Dec. 23, 1969 SE PUAN YU 3,486,132

GUNN EFFECT DEVICE HAVING IMPROVED PERFORMANCE

Filed March 20, 1968 3 Sheets-Sheet 1

Fig. 1.

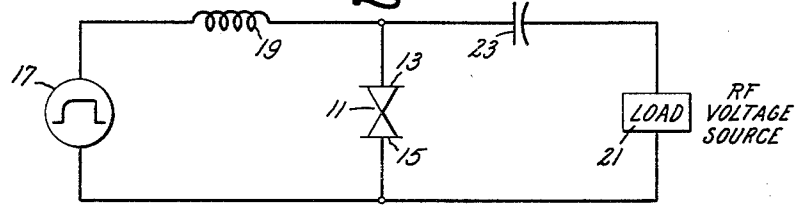


Fig. 4.

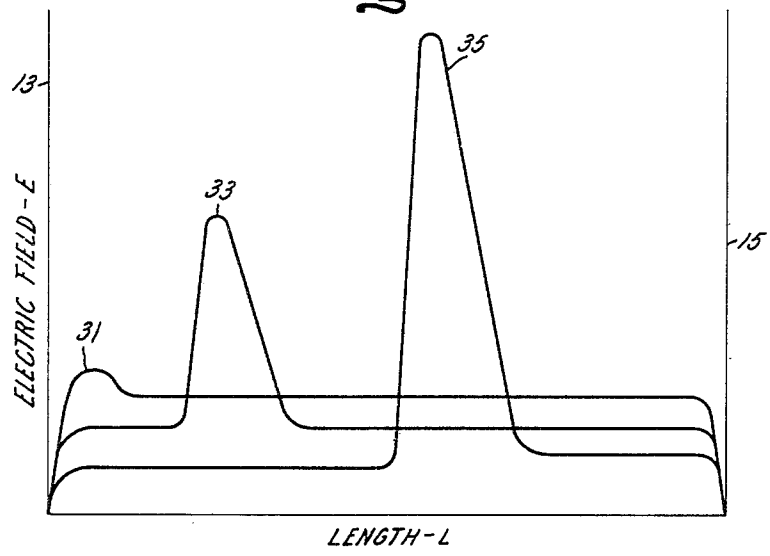
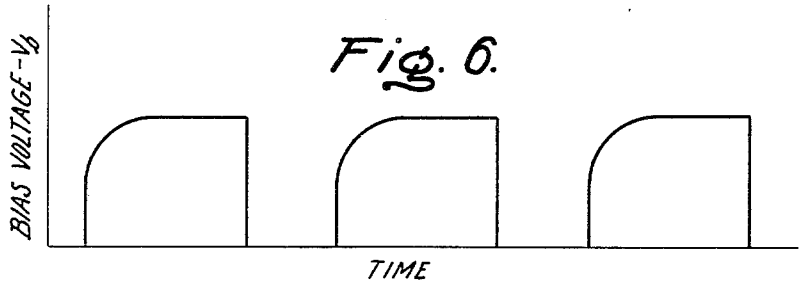


Fig. 6.



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GUNN EFFECT DEVICE HAVING IMPROVED PERFORMANCE

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Fig. 2.

