1. INTRODUCTION

The application of two-terminal semiconductor devices at microwave frequencies has been increased usage during the past decades. The CW, average, and peak power outputs of these devices at higher microwave frequencies are much larger than those obtainable with the best power transistor.

The common characteristic of all active two-terminal solid-state devices is their negative resistance. The real part of their impedance is negative over a range of frequencies.

In a positive resistance the current through the resistance and the voltage across it are in phase. The voltage drop across a positive resistance is positive and a power of (I2 R) is dissipated in the resistance.

In a negative resistance, however, the current and voltage are out of phase by 180°. The voltage drop across a negative resistance is negative, and a power of ($-I^2R$) is generated by the power supply associated with the negative resistance.

In other words, positive resistances absorb power (passive devices), whereas negative resistances generate power (active devices).

The differences between microwave transistors and transferred electron devices (TEDs) are fundamental. Transistors operate with either junctions or gates, but TEDs are bulk devices having no junctions or gates. The majority of transistors are fabricated from elemental semiconductors, such as silicon or germanium, whereas TEDs are fabricated from compound semiconductors, such as gallium arsenide (GaAs), indium phosphide (InP), or cadmium telluride (CdTe).

TEDS operate with 'hot' electrons whose energy is much greater than thermal energy.

2.GUNN DIODES-GaAs DIODE

Gunn Diode is a one kind of transferred electronic device and exhibits negative resistance characteristic.

Gunn-effect diodes are named after J. B. Gunn, who in 1963 discovered periodic fluctuations of current passing through then-type gallium arsenide (GaAs) specimen when the applied voltage exceeded a certain critical value.

These are bulk devices in the sense that microwave amplification and oscillation are derived from the bulk negative-resistance property of uniform semiconductors rather than from the junction negative-resistance property between two different semiconductors, as in the tunnel diode.

3. GUNN EFFECT

A schematic diagram of a uniform n-type GaAs diode with ohmic contacts at the end surfaces is shown in Fig.1.

J. B. Gunn observed the Gunn effect in the n-type GaAs bulk diode in 1963.

Above some critical voltage, corresponding to an electric field of 2000-4000 volts/cm, the current in every specimen became a fluctuating function of time. In the GaAs specimens, this fluctuation took the form of a periodic oscillation superimposed upon the pulse current. The frequency of oscillation was determined mainly by the specimen, and not by the external circuit. The period of oscillation was usually inversely proportional to the specimen length and closely equal to the transit time of electrons between the electrodes, calculated from their estimated velocity of slightly over 107 cm/s.

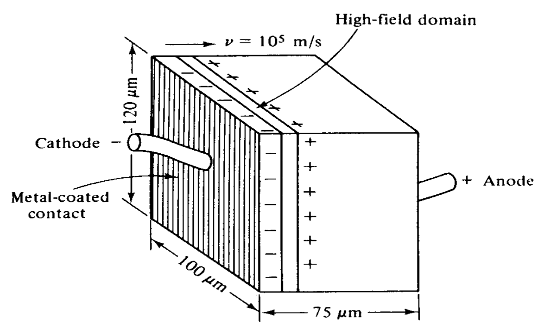


Figure 1. Schematic diagram for ntype GaAs diode.

From Gunn's observation the carrier drift velocity is linearly increased from zero to a maximum when the electric field is varied from zero to a threshold value. When the electric field is beyond the threshold value of 3000 V/cm for the n-type GaAs, the drift velocity is decreased and the diode exhibits negative resistance.

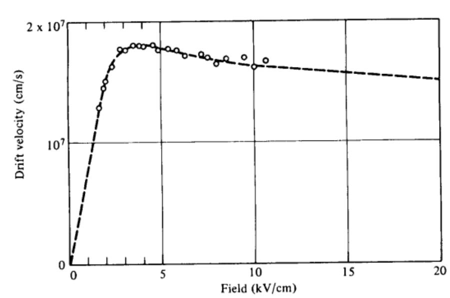


Figure 2. Drift velocity of electrons in n-type GaAs versus electric field.

4. RIDLEY-WATKINS-HILSUM (RWH) THEORY

The fundamental concept of the Ridley-Watkins-Hilsum (RWH) theory is the differential negative resistance developed in a bulk solid-state III-V compound when either a voltage (or electric field) or a current is applied to the terminals of the sample. There are two modes of negative-resistance devices: voltage-controlled and current-controlled modes as shown in Fig.3.a and Fig.3.b

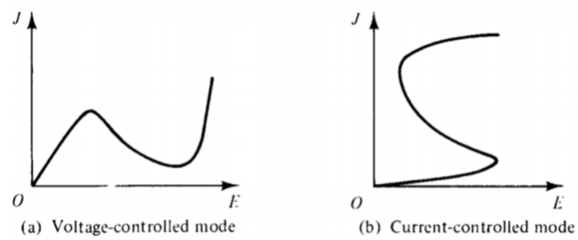


Figure 3. Diagram of negative resistance

In the voltage-controlled mode the current density can be multivalued, whereas in the current-controlled mode the voltage can be multivalued. The major effect of the appearance of a differential negative-resistance region in the current density-field curve is to render the sample electrically unstable. As a result, the initially homogeneous sample becomes electrically heterogeneous in an attempt to reach stability. In the voltage-controlled negative-resistance mode high-field domains are formed, separating two low-field regions. The interfaces separating low and high-field domains lie along equipotential; thus they are in planes perpendicular to the current direction as shown in Fig. 4(a). In the current-controlled negative-resistance mode splitting the sample results in high-current filaments running along the field direction as shown in Fig. 4(b).

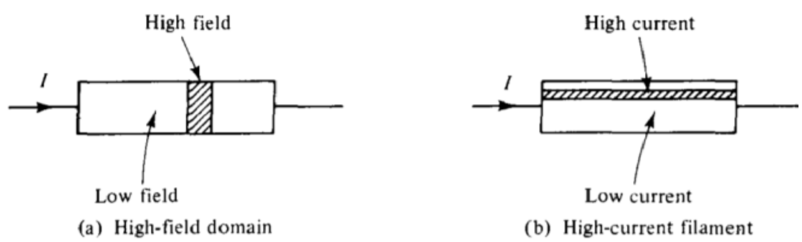


Figure 4.Diagrams of high field domain and high current filament.

Expressed mathematically, the negative resistance of the sample at a particular region is

$$\frac{dI}{dV} = \frac{dJ}{dE} = \text{negative resistance} \qquad ..(1)$$

If an electric field E0 (or voltage V0) is applied to the sample, for example, the current density lo is generated. As the applied field (or voltage) is increased to E2 (or V2), the current density is decreased to J2. When the field (or voltage) is decreased to E1 (or V1), the current density is increased to J1 . These phenomena of the voltage-controlled negative resistance are shown in Fig. 5(a). Similarly, for the current-controlled mode, the negative-resistance profile is as shown in Fig. 5(b).

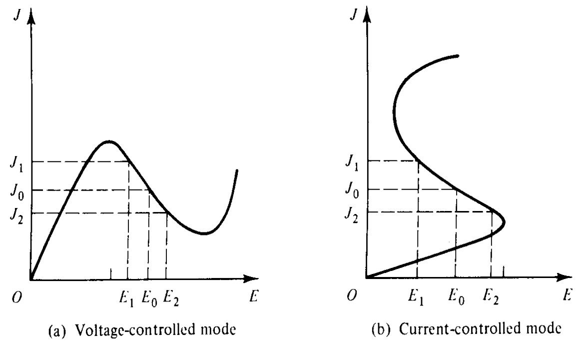


Figure 5.Multiple values of current density for negative resistance.

5. TWO-VALLEY MODEL THEORY

According to the energy band theory of then-type GaAs, a high-mobility lower valley is

Valley	Effective Mass	Mobility	Separation
	Me	μ	ΔE

separated by an energy of 0.36 eV from a low-mobility upper valley as shown in Fig. 6.

