MODULE V

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Tuesday

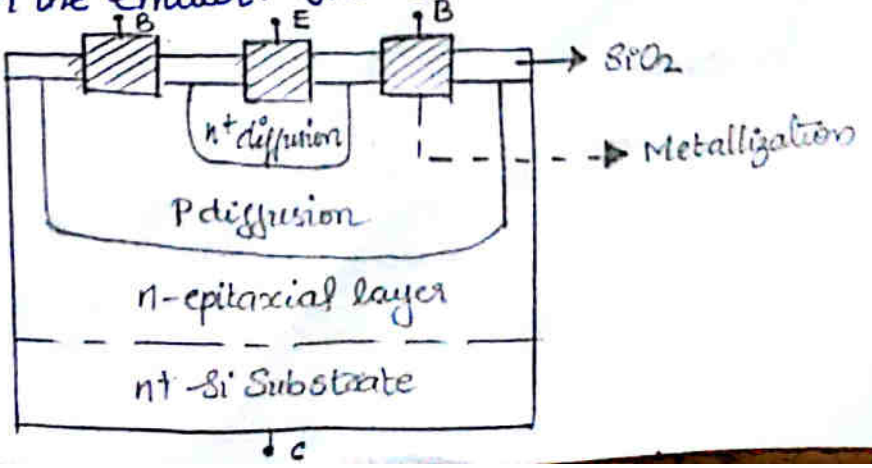
SOLID STATE MICROWAVE DEVICES

MICROWAVE BIPOLAR TRANSISTOR

The micro wave bipolar transistor is a non linear device which is mostly silicon npn type operating upto 5GHz. The Geometry of the transistor can be characterised as interdigitated geometry over lay geometry and matrix geometry. These geometries have aside emitter area to overcome transit time limitations. The interdigitated geometry is used for small signal, small power circuits. Thes over lay and matrix types are used for small power only. For high frequency applications the NPN structure is preferred because the electron mobility is higher than hole mobility. Diffusion and ion implantation are the common methods used for transistor fabrications.

Basic Construction

An epitaxial n layer is grown over a low resistivity n^+ Silicon substrate above the epitaxial layer a p region is diffused forming the base & n^+ layer is diffused over the P region to form the emitter. The silicon substrate acts as the collector



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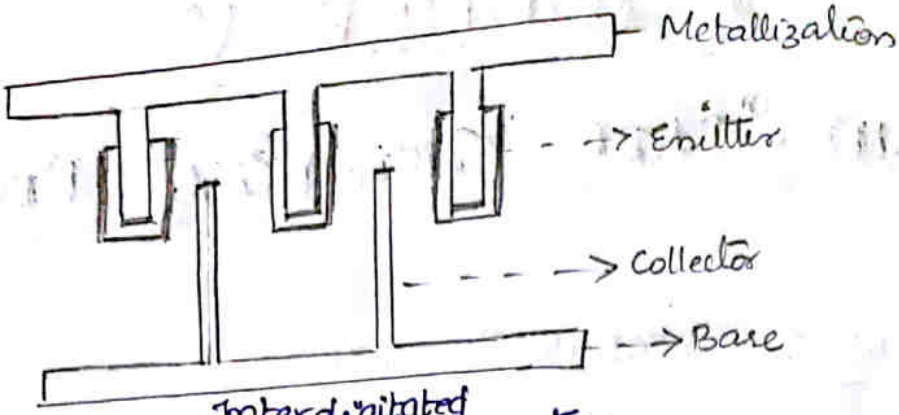

Fig: Integrated Interdigitated Geometry.

The microwave bipolar transistors are active three terminal devices which is commonly used for amplification process & wheel Switching phenomena. The three regions of the transistor are emitter, base & collector. The emitter region forms the i/p of the device and the collector region forms the o/p of the device. The emitter region of the transistor is heavily dopped & has moderate area of cross section. The base of the transistor is thin and lightly dopped to reduce the recombination rate. The collector region of the transistor is large and moderately dopped. (The charge carriers from the emitter are supplied to the collector through the base) When the charge carriers from the emitter reach the base some of them recombine with the charge carriers in the base. The remaining charge carriers are directed towards the collector constituting the collector current or o/p current.