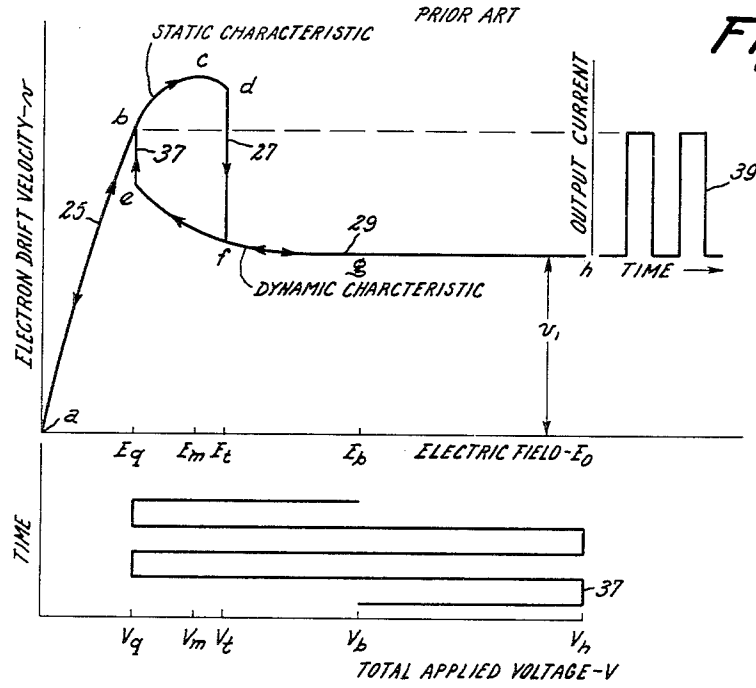
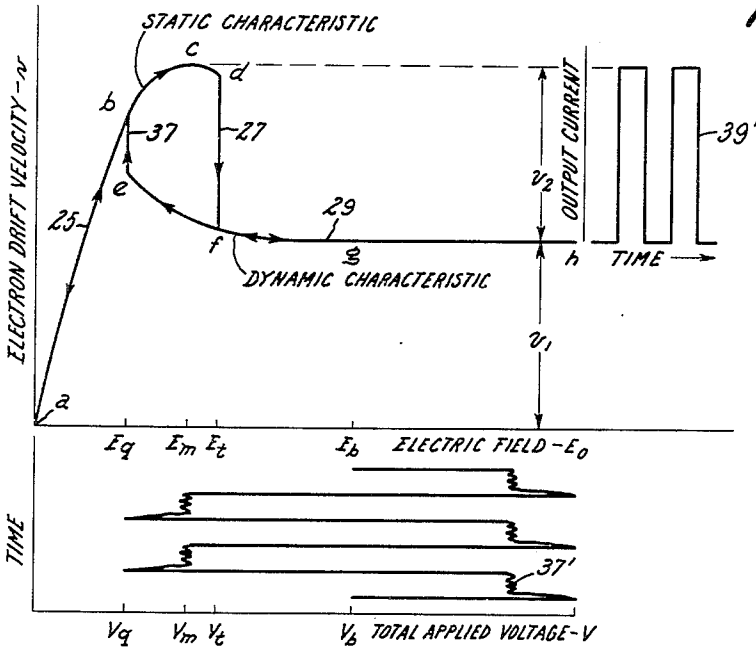


Fig. 3.



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Fig. 5.

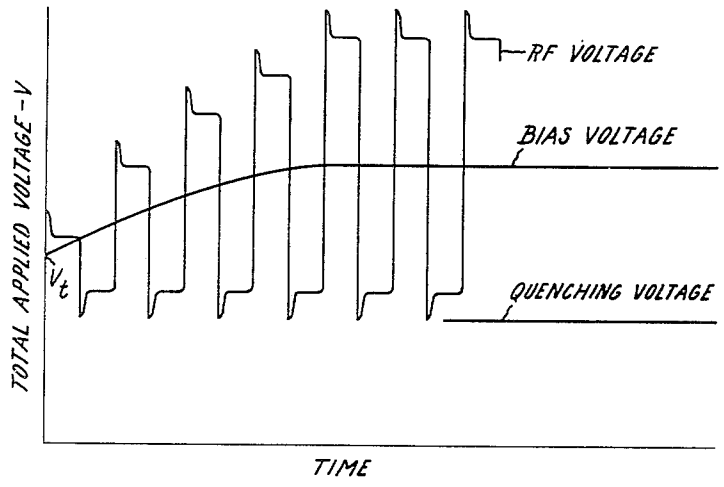
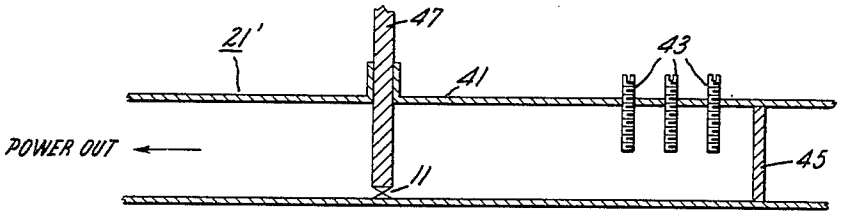


Fig. 7.