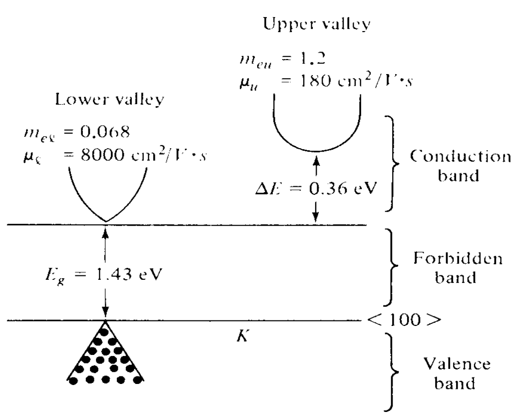


Figure 6.Two-valley model of electron energy versus wave number for n-type GaAs.

TABLE 1. DATA FOR TWO VALLEYS IN GaAs

Lower	Mel = 0.068	µl = 8000 cm2/v-sec	ΔE = 0.36 eV
Upper	Meu= 1.2	µu = 180 cm2/v-sec	ΔE = 0.36 eV

Electron densities in the lower and upper valleys remain the same under an equilibrium condition. When the applied electric field is lower than the electric field of the lower valley (E<Ee), no electrons will transfer to the upper valley as shown in Fig. 7(a).

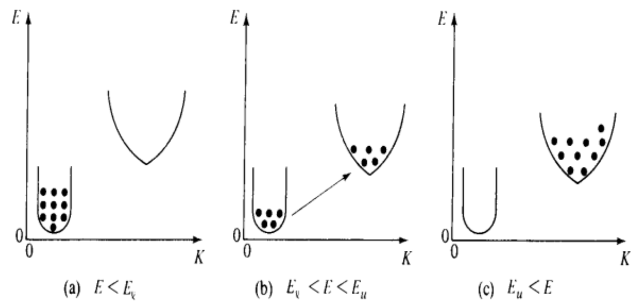


Figure 7 Transfer of electron densities.

When the applied electric field is higher than that of the lower valley and lower than that of the upper valley (Ee<E<Eu), electrons will begin to transfer to the upper valley as shown in Fig. 7(b). And when the applied electric field is higher than that of the upper valley (Eu<E), all electrons will transfer to the upper valley as shown in Fig. 7(c). If electron densities in the lower and upper valleys are ne and nu , the conductivity of the n -type GaAs is

$\sigma = e(n_l \mu_l + n_u \mu_u)$ ..(2)

Where,e = the electron charge

µ = electron mobility

n = ne + nu is the electron density

When a sufficiently high field Eis applied to the specimen, electrons are accelerated and their effective temperature rises above the lattice temperature. Furthermore, the lattice temperature also increases. Thus electron density n and mobility µ are both functions of electric field E. Differentiation of Eq. (7-2-2) with respect to E yields

$\frac{d\sigma}{dE} = e\left(\mu_l \frac{dn_l}{dE} + \mu_u \frac{dn_u}{dE}\right) + e\left(n_l \frac{d\mu_l}{dE} + n_u \frac{d\mu_u}{dE}\right)$ ..(3)

If the total electron density is given by n $=n_l + n_u$ and it is assumed that μ_l and μ_u are proportional to Ep, where p is a constant, then

$$\frac{d}{dE}(n_l + n_u) = \frac{dn}{dE} = 0 \quad ..(4)$$

$$\frac{dn_l}{dE} = -\frac{dn_u}{dE} \quad ..(5)$$

and $$\frac{d\mu}{dE} \propto \frac{dE^p}{dE} = pE^{p-1} = p\frac{E^p}{E} \propto p\frac{\mu}{E} = \mu\frac{p}{E} \quad ..(6)$$

Substitution of Equation (4) to (6) into Eq. (3) results in

$$\frac{d\sigma}{dE} = e(\mu_l - \mu_u)\frac{dn_l}{dE} + e(n_l\,\mu_l + n_u\mu_u)\frac{p}{E} \ldots(7)$$

Then differentiation of Ohm's law J =σE with respect to E yields

$$\frac{dJ}{dE} = \sigma + \frac{d\sigma}{dE}E \quad ..(8)$$

Equation (8) can be rewritten

$$\frac{1}{\sigma}\frac{dJ}{dE} = 1 + \frac{d\sigma/E}{\sigma/E} \quad ..(9)$$

Clearly, for negative resistance, the current density J must decrease with increasing field E or the ratio of dJ/dE must be negative. Such would be the case only if the right-hand term of Eq. (9) is less than zero. In other words, the condition for negative resistance is

$$-\frac{d\sigma/E}{\sigma/E} > 1 \quad ..(10)$$

Substitution of Equation (2) and (7) with f = nu/nl results in [2]

$$\left[\left(\frac{\mu_l - \mu_u}{\mu_l + \mu_u f}\right)\left(-\frac{E}{n_l}\right)\frac{dn_l}{dE} - p\right] > 1 \quad ..(11)$$

6. APPLICATION OF GUNN DIODE

In Radar Transmitters (police Radar, CW Doppler radar).

Pulsed Gunn diode oscillators used in transponders, for air traffic control and in industry telemetry system.

Fast combinational and sequential logic amplifier.

As pump source in preamplifier.

In microwave receiver as low and medium power oscillator.

Domain Formation:

Differential resistance occur when an electric field of a certain range is applied to a multivalley semiconductor, such as then-type GaAs. due to that decrease in drift velocity with increasing electric field. Its leads to formation of a high-field domain for microwave generation andamplification.

In the n-type GaAs diode the majority carriers are electrons. When a small voltage is applied to the diode, the electric field and conduction current density are uniform diode.

$$J = \sigma E_x = \frac{\sigma V}{L} U_x = \rho \vartheta_x U_x$$

Where

J = conduction current density = conductivity

Ex = electric field in the x direction

L = length of the diode

V = applied voltage

p = charge density

v = drift velocity

U = unit vector

The current is carried by free electrons that are drifting through a background of fixed positive charge.

When the applied voltage is above the threshold value, which measuredabout 3000 V/cm times the thickness of the GaAs diode, a high-field domain is formed near the cathode that reduces the electric field.

$$V = -\int_0^L E_x \, dx$$

The high field domain then drifts with the carrier stream across the electrodes and disappears at the anode contact. When the electric field increases, the electron drift velocity decreases and the GaAs exhibits negative resistance.

As shown fig 1(b) below there exists an excess (or accumulation) of negative charge that could be caused by a random noise fluctuation or possibly by a permanent nonuniformity in doping in the n-type GaAs diode.

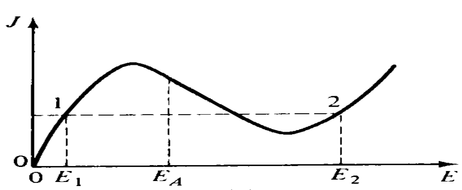
An electric field is then created by the accumulated charges as shown in Fig 1(d). The field to the left of point A is lower than that to the right. If the diode is biased at point EA on the J-E curve, implies that the carriers (or current) flowing into point A are greater than those flowing out of point A,therefore increasing the excess negative space charge at A.

when the electric field to the left of point A is lower than it was before, the field to the right is then greater than the original one, resulting in an even greater space-charge accumulation. process continues until the low and high fields both reach outside the differential negative-resistance region Fig1(a).

This process, depends on condition that the number of electrons inside the crystal is large enough to allow the necessary amount of space charge to be built up during the transit time of the space-charge layer.

The electric field in side the dipole domain would be greater than the fields on either side of the dipole in Fig 2.(c). Because of the negative differential resistance, the current in the low-field side would be greater than that in the high-field side.

Then the dipole field reaches a stable condition and moves through the specimen toward the anode. When the high-field domain disappears at the anode, a new dipole field starts forming at the cathode and the process is repeated.



