, 29, the nonlinear distortions are minimized as in a push-pull stage, and there is no D.C. added to the signal D.C.

Among the advantages of supplying NRD amplifier stages with square waves is the ease with which feedback and interaction via the impedance of one common supply are avoided. FIG. 31 shows a cascade of three stages as that of FIG. 27, like parts being designated with like numerals. A.C. and D.C. signal source 337 of impedance 339 is connected via first NRD343, to a first interstage coupling 403. Its output is connected via second NRD343', to a second interstage coupling 403'; and its output is connected via third NRD343'' to the load 341 of impedance $Z_L$. Each stage is fed via a small transformer, 345, 345', 345''; the primaries are fed, via series resistors 349, 349', 349'' respectively, all in parallel from a common squarewave source 347 whose output need neither be flat-topped, nor constant, nor have a low source impedance at the signal frequencies. The interstage couplings 403, 403' are designed to pass D.C. and signal frequencies.

The use of the NRD as a D.C. fed memory element was implied in connection with its bistable characteristics in the circuit of FIG. 9. Squarewave supplied NRD's also offer interesting bistable—or memory—circuits.

In FIG. 32 are shown two similar NRD's 409 and 411, both fed from a squarewave source 405 via common series resistance 407. Connected in series with each NRD is a parallel combination of a resistor and a capacitor, 413 and 417, in series with 409 forming branch A, and 415 and 419 in series with 411 forming branch B. With the voltage of source 405 exceeding the NRD peak voltage, at least one NRD, say 409 in branch A, will have fired and pass substantial current. The voltage drop on common resistance 407 will then hold the other NRD411, below firing potential. At the end of any half cycle there will thus be a perceptible voltage, of opposing polarity, on capacitor 417, due to substantial current through resistor 413, but nearly no voltage on capacitor 419 since the current in branch B is negligible. With the end of the half cycle the source 405 suddenly reverses polarity; the charge remaining in capacitor 417, now of aiding polarity, will then help the NRD409 in branch A to fire first and the current it draws will again prevent the NRD411 in branch B from firing. During the half cycle the capacitor 417 has time to reverse the polarity of its charge, ready to aid again at the end of that half cycle. Thus the branch A that was ON during one half cycle will be ON again during the next, and so on, while the branch B that was OFF will be OFF again. In practical use, triggering means, e.g. voltage pulses, would determine which branch if to be ON and to stay ON until triggered differently.

FIG. 33 shows a variant of FIG. 32 but saves one capacitor. Like components are marked with like numerals, but instead of one capacitor each in the branches A and B the single capacitor 421 is used. It reverses its charge during each half cycle but with such phase as always to aid the firing of that branch that had last been ON.

Further saving in components is offered in the circuit of FIG. 34 using only one NRD but stipulating that the supplied square wave is kept regulated with level at voltage $E_0$, a little but safely below the peak ("firing") voltage $E_p$ of the NRD 427, as plotted in FIG. 35. The circuit comprises only the squarewave source 423 with source resistance 425, the NRD 427 and in series with it the parallel combination of resistor 429 and capacitor 431. Let it first be assumed that the NRD is OFF and the current through it, $i_1$, is negligible, as defined in FIG. 35 by the intercept of the NRD characteristic 433 with the straight line 435 starting at $E_0$ and of a slope corresponding to the total circuit resistance. The voltage built up on the capacitor 431 at the end of a half cycle is then the difference between $E_0$ and $E_1$, too small when added to $E_0$ after polarity reversal to reach $E_p$ and to fire the NRD; it stays OFF. Let it now, however, be fired—e.g. by a trigger pulse—by means not shown. When it is ON, the then substantial current $i_2$ will cause a voltage drop on resistor 429 that charges capacitor 431 to the difference between $E_0$ and $E_2$, or at least nearly so. This voltage, when added to $E_0$ after polarity reversal of the supplied square wave, is sufficient to let NRD 427 fire: it will thus again be ON, and so forth. The time constant of combination 429 and 431 should be larger than the time the—approximate—square wave requires for polarity reversal; but it should be rather less than the duration of each half cycle. The more nearly capacitor 431 is charged to $(E_0-E_2)$ the easier will be the tolerances on $E_0$ of the source and $E_p$ of the NRD.