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3,486,132

GUNN EFFECT DEVICE HAVING IMPROVED PERFORMANCE

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Int. Cl. H03b 5/12, 5/36, 7/14
U.S. Cl. 331—107 6 Claims

ABSTRACT OF THE DISCLOSURE

In a Gunn effect device operated in the quenched domain mode, the applied pulsed bias voltage and RF voltage and resulting output current are optimized to improve the efficiency. In each pulse, a time varying bias voltage is applied until the RF voltage reaches steady state, and the RF voltage is rectangular in waveform with a spike at one leading edge so that the total voltage is below the quenching voltage to quench the domain, and then changes to the voltage which produces maximum electron drift velocity, where the device operates for most of the half cycle and produces maximum current amplitude.

This invention relates to the improvement of the performance of Gunn effect devices, and more particularly to Gunn effect devices which are operated in the quenched domain mode at higher efficiencies than have been achieved heretofore.

The discovery was made in 1963 by J. B. Gunn that microwaves could be generated by applying a steady D-C voltage across a crystal of gallium arsenide. As the electric field produced in the crystal of n-type gallium arsenide is increased, the current is at first proportional to the applied voltage in accordance with Ohm's law, but at a threshold value of the electric field there is a steady oscillation of current whose frequency is in the microwave region. The Gunn effect can be observed in other semiconductor materials such as n-type indium phosphide and cadmium telluride having a similar or closely related electronic structure. It is now generally accepted that the Gunn effect is associated with the transfer of "hot" electrons between conduction-band valleys separated in energy by a fraction of an electron-volt. As the electron activity is increased by the applied field, electrons are transferred from a low-energy, high mobility sub-band to a higher energy, low mobility sub-band. The transferred electron mechanism gives rise to a voltage controlled bulk negative differential resistance, since as the electric field is increased more electrons are transferred into the higher energy, low mobility sub-band where they become less effective in the conduction process. If the rate at which electrons are removed from the conduction process is high enough, the current will decrease even though the electric field is being increased. The portion of the current versus applied voltage curve in which the current falls as the applied voltage is increased is called the region of negative differential resistance.

For bias voltages which produce electric fields in the negative differential resistance region (the applied voltage divided by the length of the specimen is the electric field in the specimen), it has been shown by thermodynamical considerations that the material making up the Gunn effect device, which is also known as a Gunn

diode or Gunn oscillator, ordinarily breaks up into a high-field domain and a lower field region. A small domain forms near the cathode of the device within which the field is very high, whereas in the rest of the device, outside of the domain, the field has a small value. This situation is inherently unstable, and the high-field domain moves across the device from one electrode to the other, growing constantly larger, and as it disappears at the other electrode a new high-field domain nucleates. The period of the resulting current oscillations is given by the transit time for the moving high-field domain to transverse the length of the device. This is the original mode of operation discussed by Gunn and is known as the Gunn mode. The output frequency of a Gunn effect device operated in this manner is thus inversely proportional to the length of the sample. The conventional Gunn mode diode, since it is a transit-time device, must be kept thin to achieve the higher microwave frequencies, and this limits its power capabilities.

Another mode of operation which has been suggested for a Gunn effect device is the quenched domain mode, and is characterized by quenching or extinguishing the high-field domain after launching before it has completely traversed the length of the sample. This is done by applying to the device, in addition to the D-C biasing voltage, a radio frequency voltage produced by a tuned circuit having a magnitude comparable to the bias voltage such that when the domain is launched the total voltage across the device exceeds the threshold voltage, and it is suppressed when the total voltage falls to a sufficiently low value below the domain quenching voltage. The domain is therefore quenched in a time that is less than one complete period of Gunn oscillation, and a new domain nucleates instantly. Frequencies considerably higher than the transit-time frequency can be achieved. It is the improvement of performance of the Gunn effect device operated in the quenched domain mode to which the present invention is addressed.