(a)

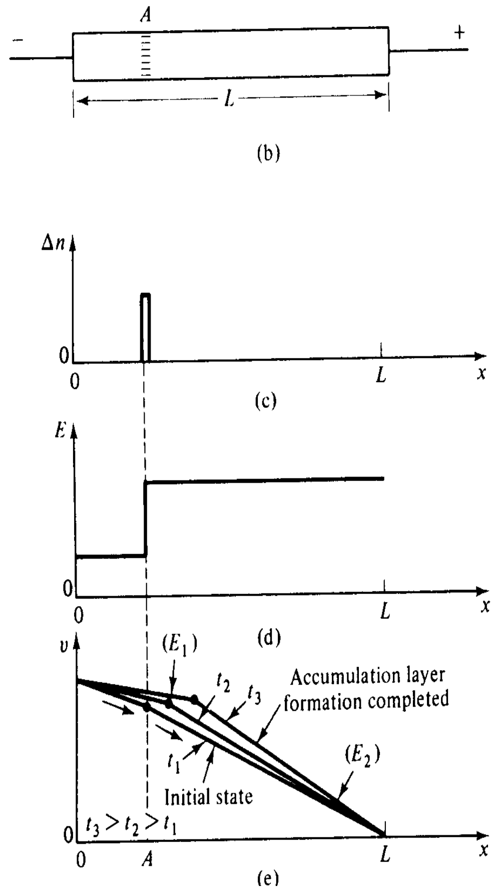


Figure 1: formation of an electron accumulation layer in GaAs.

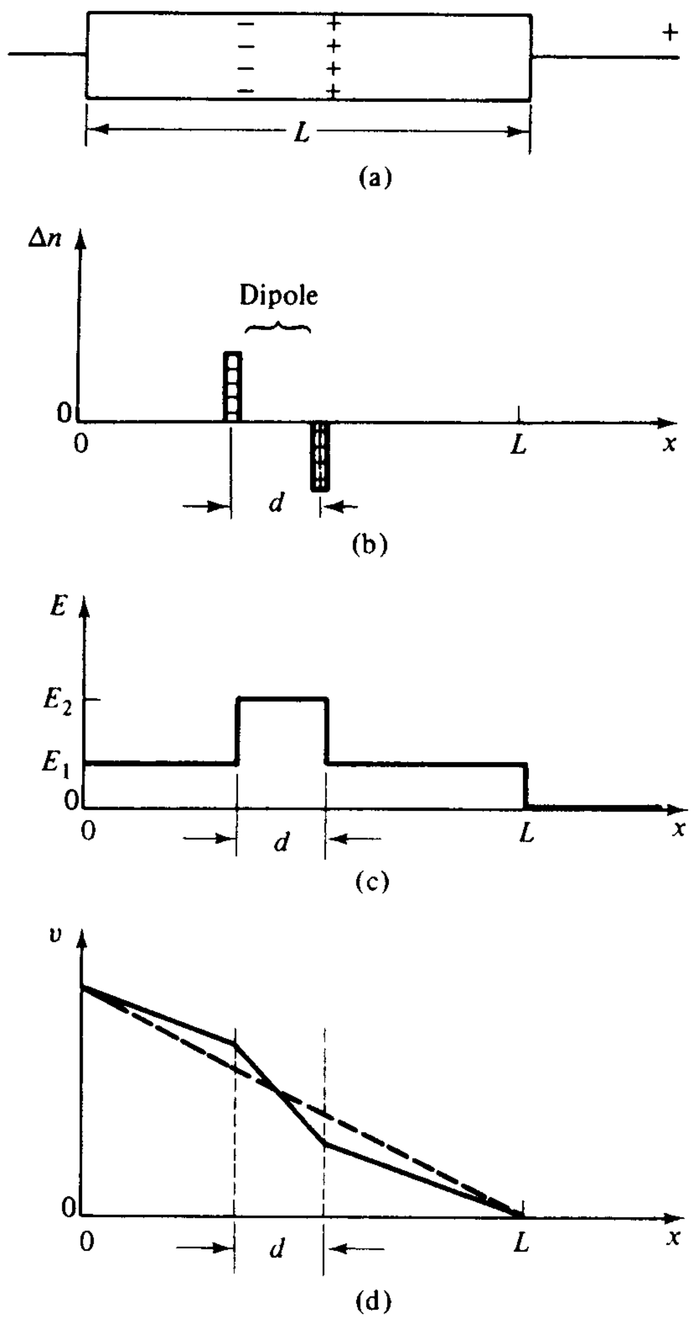


Figure2: formation of an electron dipole layer in GaAs.

Properties of High field domain

Will start to form whenever the electric field in a region of the sample increases above the threshold E.When the electric field increases, the electron drift velocity decreases and the GaAs diode exhibits negative resistance.

If additional voltage is applied, the domain will increase in size and absorb more voltage than was added and the current will decrease.

domain will not disappear before reaching the anode unless the voltage is dropped appreciably below threshold.

New domain formation can be prevented by decreasing the voltage slightly below threshold.

Domain will modulate the current through a device as the domain passes through regions of different doping and cross-sectional area,or domain may disappear. Effective doping may varied in region.

The domain length is inversely proportional to the doping. devices with the same product of dopingmultiplied by length will behave similarly in terms of frequency multiplied by length.

Domain can be detected by a capacitive contact.Presence of a domain anywhere in a devicecan be detected by a decreased current.

Modes of operation of Gunn diode

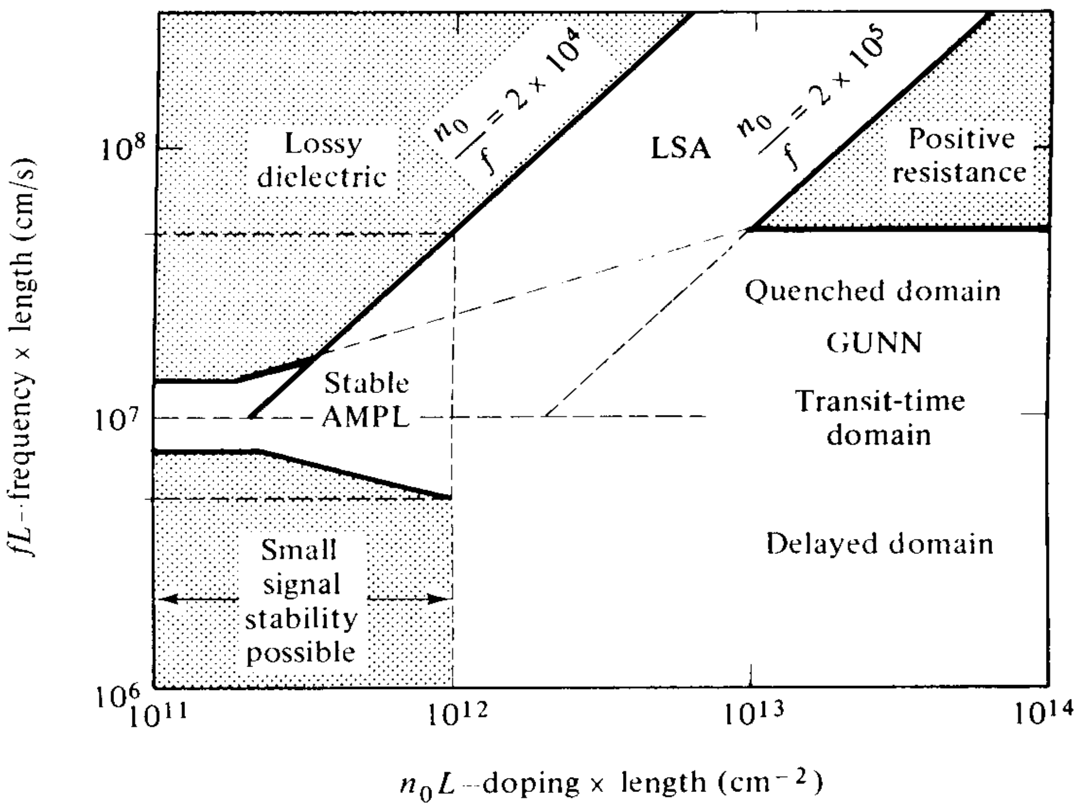


Figure 3: Modes of operation for Gunn diodes

Gunn first announced his observation of microwave oscillation in the n-type GaAs and n-type InP diodes in 1963, various modes of operation have been developed, depending on the material parameters and operating conditions.