Modes of Operation

The microwave transistors have four modes of operation depending on the polarity of the applied voltage.

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1. NORMAL MODE

In this mode the emitter base junction of the npn transistor is forward biased & collector base junction is reverse biased. Most transistor amplifiers is operated in normal mode.

2. SATURATION MODE

When both the emitter base junction & collector base junct' are forward biased the transistor is in saturation mode with low resistance and acts like a short circuit.

3. CUT OFF MODE.

When both the T^r junctions are reverse biased the T^r is operated in cut off mode. The T^r acts like an open ckt. Both the saturation & cut off modes are used when transistor acts as a switch.

4. INVERTED ACTIVE MODE.

In this mode the Emitter base junction is reverse biased & collector base junct^n is FB.

Power Frequency Limitations

Microwave transistors have limitations on frequency & power. These limitations can be due to maximum velocity of carriers, maximum electric field & max current. The four basic equations for the power frequency limitation are

1) Voltage - frequency limitation.

$$V_m f_T = \frac{E_m V_s}{2\pi}$$

where f_T – cut off frequency

$$f_T = 1/2\pi\tau$$

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$$\tau = \frac{L}{V}$$

V_m - maximum voltage

V_s - velocity

E_m - max electric field.

When, the length decreases the average time τ decreases as a result the frequency increases. When the frequency increases the applied max voltage decreases.

L↓ τ↓ F↑ V_m↓

ii) Current frequency limitation

$$I_m X_c f_T = \frac{E_m V_s}{2\pi}$$

where, X_c - impedence

I_m - max current

If the impedence level is zero, the maximum current is infinite. The impedence value should be maintained in a such a way that max current is obtained for producing max power.

iii) Power - frequency limitation.

$$\sqrt{P_m X_c} f_T = \frac{E_m V_s}{2\pi}$$

If the value of X_c is zero, the maximum power delivered is infinite.

iv) Power Gain frequency limitation

$$\sqrt{G_m V_m V_{th}} f_T = \frac{E_m V_s}{2\pi}$$

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G_m – max gain

V_{th} – thermal voltage.

V_m – maximum voltage.

If the frequency increases, the gain of the device decreases.

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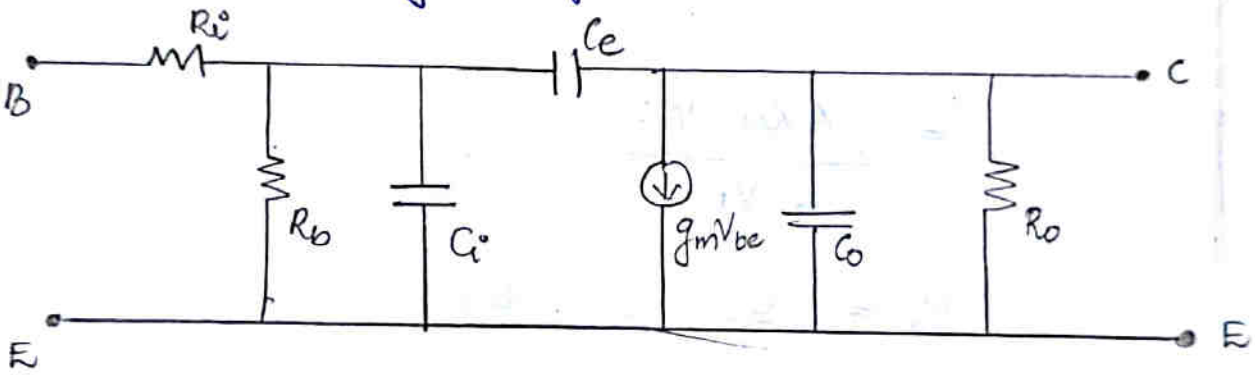
Equivalent Model of Microwave Bipolar Transistor

Hybrid Pi equivalent model is commonly used in normal active mode for small signal operations



A change of emitter voltage V_{be} at the i/p terminal will induce a change of collector current at the o/p terminal. The mutual conductance or transconductance for the small signal model is given by

$$g_m = \frac{\partial i_c}{\partial V_{be}} \quad \text{— (1)}$$

The density of charge carriers across the junction is given by

$$n_{p(0)} = n_{p0}\, e^{V_{be}/V_T} \quad \text{— (2)}$$

The collector current is defined based on the charge density as

$$i_c = \frac{qA D_n n_{p(0)}}{L_n} \quad \text{— (3)}$$

where, q – charge

A – area of cross section

D_n – diffusion constant

$n_{p(0)}$ – charge density L_n – length.