An object of the invention is to operate a Gunn effect device to achieve higher efficiencies than have been attained heretofore.

Another object is to provide a new and improved circuit for producing high frequency currents which employs a Gunn effect device operated in the quenched domain mode in an optimized manner to achieve greater amplitude of the output current.

Yet another object is the provision of such a circuit wherein the performance of the Gunn effect device operating in the quenched domain mode is optimized by control of its voltage and current waveforms.

In accordance with the invention, a circuit for producing a high frequency current comprises a Gunn ducing a high frequency current comprises a Gunn effect device having a threshold voltage at which a high-field domain is launched for movement from one of its electrodes toward the other electrode. Means are provided for applying to the device a time varying unidirectional biasing voltage having a magnitude at least equal to the threshold voltage, and other means are provided for simultaneously applying to the device a radio frequency voltage which has a period less than the transit time of the domain. The radio frequency voltage has a substantially rectangular waveform with a slender spike at one leading edge and an amplitude such that the total applied voltage due to the superimposed biasing voltage and radio frequency voltage in one half cycle thereof is

initially equal to or less than the quenching voltage so that the high-field domain is quenched, whereafter the total applied voltage changes to a substantially constant value for the remainder of the half cycle and approximately equals the voltage at which maximum electron drift velocity occurs. On the other half cycle the total voltage is a high voltage at which the high field drift velocity occurs. In this way the voltage and output current waveforms of the Gunn effect device are optimized, and theoretical efficiencies as high as 27 percent are achieved.

The foregoing and other objects, features, and advantages of the invention will be apparent from the following more particular description of a preferred embodiment of the invention, as illustrated in the accompanying drawings wherein:

FIG. 1 is a schematic circuit diagram of an illustratory circuit comprising a Gunn effect device connected for operation in the quenched domain mode;

FIG. 2 is an electron drift velocity versus electric field characteristic curve for the Gunn effect device to which is added waveforms of the applied RF voltage and output current illustrating a prior art method of operating the Gunn effect device in the quenched domain mode;

FIG. 3 is similar to FIG. 2 but shows the waveforms of applied RF voltage and output current for more efficient operation of the Gunn effect device in accordance with the invention;

FIG. 4 shows a plot of electric field versus device length illustrating the high-field domain at several time intervals as it propagates across the device;

FIG. 5 is a characteristic curve of the applied electric field versus time showing the use of a time varying bias voltage during the RF voltage build-up period;

FIG. 6 is a diagram to a larger scale showing the waveform of the train of pulses produced by the pulsing circuit of FIG. 1; and

FIG. 7 is a cross-sectional diagram of an illustratory multi-mode tuned circuit which produces a rectangular RF voltage with a spike at the leading edge as shown in FIG. 3.

The Gunn effect device or Gunn oscillator **11** shown in FIG. 1 comprises for instance a crystal of n-type gallium arsenide between two electrodes **13** and **15**. In this circuit, the Gunn effect device **11** is connected for operation in the quenched domain mode, and provision is made for applying a steady D-C voltage to the device **11** on which is superimposed a radio frequency voltage. The source of D-C biasing voltage for the device **11** is a pulsing circuit **17** for producing a pulsed waveform as shown in greater detail in FIG. 6 which will be explained later. Although pulse operation is preferred, continuous operation of a Gunn diode is feasible if it is properly designed. The pulsing circuit **17** is connected in series circuit relationship with a high frequency choke **19** across the two electrodes **13** and **15** of the device **11**. The choke **19** prevents the applied RF voltages from reaching the source of D-C biasing voltage. The source of RF voltage is provided by a multi-mode tuned circuit **21** connected in series circuit relationship with a by-pass capacitor **23** across the electrodes **13** and **15** of the device **11**. The capacitor **23** presents a low impedance for the RF voltage but prevents the direct current biasing voltage from reaching the load **21**. As will be described in greater detail later, the applied RF voltage is produced by the output RF current of the Gunn effect device **11** which flows through the load **21**. Although such an arrangement is advantageous, it is not an essential condition for the practice of the invention, and the Gunn effect device **11** can be connected in other circuits in which the D-C current flows through the load, and in which the source of RF voltage is provided by different circuit elements than those which comprise the load.