Formation of strong space-charge instability depends on the conditions that enough charge is available in the crystal.

four basic modes of operation of uniformly doped bulk diodes with low-resistance contact are as follows

Transit Time Domain mode

Delayed Domain mode

Quenched Domain mode

limited space charge accumulation mode

1.Transit TimeDomain mode:

in the region where the product of frequency multiplied by length is about 107 cm/s and the product of doping multiplied by length is greater than l012/cm2.the device is unstable because of the cyclic formation of either the accumulation layer or the high-field domain.

f = Vd/L in these mode is slightly sensitive to the applied voltages since the drift velocity Vd depends on the bias voltages.

Vd= f .L = 107 cm/s when Vd = VS, thenhigh field domain is stable.

Bias voltage is normally maintain little higher Eth .

At this instant Oscillation period = Transit Time (τo = τt).

Operating ‘f’ depends on ‘Vd’ hence on bias voltage > Eth.

It is a low power,low efficiency mode and requires that operating frequency laser then 30GHz.

These limit on frequency is due to that device length .

2. Delayed Domain mode:This mode is defined in the region where the product of frequency times length is about 107 cm/s and the product of doping times length is between 1011 and l012/cm2.

When transit time is chosen that domain is collected E <Eth ,new domain can not form until field rises again above threshold.

Oscillation period is greater than transit time τo < τt

This dealy inhabited mode has an 20 % Efficiency.

Operatingfrequency can be less than or equal to Gunn Mode frequency

3.Quenched Domain mode: This mode is defined in the region where the product of frequency times length is above 107 cm/s and the quotient of doping divided by frequency is between 2 x 104and 2 x 105.

It is bias field drops below sustaining field Esduring the negative half cycle domain collapses before it reaches the anode.i.e The domain disappear somewhere in the sample itself.

Operating frequency will be higher than Gunn Mode and delayed mode, certainly this depend on the external circuit.

When bias field swings back above threshold value Vth, new domain formed and process repeats,hence in that mode domain is quenched before it reches the anode.

Frequency of resonant circuit then the transit time frequency is 13%.

4.Limited Space Charge Accumulation mode: This mode occurs only when there is either Gunn or LSA oscillation, and it is usually at the region where the product of frequency times length is too small to appear in the figure. When a bulk diode is biased to threshold, the average current suddenly drops as Gunn oscillation begins.

It gives high power upled high efficiency

The domain is not allowed to form

RF voltage and frequency are so chosen that they do not have sufficient time to form domain above threshold.

IN LSA mode high power and high η(20%),16 to 23% compare to 5% for gunn mode The field No peak value permits high operating voltage.

Operating frequency is 0.5-50 times more than Gunn Mode.

It can be used up to 100 GHz and is dependent on external resonating circuits.

High Power and High Efficiency.

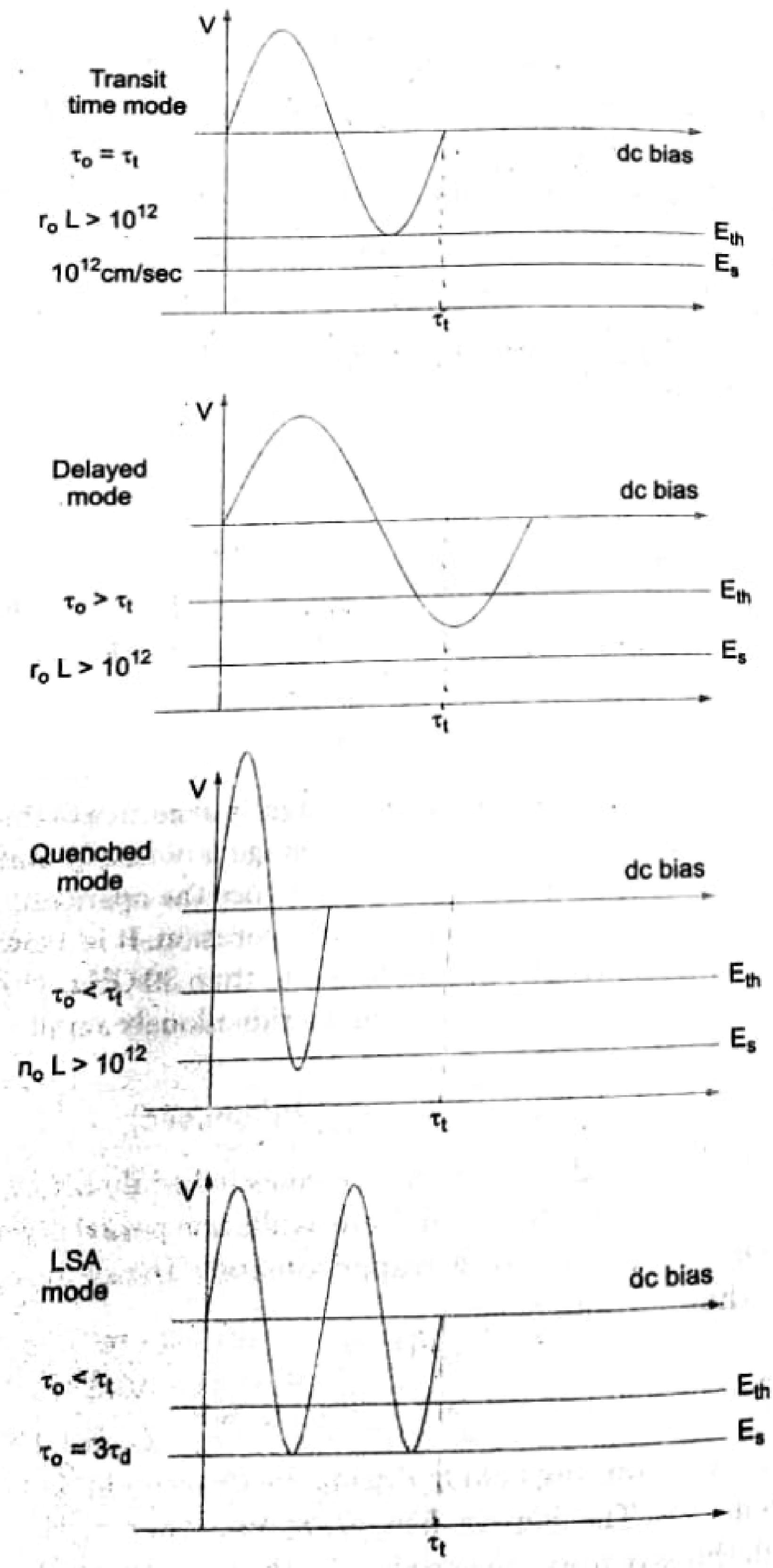


Fig. 9.47 Gunn diode modes.

Parametric Amplifier

Parametric amplifier first propounded by Lord Reyleigh in 1880’s for mechanical system and by R.Harteley in 1930’s for electrical applications. A parametric amplifier is one that uses non linear reactance or a time varying reactance for its application. In fact parametric devices basically depend on the possibility of increasing the energy of the signal at one frequency by supplying energy at some other frequency.

Consider the simple tank circuit in which we can separate the plates of capacitor used mechanically. Amplification is obtained by pulling capacitor plates apart when **‘V’** and **‘Q’** are at maximum value.

$$V = \frac{Q}{C} \qquad \& \quad C = \frac{\varepsilon_0 \varepsilon_r A}{d}$$

To obtain amplification capacitor plates are pulled apart when the charge and the voltage are at their maximum. Because of electric field between the plates,it requires an expenditure of energy to pulled the plates apart. This mechanical energy appears as additional electric energy stored in the capacitor.The voltage and charge continue the oscillation towards zero. At zero voltage the capacitance plates are brought back to their original separation and this requires no expenditure of energy as the electric field is also zero now.The voltage and charge now swing to their wave maximum at which plates are pulled apart once again and the process can be continued at each maximum and minimum voltage and hence signal builts up.