It will be understood that each of the elements described above, or two or more together, may also find a useful application in other types of a negative resistance device differing from the types described above.

While the invention has been illustrated and described as embodied in a negative resistance device incorporated in various circuit arrangements, it is not intended to be limited to the details shown, since various modifications and structural changes may be made without departing in any way from the spirit of the present invention.

Without further analysis, the foregoing will so fully reveal the gist of the present invention that others can by applying current knowledge readily adapt it for vari-

ous applications without omitting features that, from the standpoint of prior art, fairly constitute essential characteristics of the generic or specific aspects of this invention and, therefore, such adaptations should and are intended to be comprehended within the meaning and range of equivalence of the following claims.

What is claimed as new and desired to be secured by Letters Patent is:

1. A current controlled negative resistance device comprising, in combination, at least two electrodes of conductive material; and a semiconductor body arranged between and in direct contact with said two electrodes, the material of said electrodes and said semiconductor body being such and said semiconductor between said two electrodes being so thin that the electric field caused by the contact potential between at least one of said electrodes and said semiconductor body penetrates at least substantially said semiconductor body and the materials of said electrodes and said semiconductor body being such that said penetrating field causes said semiconductor body to assume a characteristic having a region of current-controlled negative resistance.

2. A symmetrically bipolar current controlled negative resistance device comprising, in a substantially symmetrical combination at least two electrodes of conductive material; and a semiconductor body arranged between and in direct contact with said two electrodes, the material of said electrodes and said semiconductor body being such and said semiconductor between said two electrodes being so thin that the electric field caused by the contact potential between at least one of said electrodes and said semiconductor body penetrates at least substantially said semiconductor body and the materials of said electrodes and said semiconductor body being such that said penetrating field causes said semiconductor body to assume a characteristic having two regions of current-controlled negative resistance.

3. A current-controlled negative resistance device comprising, in combination, at least two electrodes of conductive material; and a film-like layer of semiconductor body arranged between said two electrodes and in direct contact with said two electrodes, the material of said electrodes and said semiconductor body being such and said semiconductor between said two electrodes being so thin that the electric field caused by the contact potential between at least one of said electrodes and said semiconductor body penerates at least substantially said semiconductor body and the materials of said electrodes and said semiconductor body being such that said penetrating field causes said semiconductor body to assume a characteristic having a region of current-controlled negative resistance.

4. A current-controlled negative resistance device comprising, in combination, two electrodes of conductive material; a semiconductor body arranged between and in direct contact with said two electrodes and having at least one lateral exposed surface; and an auxiliary conducting member connected with one of said two electrodes and arranged opposite said exposed lateral surface of said semiconductor body and spaced therefrom, the material of said electrodes, said auxiliary conducting member and said semiconductor body being such and said semiconductor between said two electrodes being so thin that the electric field caused by the contact potential between at least one of said electrodes and said semiconductor body penetrates at least substantially said semiconductor body and the materials of said electrodes and said semiconductor body being such that said penetrating field causes said semiconductor body to assume a characteristic having a region of current-controlled negative resistance.

5. A current-controlled negative resistance device operable as a transducer comprising, in combination, at least two electrodes of conductive material, one of said electrodes being stationary and the other electrode being movable relative to said one electrode; a semiconductor body arranged between and in direct contact with said two electrodes, the material of said electrodes and said semiconductor body being such and said semiconductor between said two electrodes being so thin that the electric field caused by the contact potential between at least one of said electrodes and said semiconductor body penetrates at least substantially said semiconductor body and the materials of said electrodes and said semiconductor body being such that said penetrating field causes said semiconductor body to assume a characteristic having a region of current-controlled negative resistance.

6. In combination, a current-controlled negative resistance device having in its negative characteristic a non-linear portion; and in series-connection therewith a non-linear positive resistance device having in its characteristic and operated in a region of such curvature that it serves to compensate the non-linearity of said characteristic of said current-controlled negative resistance device so that the overall characteristic of said combination is negative and substantially linear over said operating region.