The fundamental principles of a Gunn oscillator or Gunn effect device have been referred to previously, and will be briefly reviewed with reference to FIGS. 2 and 4. In a Gunn effect device the current i is directly proportional to the low field electron drift velocity v and is more particularly given by the equation $i=n_0v$, where n_0 is the donor density. The voltage V across the two electrodes of the device is directly proportional to the spatial-average electric field E_0 in the device and is given by the equation $V=E_0L$ which L is the device length between the electrodes. FIG. 2 shows the electron drift velocity versus electric field (v–E_0) characteristics, from which the current versus voltage (i–V) relation can be determined. In FIG. 2, curve **25** represents the static characteristic of the device which depends on the material property alone and substantially follows Ohm's law from the point a to the point c. That is, as the applied voltage V or electron drift velocity v is increased, the electric field E_0 or current i increases also. Between the point c at which maximum electron drift velocity occurs and the point d, deviations from Ohm's law begin to appear and the device has begun to enter the negative differential resistance region. In the negative differential resistance region the electron drift velocity decreases even though the electric field is being increased, and this is due to the transfer of electrons from a low-energy, high mobility sub-band to a higher energy, low mobility sub-band where they come less effective in the conduction process. At a particular threshold value of the electric field E_t, there is an abrupt change of electron drift velocity approximately as indicated by the straight line curve segment **27**, and as the electric field is further increased the device follows the dynamic characteristic curve **29**. A large n_0L product is assumed such that both the positive and the negative dielectric relaxation times are short compared to the RF period. The abrupt change in electron drift velocity in shifting from the static characteristic **25** to the dynamic characteristic **29** gives rise to the RF current. At the threshold electric field E_t a high-field domain is formed in the device, and the dynamic characteristic **29** then applies rather than the static characterisic **25**. The dynamic characteristic of the device depends on the material property and also on the product of the donor density n_0 and the length L of the device, i.e., the n_0L product.

The formation and propagation of the high-field domain is shown graphically in FIG. 4, wherein the electric field E is plotted against the length of the device L as the abscissa. When the voltage which produces the threshold electric field is applied, a small high-field domain indicated by the curve **31** nucleates at the one electrode **13** and moves across the device toward the other electrode **15**, growing larger as it propagates across the length of the device. Curves **33** and **35** show the increase in the size of the high field domain as it moves across the device. Upon reaching the electrode **15**, the high-field domain disappears and a new domain nucleates at the first electrode **13**, and the new domain in turn moves across the device growing larger as it proceeds toward the second electrode **15**. The time to traverse from one electrode to the other is known as the transit time.

In the Gunn mode of operation of a Gunn effect device, the high-field domain is permitted to propagate over the entire length of the device from one electrode to the other, and the period of the device current is equal to the transit time. In the quenched domain mode of operation, the high field domain nucleates at one of the electrodes but is quenched at a selected point along the length of the device before it has moved all the way over to the other electrode. This is done by superimposing a radio frequency field onto the biasing field, where the frequency of the radio frequency field is less than the transit time of the device. In order to obtain maximum efficiency, the D-C biasing voltage V_b (see FIG. 2) which produces the desired biasing field E_b is chosen such that the bias field

E_b is many times the field E_m at which maximum electron drift velocity occurs. FIG. 2 shows a prior art method of operating a Gunn effect device in the quenched domain mode wherein a rectangular RF voltage is superimposed on the biasing voltage to produce a rectangular output current. The RF voltage waveform **37** is plotted with respect to time at the bottom of the figure, while the output current waveform **39** is shown plotted with respect to time at the side of the figure. The RF voltage is symmetrical, and the sum of the simultaneously applied biasing voltage and RF voltage is the total applied voltage V shown at the bottom of FIG. 2.