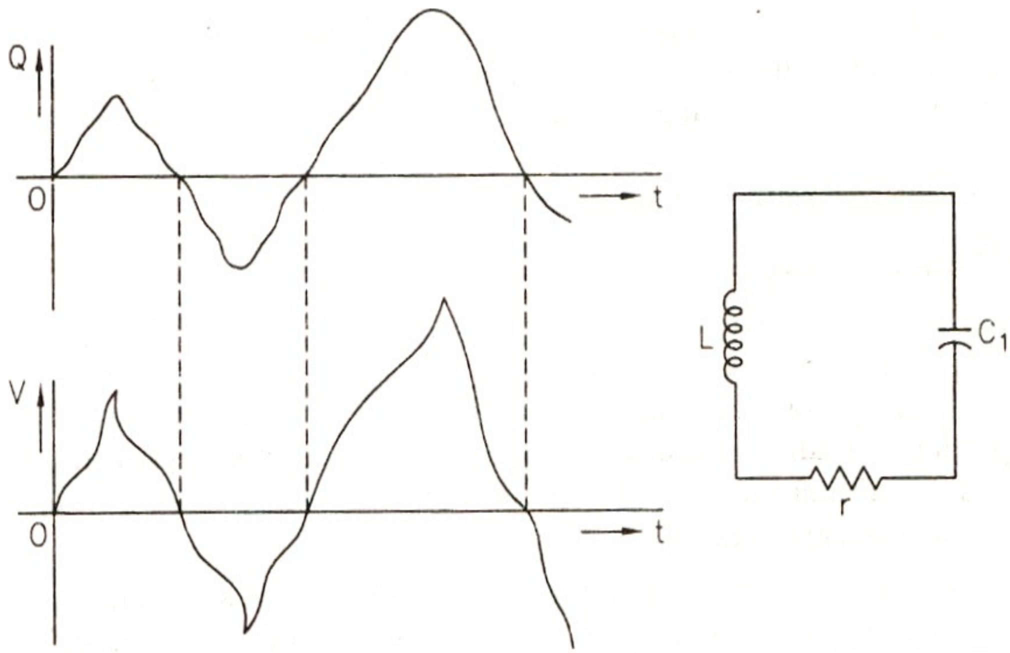


Fig.1.1 Tank circuit

Varactor diode is the most widely used active element in parametric amplifier. Parametric amplifier is low noise amplifier because no resistance is involved in the amplification process. There will be no thermal noise as the active device involved is reactive. Amplification is obtained if the reactance is varied at some frequency higher than the frequency of the signal being amplified.

1.2 Amplification Mechanism of a Parametric Amplifier:

In a parametric amplifier the pump generator acts as a local oscillator and varactor diode C(t) as the mixer as shown in fig 1.2.

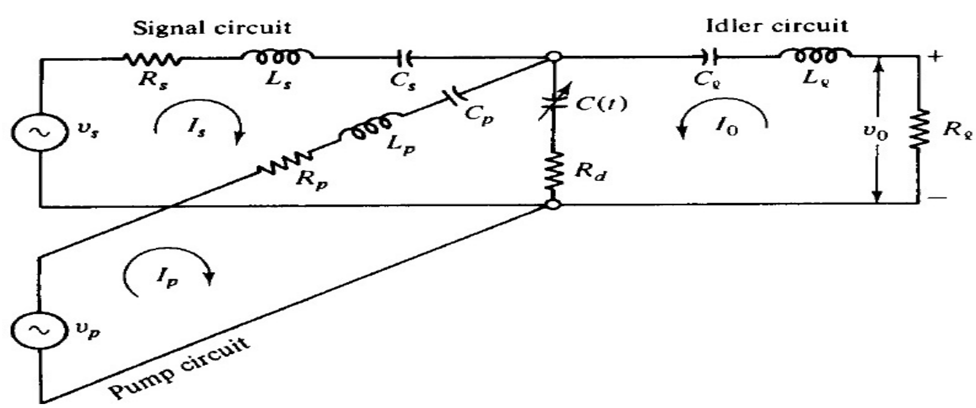


Fig 1.2 Equivalent circuit of parametric amplifier

The signal frequency f_s and pump frequency f_c are mixed in a non linear capacitor C(t) to generate voltages at fundamental frequencies f_p and f_s as well as the sum and the difference frequencies $mf_p \pm nf_s$ across C(t). An output voltage at f_o is obtained across load resistance $R_{L.}$ The output circuit which does not require external excitation is called Idler circuit.The output frequency f_o in the Idler circuit is expressed as the sum and the difference frequency of f_s and $f_{p.}$

If $f_o > f_s$ the device called up converter.

If $f_o < f_p$ the device called down converter.

1.3 Parametric Up Converter(PUC)

In a PUC the output equal to sum of f_s and f_p(f_o=f_s +f_p)and there is no power flow in the parametric amplifier at frequency other than the signal,pump output frequencies.

For PUC,we define three parameters the power gain, noise figure and bandwidth.

1.Power Gain: The maximum power gain for PUC is given by

Maximum Power gain $$= \frac{f_s}{f_o}\frac{x}{(1+\sqrt{1+x})^2}$$

where

$$x = \frac{f_s}{f_o}(\gamma Q)^2$$

and f_o=f_s +f_p

$$Q = \frac{1}{2\pi f C R_d}$$

where R_d= series resistance of pn junction

γQ= figure of merit for non linear capacitance

As R_d tends to zero,γQ tends to ∞ and gain degradation factor is unity.

2.Noise Figure: The noise figure(F) ,for PUC is given by

$$F = 1 + \frac{2T_d}{T_o}\left[\frac{1}{\gamma Q} + \frac{1}{(\gamma Q)^2}\right]$$

Where T_d= diode temperature in K

T_o= ambient temprature(300 K)

In typical microwave diode γQ=10,f_o/f_s=300 K, the minimum noise figure is 0.90 dBwhich is far less as compared to 3 to 4 dB of TWT.

3. Bandwidth: The bandwidth of PUC is given by

$$BW = \frac{\gamma_o}{2} \frac{\sqrt{f_i}}{f_s \times Gain}$$

For a typical microwave diode f_o/fs=10 and $\gamma = 0.2$ and BW=1.26.

1.4 Parametric Down Converter(PDC):

For parametric amplifier to act as a PDC,$f_s=f_p+f_0$.This means that input power must feed into the Idler circuit and the output power must move out from the signal circuit.The gain of PDC is given by

Gain(actually loss) $$= \frac{f_s}{f_o} \frac{x}{(1+\sqrt{1+x})^2}$$

Expression for Noise figure and BW of PDC is similar to PUC

Negative resistance parametric amplifier

If the significant portion of power flow flows only at f_s ,f_p and f_i , regenrative condition with possibility of oscillation at both signal and Idler frequency will occur.When the mode operates below the oscillation threshold the device behave as bilateral negative resistance para amp.

Degenerate Parametric amplifier :

The degenerate parametric amplifier or oscillator is defined as a negative resistance amplifier with the signal frequency(fs)equals to idler frequency(fi).Since the idler frequency(fi)is the difference between the pump frequency(fp)and the signal(fs),the signal frequency is just half of pump frequency(fp).The bandwidth and gain are same as upconverter.It is a simple device uses a relatively low pump frequency(fp)and low noise figure.

Non-degenerate parametric amplifier :

In this, the signal and idler frequencies are not same but are clearly seperated.The pump frequency need not be multiple of signal frequency**.**

There are three parameters of PDC power gain,bandwidth and noise figure.