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Sub eq (2) in eqt^{n} (3)

$$i_C = \frac{q A D_n n_{p0} e^{V_{be}/V_T}}{L_n} \quad \text{— (4)}$$

$$\therefore g_m = \frac{\partial i_C}{\partial V_{be}}$$

$$g_m = \frac{q A D_n n_{p0} e^{V_{be}/V_T}}{L_n V_T}$$

$$= \frac{q A D_n n_{p(0)}}{L_n V_T}$$

$$\boxed{g_m = \frac{i_C}{V_T}} \quad \text{— (5)}$$

diffusion capacitance,

$$C_{be} = \frac{dQ_b}{dV_{be}}$$

where, Q_b - charge stored in the base.

$$Q_b = \frac{q n_{p(0)} W_b A}{2}$$

Sub. for $n_{p(0)}$ from (2)

$$Q_b = \frac{q n_{p0} e^{V_{be}/V_T} W_b A}{2}$$

$$\therefore C_{be} = \frac{q W_b A n_{p0} e^{V_{be}/V_T}}{2 V_T}$$

$$C_{be} = \frac{q W_b A n_{p(0)}}{2 V_T}$$

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$$C_{be} = \frac{i_c L_n \omega_b}{2 V_T D_n}$$ from eqtn 3.

from eqtn (5)

ie, $$C_{be} = \frac{g_m L_n \omega_b}{2 D_n}$$

If, $L_n = \omega_b$

$$\boxed{C_{be} = \frac{g_m \omega_b^2}{2 D_n}}$$

The i/p conductance,

$$g_b = \frac{i_c}{h_{fe} V_T}$$

$$\boxed{g_b = \frac{g_m}{h_{fe}}}$$

where, h_{fe} - i/p resistance / Forward emitter resistance.

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Tunnel Diodes

The tunnel diode is a PN junction device, that operates in certain regions of V-I characteristics by the tunneling of electrons across the potential barrier of the junction. This device can be used in high speed switching and logic circuits. Tunnel diodes are useful in many applications such as microwave amplifiers, microwave oscillators etc because of its low cost, light weight, high speed, low power, low noise and high peak current to valley current ratio, characteristics.

Principle of operation

i) Under Equilibrium

The fermi level is constant throughout the junction, the fermi level lies below the valence band in the P side & above the conduction

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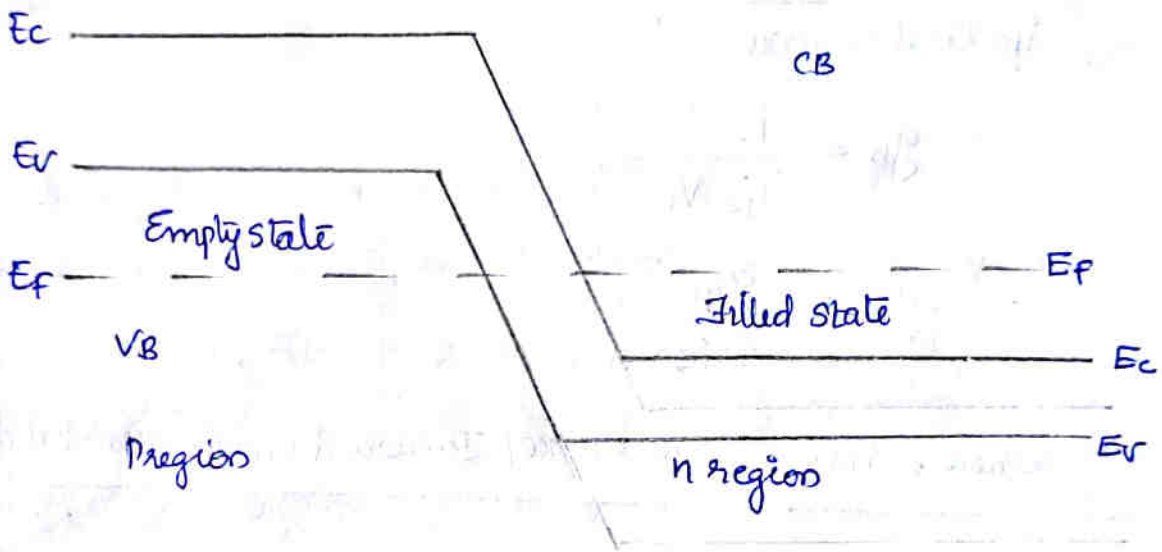
band in 'n' side. Since there are no filled states on one side of the junction which is at the same energy level as the empty state on the other side no flow of charge occurs in either directions & the current is zero. [The bands must overlap for the fermi level to be Constant]. With a small FB or RB, filled and empty states appear on opposite sides seperated by width of the depletion region