Assuming that a high-field domain has already formed and that the RF waveform **37** has achieved its constant steady state value, application of an instantaneous RF voltage which changes the total applied voltage from V_b to its high value V_h causes the Gunn effect device **11** to operate along the dynamic characteristic **29** from the point *g* to the point *h*. The portion of the dynamic characteristic **29** between points *g* and *h* is substantially horizontal, and there is little if any change in the electron drift velocity *v*. The electron drift velocity at this time is shown as v_1 and is the drift velocity which results when the applied field is high. The output current is substantially constant at its minimum value and remains at this minimum during the half cycle when the high RF field is applied. Upon the downswing of the instantaneous RF voltage, the total applied voltage changes from its highest to its lowest value, and the Gunn effect device operates along the dynamic characteristic **29** from the point *h* proceeding through the points *g* and *f* to the point *e*. It does not follow curve **27** at point *f* because of hysteresis of the operating characteristics. The lowest applied total voltage is chosen such that it is equal to or less than the quenching voltage V_q at which the high-field domain is quenched. Since the high-field domain then no longer exists, the Gunn effect device shifts immediately from operation along the dynamic characteristic **29** to operation along the static characteristic **25**. An abrupt change of electron drift velocity occurs as indicated by the straight line curve segment **37** which, in combination with the change in electron drift velocity as the device operates along the dynamic characteristic from the point *h* to the point *e*, gives rise to an increase in the device current. During the half cycle in which the rectangular RF voltage remains at its low value so that the total voltage is constant at the value V_q, the device operates at the point *b* on the static characteristic **25**. The output current remains constant at the maximum current achieved when the RF voltage has the pure rectangular waveform indicated at **37**.

Upon the upswing of RF voltage, the total applied voltage changes from V_q to V_h, the Gunn effect device operates initially along the static characteristic **25** and moves from the point *b* quickly past the point *c* at which the maximum electron drift velocity occurs to the point *d* at which the threshold voltage V_t is reached. A new high-field domain nucleates and begins to propagate from one electrode of the device toward the other electrode. Upon the formation of the new high-field domain, the device shifts abruptly along the straight line curve segment **27** to the dynamic characteristic **29** intersecting it at the point *f*. The operation thereafter is along the dynamic characteristic from the point *f* through the point *g* to the point *h*. The abrupt change of electron drift velocity along the straight line curve segment **27**, in combination with the small change in drift velocity which occurs as the high field is applied, gives rise to the device current which falls almost instantaneously from its maximum value to its minimum value. A complete cycle of operation of the device is completed, and the succeeding cycles are identical in that a new high-field domain is formed and then quenched in accordance with the periodic oscillation of the total applied voltage that gives rise to an oscillatory RF output current.

In this prior art quenched domain mode of operation of a Gunn effect device using a rectangular RF field superimposed upon the bias field, it will be noted that the bias field E_b is many times E_m, the field at which the maximum drift velocity occurs, in order to obtain maximum efficiency. The amplitude of the RF field is sufficiently large so that the total field is less than the quenching field E_q when the RF field is at its maximum. As was previously explained, the period of the RF field is shorter than the domain transit time. Under these conditions the transition between the static characteristic **25** and the dynamic characteristic **29** is entirely controlled by the RF field, which is rectangular, and the device current waveform is also rectangular. Due to hysteresis the quenching field E_q is smaller than E_m, the field which produces the maximum electron drift of velocity. Consequently, the maximum current amplitude or current swing is not realized when a pure rectangular RF field is used.