1.Power Gain: The output power is taken from the resistance R_i at a frequency f_i and converter gain from f_s to f_i is given by

Gain $= \frac{4f_i}{f_s}\frac{R_g}{R_{T_S}}\frac{R_i}{R_{T_i}}\frac{\alpha}{(1-\alpha)^2}$

Where $f_i = f_P - f_S$

R_g = Signal generator output resistance

R_i = Idler generator output resistance

R_{ts} = Total series resistance at f_S

R_{ti} = Total series resistance at f_i

$\alpha = R / R_{ts}$

R = Equivalent Noise resistance $R = \frac{\gamma^2}{\omega_g \omega_i C^2 R_{T_i}}$

2. Noise Figure: It is same as PUC.

3.Bandwidth: It is given by

$$BW = \frac{\gamma_o}{2}\frac{\sqrt{f_i}}{f_s \times Gain}$$

If gain = 20dB, $f_i = 4 f_S$ and γ =0.3 then BW = 0.03

Advantages and limitations of parametric amp:

1)Noise figure: Typical value 1-2 dB.

2) Frequency:40-200 GHz.

3) Bandwidth: Generally small due to presence of tuned circuits.

4) Gain: typical value 20-80 dB.

Applications of parametric amp:

1)Radio telescopes.

2)Space probe tracking and communications.

3)Tropospheric scatter receivers.

4)Long range RADAR.

5)Satellite ground stations.

6)Radio astronomy etc.

Questions asked in university exam:

1. Explain the principle of operation of parametric amplifier with the help of neat diagram. Also explain degenerate and non-degenerate modes of operation.(W-17)

2. Show that negative resistance device when use in system act as amplifier.(W-18)

3. Explain operation of parametric amplifier as up converter and down converter.Why does it offer low noise amplification? (S-16, W-16, W-15)

IMPATT:-

- IMPATT diode stands for Impact Avalanche and Transit Time Diode.
- A theoretical Read diode made of an n^+ -p-i-p^+ or p^+ -n-i-n^+ structure has been analyzed.
- Its basic physical mechanism is the interaction of the impact ionization avalanche and the transit time of charge carriers. Hence the Read-type diodes are called IMPATT diodes.
- These diodes exhibit a differential negative resistance by two effects:
  1. The impact ionization avalanche effect, which causes the carrier current Io(t) and the ac voltage to be out of phase by 90°
  2. The transit-time effect, which further delays the external current I(t) relative to the ac voltage by 90° .
- IMPATT diodes consist of a high doping avalanching region followed by a drift region where the field is low enough that the carriers can traverse through it without avalanching.
- The Read diode is the basic type in the IMPATT diode family. The others are the one-sided abrupt p-n junction, the linearly graded p-n junction (or double-drift region), and the p-i-n diode .
- The principle of operation of these devices, however, is essentially similar to the mechanism described for the Read diode.

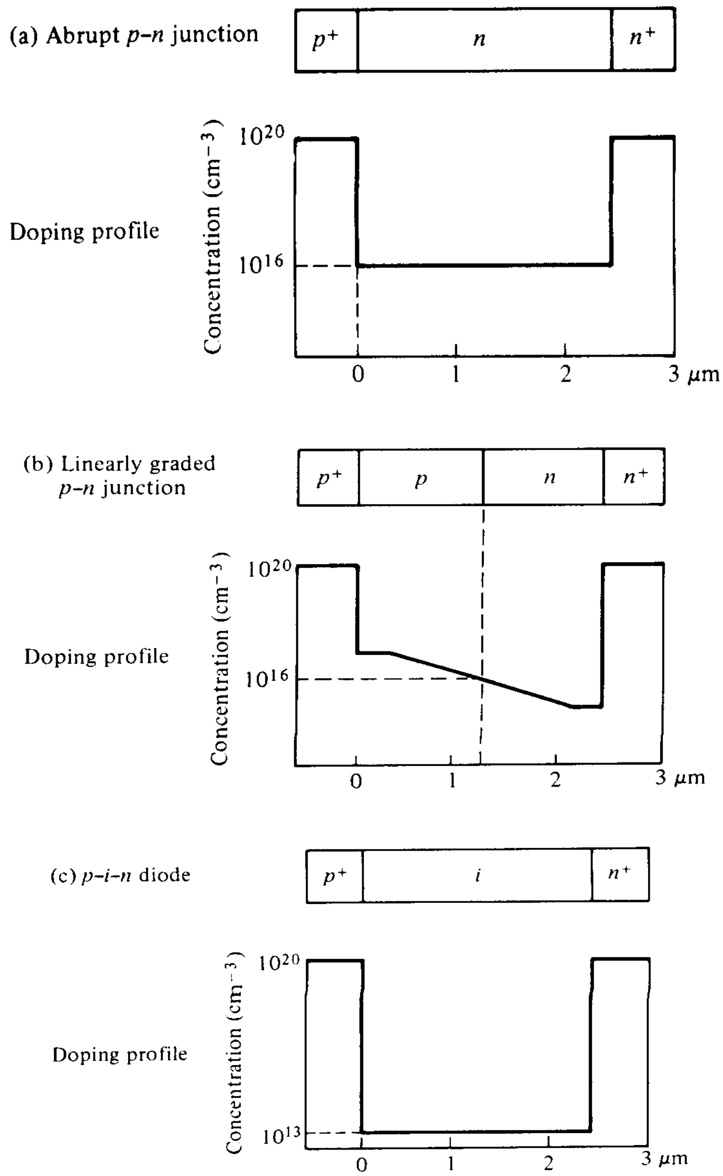


Fig: Three typical silicon IMPATT diodes.

Negative Resistance:

Small-signal analysis of a Read diode results in the following expression for the real part of the diode terminal impedance.

$$R = Rs + \frac{2L^2}{v_d \epsilon_s A} \frac{1}{1-\frac{\omega^2}{\omega_r^2}} \frac{1-\cos\theta}{\theta}$$

Where Rs = passive resistance of the inactive region.

v_d= carrier drift velocity

L = length of the drift space-charge region

A = diode cross section

ϵ_s = semiconductor dielectric permittivity

Moreover, (θ) is the transit angle, given by

$$\theta = \omega\tau = \omega\frac{L}{v_d}$$

and w, is the avalanche resonant frequency, defined by

$$\omega_r = \left(\frac{2\alpha' v_d I_o}{\epsilon_s A}\right)^{-\frac{1}{2}}$$

Where , $\propto =$ derivative of the ionization coefficient with respect to the electric field.

- The variation of the negative resistance with the transit angle when $\omega > \omega_r$ is plotted.
- The peak value of the negative resistance occurs near $\theta = \pi$. For transit angles larger than π and approaching 3π /2, the negative resistance of the diode decreases rapidly.
- The Read-type IMPATT diodes work well only in a frequency range around the π transit angle.

i.e.

$$f = \frac{1}{2\tau} = \frac{v_d}{2L}$$

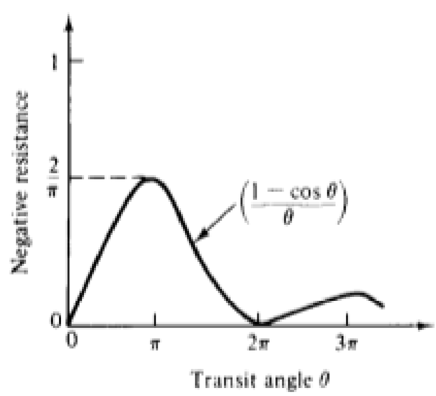


Fig: Negative resistance versus transit angle.

Power Output and Efficiency:

The maximum voltage that can be applied across the diode is given by

$$V_m = E_m L$$

where L is the depletion length and Em is the maximum electric field.