ii) Under Forward Bias

When the FB is applied across the junction the potential barrier is decreased by the magnitude of applied voltage. A difference in fermi levels is created in both sides. Since, there are filled states in the conduction band of 'n' region at the same energy level as the allowed empty states in the valence band of p region electrons tunnel through the barrier from n region to p region giving rise to forward tunneling current from P region to n region. As the FB is increased to a max voltage a max no: of electron can tunnel through the barrier producing peak current. If the voltage is increased further, the tunneling current decreases as there are no empty states available in the P region. When the FB voltage is

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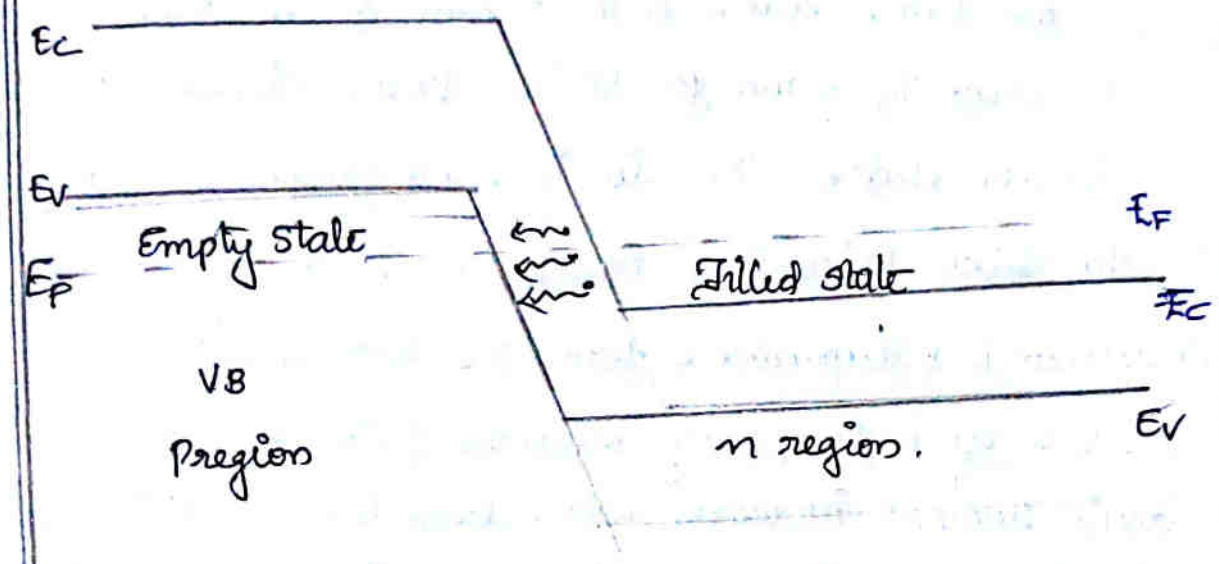
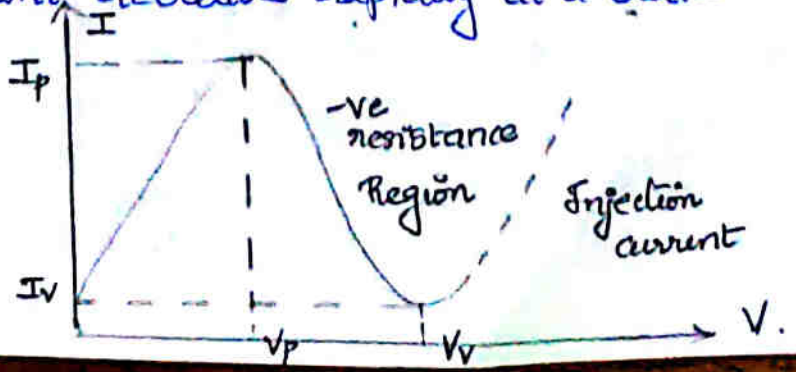
increased further, the current flow increases which is mainly due to minority charge carriers and is known as "injection current".