7. A current-controlled negative resistance device comprising, in combination, a layer of semiconducting material of substantially homogenous conductivity formed on a first conducting electrode and contacting it with its one face, and a second conducting electrode contacting the other face of said layer, said semiconducting material layer being penetrated by the electric field due to the contact potential of at least one of said electrodes when operating potentials are applied to them.

8. A circuit arrangement presenting a very high resistance for a part of its current vs. voltage characteristic, comprising, in combination, current-controlled negative resistance device having a predetermined value of negative resistance in a selected region of operation; and a positive resistance device connected in parallel with said negative resistance device so as to form a parallel-combination and having a value close to said negative resistance value of said negative resistance device in said selected region of operation, whereby the resulting resistance of said parallel-combination in said selected region of operation is caused to be very high and current stable when it is negative.

9. A polarity-reversing voltage divider circuit comprising, in combination, two input terminals for applying a given voltage of given polarity; a resistive series-combination connected across said input terminals and comprising current-controlled negative resistor of given value and a positive resistor of larger value in series with each other; and two output terminals respectively connected with the ends of said negative resistor, so that upon application of said given voltage of given polarity to said input terminals a voltage proportional to said input voltage and of opposite polarity is available at said output terminals.

10. A polarity-reversing voltage divider circuit comprising, in combination, two input terminals for applying a given voltage of given polarity; a resistive series-combination connected across said input terminals and comprising current-controlled negative resistor of given value and a positive resistor of a value twice said first mentioned value in series with each other; and two output terminals respectively connected with the ends of said negative resistor, so that upon application of said given voltage of given polarity to said input terminals a voltage proportional to said input voltage and of opposite polarity is available at said output terminals.

11. A phase-splitting voltage divider circuit comprising, in combination, two input terminals for applying a given signal voltage; a resistive series-combination connected across said input terminals and comprising current-controlled negative resistor of given value and a positive re-

sistor of a value twice said first mentioned value in series with each other; and two output terminals respectively connected with the ends of said positive resistor, so that upon application of said given signal voltage to said input terminals a push-pull output signal proportional to said input voltage is available at said output terminals.

**12.** A circuit arrangement comprising, in combination, a symmetrically bipolar current-controlled negative resistance device; and means for supplying substantially square wave alternating current to said negative resistance device, so that both the operating current in the circuit arrangement and the negative resistance have substantially the same mean valves during both half cycles of said square wave alternating current, while the non-linear characteristics thereof are of opposite curvatures, respectively.

**13.** A sine-wave generator circuit comprising, in combination, a symmetrically bipolar current-controlled negative resistance device; means including series resistance for supplying substantially square wave alternating current via said resistance to said negative resistance device; and a series-tuned resonance circuit comprising inductance and capacitor means connected across the terminals of said negative resistance device.

**14.** In an amplifier circuit in combination, a source of signals; load impedance means connected with said source; a symmetrically bipolar current-controlled negative resistance device connected with said source for amplifying said signals fed by said source to said load impedance means; and a source of substantially square wave alternating current for supplying said negative resistance device therewith, so that both the operating current in the circuit arrangement and the negative resistance have substantially the same mean values during both half cycles of said square wave alternating current, while the non-linear characteristics thereof are of opposite curvatures, respectively.

**15.** A bistable circuit comprising, in combination, at



least one symmetrically bipolar current-controlled negative resistance device having a predetermined peak voltage and being capable of being either in low-current or in high-current state; a source of square wave alternating voltage including a series resistance feeding said negative resistance device via said resistance, said voltage having an amplitude below said peak voltage and therefore insufficient to fire said current-controlled negative resistance device after a polarity reversal; capacitor means so connected in shunt to a resistance passed by at least part of the current through said negative resistance device that the charge of said capacitor means varies in proportion to said current and aids the firing of said negative resistance device after polarity reversal of said square wave alternating current, said capacitor means being so dimensioned that the voltage stored therein is insufficient to aid the firing of said current-controlled negative resistance device if the latter has been in its low-current state during the preceding half cycles of said square wave voltage, but is sufficient to aid firing said current-controlled negative resistance device if the latter has been in its high-current state during the preceding half cycle of said square wave voltage.

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