The maximum current is given by

$$I_m = J_m A$$
$$= \sigma E_m A$$
$$= \frac{\in_s}{\tau} E_m A$$
$$= \frac{v_d \in_s E_m A}{L}$$

Therefore the upper limit of the power input is given by

$$P_m = I_m V_m$$
$$= E_m^2 \in_s v_d A \qquad \text{----(1)}$$

The capacitance across the space-charge region is defined as

$$C = \frac{\in_s A}{L} \qquad \text{----(2)}$$
$$\in_s = \frac{C\,L}{A}$$

and $C = \frac{1}{2\pi X_c f}$

$$\in_s = \frac{L}{2\pi f X_c A}$$

Power, $P_m = E_m^2 E_s V_d A$

$$= \frac{E_m^2 V_d L A}{2\pi f X_c A}$$
$$= \frac{E_m^2 V_d L}{2\pi X_c 2\pi f \tau} \qquad \tau = 1$$
$$= \frac{E_m^2 V_d^2}{4\pi^2 X_c}$$

The efficiency of the IMPATT diodes is given by

$$\eta = \frac{P_{ac}}{P_{dc}}$$

$$= (\frac{V_a}{V_d})(\frac{I_a}{I_d})$$

TRAPATT DIODE :-

- The abbreviation TRAPATT stands for trapped plasma avalanche triggered transit mode, a mode first reported by Prager . It is a high-efficiency microwave generator capable of operating from several hundred megahertz to several GHz .
- The basic operation of the oscillator is a semiconductor p-n junction diode reverse biased to current densities well in excess of those encountered in normal avalanche operation. High-peak-power diodes are typically silicon *n+ -p-p+ (*or *p+ -n-n+)* structures with then-type depletion region width varying from 2.5 to 12.5 µ,m.
- The doping of the depletion region is generally such that the diodes are well "punched through" at breakdown; that is, the de electric field in the depletion region just prior to breakdown is well above the saturated drift-velocity level.
- The device's p+ region is kept as thin as possible at 2.5 to 7.5 µ,m. The TRAPATT diode's diameter ranges from as small as 50 µ,m for CW operation to 750 µ,mat lower frequency for high peak-power devices.

OPERATION

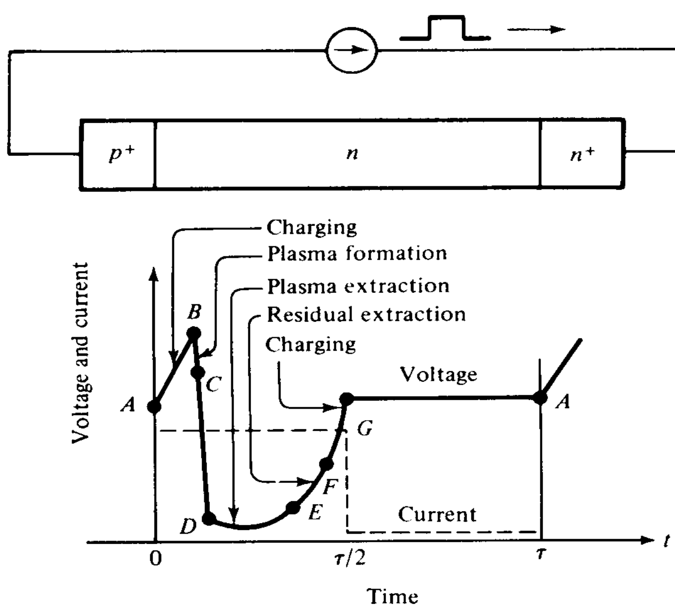


Fig: Voltage and Current Waveforms for TRAPATT Diode.

- A typical voltage waveform for the TRAPATT mode of an avalanche p+ -n-n+ diode operating with an assumed square wave current drive is shown in Fig.
- These analyses have shown that a high-field avalanche zone propagates through the diode and fills the depletion layer with a dense plasma of electrons and holes that become trapped in the low-field region behind the zone.

- At point A the electric field is uniform throughout the sample and its magnitude is large but less than the value required for avalanche breakdown. The current density is expressed by

$$J = \epsilon_S \frac{dE}{dt}$$

where $\in_s$ is the semiconductor dielectric permittivity of the diode.
- At the instant of time at point A, the diode current is turned on. Since the only charge carriers present are those caused by the thermal generation, the diode initially charges up like a linear capacitor, driving the magnitude of the electric field above the breakdown voltage.
- When a sufficient number of carriers is generated, the particle current exceeds the external current and the electric field is depressed throughout the depletion region, causing the voltage to decrease. This portion of the cycle is shown by the curve from point B to point C.
- During this time interval the electric field is sufficiently large for the avalanche to continue, and a dense plasma of electrons and holes is created. As some of the electrons and holes drift out of the ends of the depletion layer, the field is further depressed and "traps" the remaining plasma. The voltage decreases to point D.
- A long time is required to remove the plasma because the total plasma charge is large compared to the charge per unit time in the external current.
- At point E the plasma is removed, but a residual charge of electrons remains in one end of the depletion layer and a residual charge of holes in the other end. As the residual charge is removed, the voltage increases from point E to point F.
- At point F all the charge that was generated internally has been removed. This charge must be greater than or equal to that supplied by the external current; otherwise the voltage will exceed that at point A.
- From point F to point G the diode charges up again like a fixed capacitor. At point G the diode current goes to zero for half a period and the voltage remains constant at VA until the current comes back on and the cycle repeats. The electric field can be expressed as

$$E(x,t) = E_m - \frac{qN_A}{\in_S} + \frac{Jt}{\in_s}$$

where N_A is the doping concentration of then region and x is the distance.

Thus the value of t at which the electric field reaches E_m at a given distance x into the depletion region is obtained by setting$E(x,t) = E_m$, yielding

$$t = \frac{qN_A}{J} x$$

Differentiation of above equation w.r.to time t results in

$$\vartheta_s \equiv \frac{dx}{dt} = \frac{J}{qN_A}$$

where ϑ_z is the avalanche-zone velocity.

- Thus the avalanche zone (or avalanche shock front) will quickly sweep across most of the diode, leaving the diode filled by a highly conductng plasma of holes and electrons whose space charge depresses the voltage to low values. Because of the dependence of the drift velocity on the field, the electrons and holes will drift at velocities determined by the low-field mobilities , and the transit time of the carriers can become much longer than

$$\tau_s = \frac{L}{\vartheta_s}$$

  where ϑ_s is the saturated carrier drift velocity.
- Thus the TRAPATT mode can operate at comparatively low frequencies, since the discharge time of the plasma-that is, the rate Q/ I of its charge to its current can be considerably greater than the nominal transit time Ts of the diode at high field.
- Therefore the TRAPATT mode is still a transit-time mode in the real sense that the time delay of carriers in transit (that is, the time between injection and collection) is utilized to obtain a current phase shift favourable for oscillation

POWER OUTPUT AND EFFICIENCY

- RF power is delivered by the diode to an external load when the diode is placed in a proper circuit with a load. The main function of this circuit is to match the diode effective negative resistance to the load at the output frequency while reactively terminating (trapping) frequencies above the oscillation frequency in order to ensure TRAPATT operation.
- To date, the highest pulse power of 1.2 kW has been obtained at 1.1GHz (five diodes in series) , and the highest efficiency of 75% has been achieved at 0.6 GHz .

AVALANCHE TRANSIT TIME DEVICES

	IMPATT	**TRAPPAT**
Operating Frequency	0.5-100 GHZ	1-10 GHZ
Noise Figure	30 dB	60 dB Not used as an amplifier
Power output	1W (CW), 400 W (Pulsed)	Several 100 W (Pulsed)

Efficiency	3 % (CW), 60 % pulsed	20-60% pulsed
Applications	Oscillator, Amplifier	Oscillator

MASER :-

- MASER (Microwave Amplification by Stimulated Emission of Radiation) and LASER (Light Amplification by Stimulated Emission of Radiation) are the examples of stimulated emission devices.
- These can be analysed only by quantum electronics and statistical mechanics rather than by classical mechanics.
- These devices are highly directional, coherent power devices with extremely low noise figures. Hence these are used for generation and amplification of radiation and find applications in military, medicine, communications, space exploration, etc.
- Maser is a new approach for conversion of atomic energy into electromagnetic energy and hence termed as molecular amplification by stimulated emission of radiation.