Tunnel Diode Characteristics

When the applied forward voltage is bet^{n} 0 and V_p, the electrons tunnel from n region to p region, there by increasing the current as the applied forward voltage reaches a value V_p, the current flowing across the junction attains a max value called the peak current 'I_p'. When the applied voltage is increased further a decrease of current occurs this produces a region of -ve slope. The maximum value of current achieved in -ve resistance region is called Valley current, I_v at an applied valley voltage V_v. If the voltage is increased beyond the -ve resistance region the current begins to increase due to the flow of minority charge carriers. This characteristics is also known as Voltage controlled -ve resistance. as the current decreases rapidly at a critical voltage.



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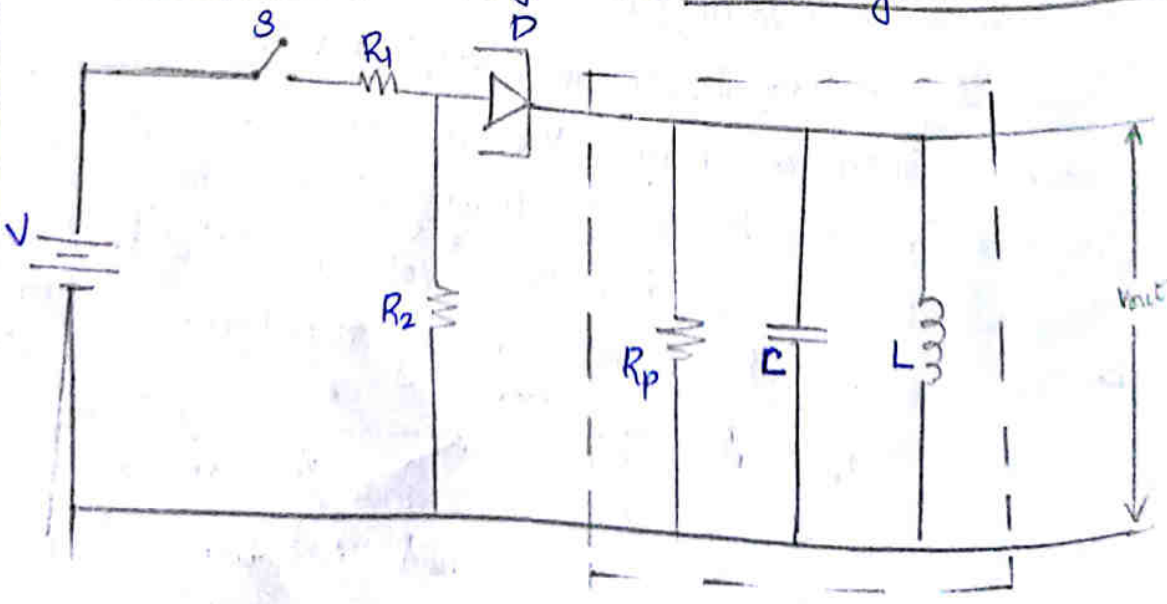
Tunnel Diode Oscillator