In accordance with the invention, the voltage and current waveforms are optimized by applying an RF field which is rectangular or substantially rectangular and has a slender spike on the leading edge (see FIG. 3). The spike quenches the high-field domain but allows the Gunn effect device **11** to be operated near E_m during most of the half cycle. As a result, the amplitude of the output current is maximized. Upon the downswing of the RF voltage waveform **37'** in FIG. 3, the total voltage at the tip of the spike on the leading edge of the waveform reaches to or exceeds the quenching voltage V_q, thereby quenching the high-field domain. The Gunn device **11** immediately shifts from the dynamic characteristic **29** along the straight line segment **37** to the static characteristic **25** where it quickly moves from the point *b* to the point *c* at which the maximum drift velocity occurs. For the remainder of the half cycle the RF waveform **37'** is substantially constant at a value such that the total applied voltage is equal to or approximately equal to V_m. The high value of the output current waveform **39'**, instead of occurring at the point *b* on the static characteristic **25** now occurs at point *c*, and there is an increased amplitude of the output current swing as compared to FIG. 2. The change in electron drift velocity now has the larger value v_2, or the velocity which results when the field is E_m and the drift velocity is at its maximum.

The RF voltage waveform **37'** in FIG. 3 is symmetrical, however it will be realized that it is not essential to have the spike at the leading edge of the substantially rectangular waveform on the other half cycle when the RF voltage is at its highest value. The different circuit arrangements for producing an RF voltage with this waveform would, however, usually produce a spike during each half cycle of operation. One way of producing a waveform of this type is to use a multiple resonant tuned circuit. It will be recalled, however, from FIG. 1 that it is usually preferable to operate the Gunn effect device **11** in the pulsed mode. This will create a problem if the pulsed waveform is rectangular since at the beginning of the pulse the amplitude of the RF voltage will be too small to quench the domain. In a parallel resonant LC circuit, the amplitude of the output voltage increases from an initial value to a steady state value after the application of energy to the circuit. This difficulty is avoided in the arrangement shown in FIG. 5 in which the bias voltage is increased gradually from an initial value which is equal to or slightly greater than the threshold voltage V_t to a constant value when the RF voltage has reached its steady state. In FIG. 5 the superposition of the gradually increasing RF voltage on the time varying bias voltage is shown, with the result that the spiked leading edge of the RF voltage waveform always reaches a low enough value to be less than the quenching voltage V_q. This would obviously not be the case if the bias voltage goes immediately to its constant value. By operating the Gunn effect device **11** with a

train of bias voltage pulses having the waveform shown in FIG. 6, the efficiency of the Gunn device is further optimized since there is a maximum amplitude oscillatory output current produced immediately as soon as the biasing pulse is applied to the device. It will be observed in FIG. 6 that the time varying portion of the bias voltage appears only at the beginning of the pulse during the RF build-up period and that the bias voltage is constant for the remainder of the pulse. The rate of increase of the magnitude of the bias voltage from an initial value to a constant value is dependent on the rate of increase of the RF voltage, and both reach a constant magnitude at the same time.

As was stated previously in regard to the discussion of the circuit of FIG. 1, the RF field is preferably produced by the flow of the RF output current of the Gunn effect device **11** through the load **21**. In order to produce the RF voltage waveform shown in FIG. 5, or FIG. 3, a certain frequency response characteristic must be imposed on the load. The desired waveform is essentially a rectangular RF voltage with a spike at the leading edge. A Fourier analysis shows that the load must have a certain resistance at ω_0, $3\omega_0$, $5\omega_0$, etc., and a short circuit at all other frequencies. That is, the load has a predetermined resistance at the fundamental frequency ω_0 and the odd harmonics, and is short circuited at all of the even harmonics. A circuit which approximately satisfies this load characteristic is shown diagrammatically in FIG. 7 and is identified by the numeral **21'**. It comprises a rectangular waveguide **41** having several tuning screws **43** and a movable shorting block **45**, and the Gunn diode **11** is mounted within the cavity at the end of bar **47**. The desired resonant frequencies are obtained by adjusting inwardly the movable short **45** and the tuning screws **43**. The desired resistance at the resonant frequencies can be obtained by adjusting the Q of each mode of oscillation. The spike at the leading edge is automatically produced when the bandwidth of the load is finite. There are, of course, other circuits which satisfy this load characteristic and which could be used as well.