Principle Of MASER :-

- As per atomic theory, electron exist at various energy levels corresponding to different orbits. They occupy lowers energy levels at extremely low temperature.
- By providing additional energy, the electrons can be raised or stimulated from this energy level.
- Quantum theory says that, the specific amount of energy or quantum that can provide the necessary energy for raising the level of electron is given by the wave mechanical equation,

  $E=h^{\gamma}$

  Where, E= energy difference in joules

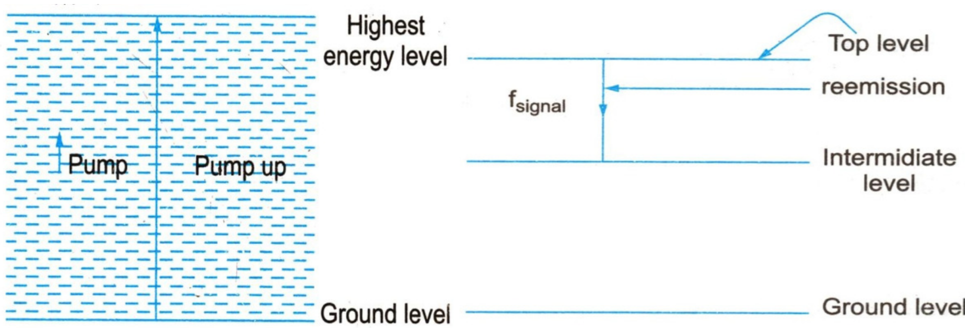
  h= Planks constant = $6.624*10^{-27}$ erg/sec or joule sec.

  $^{\gamma}$= the frequency of the impinging light particle or photon

- Atom is excited by means of absorption of quantum, causing it to remain in excited state or remit the energy at same frequency.

Pumping of atom :-

- The energy can be supplied to the atom at such a frequency that it is raised to the energy level higher than the ground level and not merely to the next higher energy level. This is called pumping the atom into the top energy level.
- Pumping is done at a frequency corresponding to the energy difference between the ground and the top energy levels.
- Re-emission of energy is stimulated at the desired frequency and the signal at this frequency is thus amplified .
- It may be noted that practically no noise is added to the amplified signal as there is no resistance involved and no electron stream to produce shot noise.
- Energy re-emission is at a microwave frequency and re-emission frequencies depend on the energy levels available in the atoms.

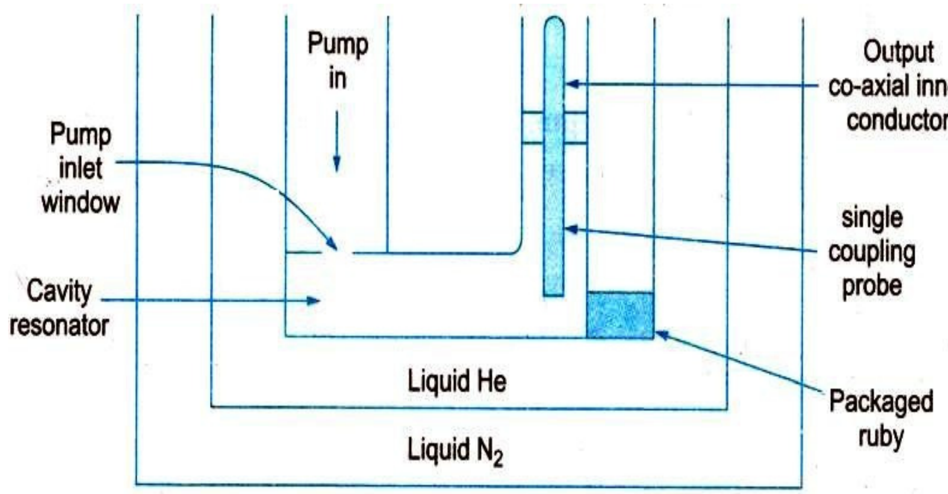


Material used :-

- Materials that are capable of being stimulated into radiating at the frequency and also amplify at low noise include gas Ammonia, hydrogen, cesium, ruby maser etc.
- The operating frequency with Ammonia , hydrogen and cesium cannot be varied.
- Maser material which is more amenable is ruby crystalline form of aluminium silica. It is lightly doped with chromium to make it para magnetic. It has three energy levels.
- Due to the presence of unpaired electron spins, they can be aligned with a dc magnetic field . A property which allows tuning facilities to different frequencies in the re-radiation process.

Helium Cooled ruby MASER cavity amplifier :-

- Cooling a Maser has the effect of reducing the noise level i.e noise figure is improved however at room temperature Maser amplifier has noise figure poorer than paramp.
- A typical helium cooled ruby maser cavity is as shown in fig:



- The ruby is located in on inductively coupled unit in a cavity resonator.
- The pump's excitation is provided by a transient or any other form of excitation which will stabilise into vibration at microwave frequency by the Q of the resonator.
- Induced transition takes place at a frequency of the resonator and microwaves energy can be tapped off by loop coupling magnetically into a coaxial cable.
- The gain bandwidth product of such an amplifier is about 35 MHz .
- Further increase in the bandwidth would reduce the gain to even less than unity . By using the travelling wave ruby structure instead of cavity , the bandwidth can be increased.

Performance Characteristics :-

1. Operating frequency: 1.6 GHz
2. Gain: 25 dB
3. Bandwidth: 25 MHz
4. Pump frequency: 48 GHz
5. Pump Power: 140 MW
6. Noise figure: Better than 0.3 dB

Applications :-

1. Low noise low level amplifier: Low level since MASER amplifier structure even for 1μω input levels.
2. Suitable for radio astronomy and other extra terrestrial communications.
3. Radio telescopes and space probe receivers.

Q 1) A negative resistance amplifier (parametric) has a signal frequency of 2 GHZ and pumped frequency of 2GHZ and pumped frequency of 12 GHZ output resistance of signal generator 60Ωand on time resistance of signal is 1KΩ. Determine:
1) power gain in db.
2) power gain if it is work as USB.

Sol:

1) power gain of LSB in dB= 10log $\left(\frac{f_p - f_s}{f_s}\right)$

$$= 10\log\left(\frac{12\times10^9 - 2\times10^9}{2\times10^9}\right)$$

$$= 10\log(5)$$

$$= 6.98 \text{ dB}$$

2) power gain of USB $= 10\log\left(\frac{f_p + f_s}{f_s}\right)$

$$= 10\log\left(\frac{12\times10^9 + 2\times10^9}{2\times10^9}\right)$$

$$= 10\log(7)$$
$$= 8.45 \text{ W}$$

Q 2) In a parametric amplifier the output to input frequency ratio is 10.The product of the quality factor and coupling constant is 10 . The product of quality factor and coupling constant is 10. Find the gain in db.

Sol:
Given : r × Q = 10 , $\frac{f_0}{f_s} = 10$

i.e. coupling constant × quality factor = figure of merit

$$r \times Q = 10$$
$$\text{Gain} = \frac{f_0}{f_s} \times \frac{x}{(1+\sqrt{1+x})^2}$$

$$= \frac{f_0}{f_s} \times (rQ)^2$$

$$= \frac{1}{10}(10)^2$$

$$X = 10$$
$$\text{Gain} = (10) \times \frac{10}{(1+\sqrt{1+10})^2}$$

Gain = 5.366
Gain = 7.29 dB.

Q 3) A negative resistance par amp has a signal frequency f_S of 2 GHz, pump frequency f_P of 12 GHz, output resistance of signal generator of R_i=16Ω and on types resistance of signal generator of R_s= 1 kΩ. Determine i) Power gain in dB ii) Power gain if it is PUC.

- Given:
- Signal frequency f_S = 2 GHz
- Pump frequency f_P=12 GHz
- Output resistance of signal generator R_i=16Ω
- Resistance of signal generator R_s= 1 kΩ.

i) Power gain in dB $$= 10 Log_{10}\left(\frac{f_p - f_s}{f_s}\right)$$

$$= 10 Log_{10}\left(\frac{12-2}{2}\right)$$

Power Gain in dB $= 6.99 dB$

ii) Power gain as PUC $$= 10 Log_{10}\left(\frac{f_p + f_s}{f_s}\right)$$

$$= 10 Log_{10}\left(\frac{f_p + f_s}{f_s}\right)$$

Power gain as PUC $= 8.45 dB$