The value of resistor should be in such a way that it biases the tunnel diode in the middle of -ve resistance region. The resistor R_1, is used for setting proper biasing point for the tunnel diode. Resistor R_2, sets proper biasing point for the tank circuit. A parallel combination of resistor R_p, inductor, L & capacitor, C forms the tank circuit which resonates at a frequency. When the switch 'S' is closed the circuit current increases whose value is determined by the value of resistor R_1 and the diode resistance. Voltage drop across the tunnel diode increases as the applied voltage increases. As a result the tunnel diode is driven into -ve resistance region. In this region current starts decreasing until the voltage across the diode equals the valley voltage. At this point further increase of the applied voltage increases the current. This increase in current will increase the voltage drop across the resistor which produces the voltage across the diode



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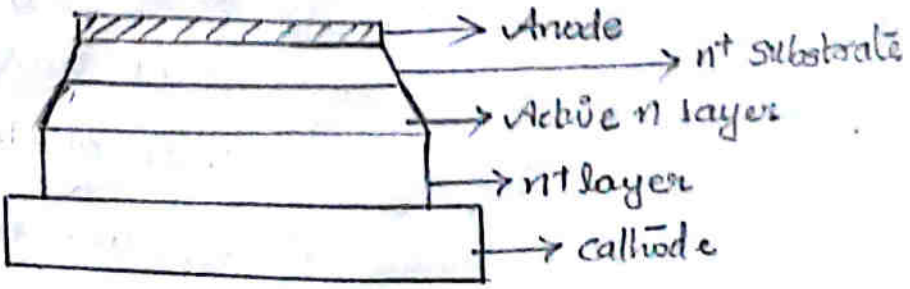
Gunn Diode.

Microwave devices that operate by transferred electron mechanism are called Gunn diodes. Some materials like GaAs shows the behaviour of -ve mobility with increase in electric field. This phenomenan is caused by the transfer of conduction band electrons from lower energy high mobility state to high energy low mobility state. This is known as 'transfered electron effect' or 'Ridley Watkins effect Hilsum' (RWH) The Devices based on this effect are called transferred electron devices. Gunn diodes are -ve resistance devices which are normally used as low power oscillators at microwave frequencies. The basic structure of Gunn diode Consists of n type GaAs Semi-Conductor. Heavily dopped n^+ regions are formed over the Substrate. If the voltage or electric field is applied to GaAs initially the current will increase with voltage. When the Voltage exceeds the threshold voltage a high electric field is produced and the electrons are excited from initial lower state to higher state. If the rate at which the electrons transfered is high the current will decrease with increase in voltage producing -ve resistance.



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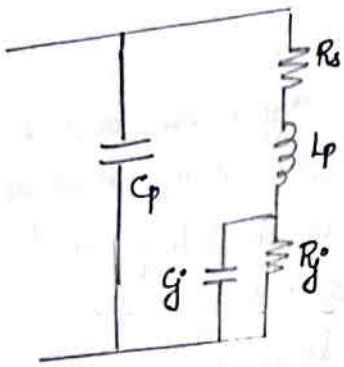

Cj - Diode Capacitance

Rj - Diode resistance

Rs - total resistance

Cp - package capacitance.

Lp - Package inductance.

→ The Conduction band has two valley's

i) Central valley with low energy & high mobility.

ii) Satellite valley with high energy & low mobility.

→ Under normal conditions electrons are in the Central Valley when the electric field increases the velocity of electrons increases. This happens only till the energy reaches the threshold value. Above the threshold value the mobility is non linear.

→ When the electric field increases beyond the threshold value the velocity of electrons in the central valley increases and gain enough energy to transfer to satellite valley. Such a transfer is defined as transferred electron mechanism. The effective mass of electrons in the satellite valley is higher than the effective mass of electron in the central valley. This results in decreased mobility of