The efficiency of a Gunn effect device operated in accordance with the teachings of the invention to produce a larger optimized output current can be as high as 27 percent. This efficiency is calculated as follows:

The D–C power input is

$$P_{dc}=E_b L\left[n_0\left(v_1+\frac{v_2}{2}\right)\right]$$

The RF output at the fundamental frequency is

$$P_{rf}=1/2\left(\frac{4}{\pi}E_d L\right)\left[\frac{4}{\pi}n_0\left(\frac{v_2}{2}\right)\right]$$

where

$$E_d=E_b-E_m$$

$$=\frac{4E_d\,Ln_0v_2}{\pi 2}$$

Thus the efficiency is

$$\eta=\frac{P_{rf}}{P_{dc}}=\frac{4E_d v_2}{\pi^2\left[E_b\left(_0+\frac{v_2}{2}\right)\right]}$$

For the case when $E_b \gg E_T$

$$E_d \rightarrow E_b \text{ and } v_2 \rightarrow v_1$$

the efficiency becomes

$$\eta=\frac{8}{3\pi^2}=27\%$$

In summary, the performance of a Gunn device is optimized by the control of its voltage and current waveforms. The device, operating in the quenched domain mode, is capable of achieving higher efficiencies than have heretofore been obtained if the applied RF voltage waveforms are substantially rectangular with a spike at the leading edge. In this manner the device operates during the majority of the half cycle at the total voltage or electric field which produces the maximum electron drift velocity. The efficiency is further improved by using a time varying biasing voltage during the time that the source of RF voltage is increasing from its initial value to its steady state value.

While the invention has been particularly shown and described with reference to a preferred embodiment thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. A circuit for producing a periodically varying high frequency current comprising the combination of

a semiconductor Gunn effect device having a threshold voltage at which a high-field domain is launched for movement from one of its electrodes toward the other electrode,

means for applying to said device a time varying unidirectional biasing voltage having a magnitude at least equal to said threshold voltage, and

means for simultaneously applying to said device a radio frequency voltage having a substantially rectangular waveform with a slender spike at one leading edge and an amplitude such that the total applied voltage due to the superimposed biasing voltage and radio frequency voltage in one half cycle thereof is initially at most equal to the quenching voltage so that the high-field domain is quenched, whereafter the total voltage changes to a substantially constant value for the remainder of that half cycle and approximately equals the voltage at which maximum electron drift velocity occurs, while on the other half cycle the total voltage is a high voltage at which the high field electron drift velocity occurs,

said radio frequency voltage having a period less than the transit time of the high-field domain,

whereby the high frequency output current of the Gunn effect device is optimized.

2. A circuit as defined in claim **1** wherein said means for applying to said device a radio frequency voltage produces a radio frequency voltage which increases from an initial amplitude to a steady state amplitude, and

said means for applying to said device a time varying unidirectional biasing voltage produces a voltage which increases in magnitude from an initial value to a constant value at a rate dependent on the rate of increase of the amplitude of said radio frequency voltage.

3. A circuit as defined in claim **1** wherein the means for applying to said device a time varying unidirectional biasing voltage produces a waveform comprising a train of identical substantially rectangular pulses each of which increases in magnitude from a value substantially equal to the threshold voltage to a constant value.

4. A circuit as defined in claim **1** wherein said means for applying to said device a time varying unidirectional biasing voltage produces a waveform comprising a train of identical substantially rectangular pulses each of which increases in magnitude from a value substantially equal to the threshold voltage to a constant value, and

said means for applying to said device a radio frequency voltage comprises a multi-mode tuned resonant circuit for producing a radio frequency voltage which increases from an initial amplitude to a steady state amplitude when one of said pulses is applied to said device.

5. A circuit as defined in claim **1** wherein said means for applying to said device a radio frequency voltage comprises a load which is effectively connected across the

electrodes of the device to be energized by the high frequency output current thereof, and wherein

said means for applying to said device a time varying unidirectional biasing voltage is also effectively connected across the electrodes of the device.

6. A circuit as defined in claim 5 wherein said load is comprised by a circuit having a selected resistance at a fundamental frequency and odd harmonics thereof and

a short circuit at other frequencies, and which has a finite bandwidth.

No references cited.

JOHN KOMINSKI, Primary Examiner

U.S. Cl. X.R.

317—234