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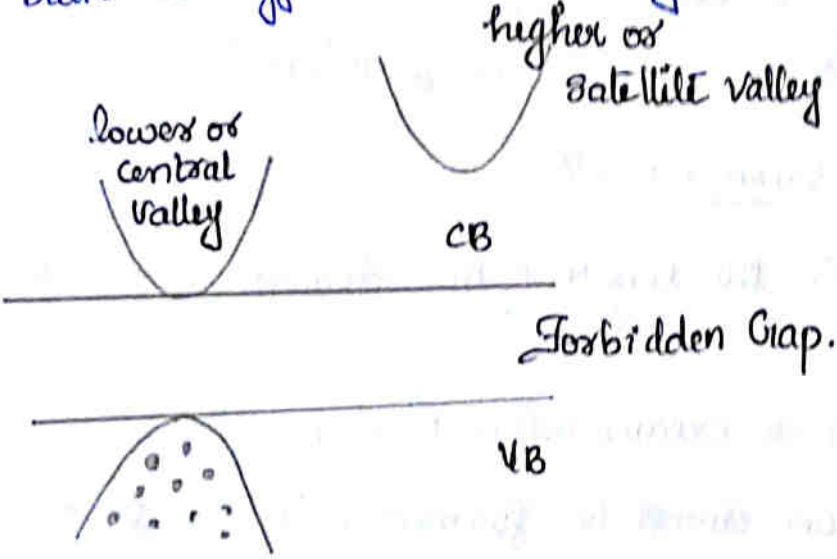
electrons in the satellite valley. Since the mobility is decreased velocity decreases. Current density, $J = q\mu E$
$= qV$.

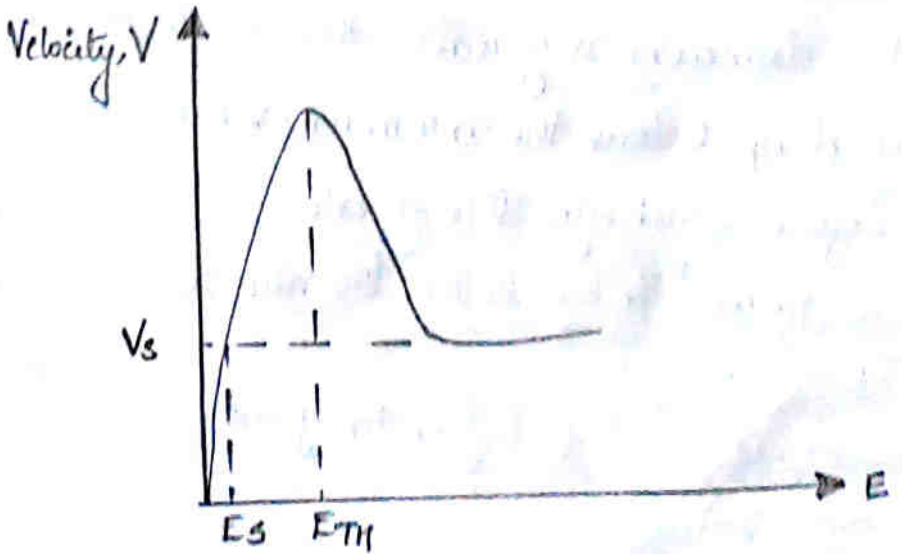
→ when velocity decreases current density decreases. Thus, when the field becomes more than the critical value the reduction in current indicate -ve resistance. This is also known as '-ve differential mobility' or 'bulk -ve differential conductivity' or 'Gunn effect' or 'RWH theory'.



Modes Of Operation.

1) Gunn Oscillation Mode.

This mode is defined in the regions where the product of frequency and length is about 10^7 cm/sec and the product of dopping & length is greater than 10^{12} cm/sec. In normal conditions Gunn diode is operated in this mode with $E > E_{TH}$.



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The three possible modes of Gunn Oscillation are

i) Transit Time Domain Mode

→ Applied velocity is equal to drift velocity
→ Oscillation period is equal to transit time. ie,
ie, $\tau_0 = \tau_t$
→ Efficiency is below 10%.
→ Length of the domain is 10^7 cm/sec.

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ii) Delayed Domain mode

→ In this mode the length of the domain is bet^n 10^6 cm/sec & 10^7 cm/sec.
→ The domain is created when $E < E_{TH}$
→ New domain cannot be formed until the field rises above the threshold.
→ Oscillation period is greater than transit time.
ie, $\tau_0 > \tau_t$
→ It is also known as inhibited mode.
→ Efficiency is about 20%

iii) Quenched Domain Mode

→ Length of the domain is greater than 2×10^7 cm/sec
→ If the field drops below the minimum value the domain colapses before reaching the anode.
→ Oscillation period is less than transit time.
ie, $\tau_0 < \tau_t$.
→ New domain is created before the field swings back above the min value.

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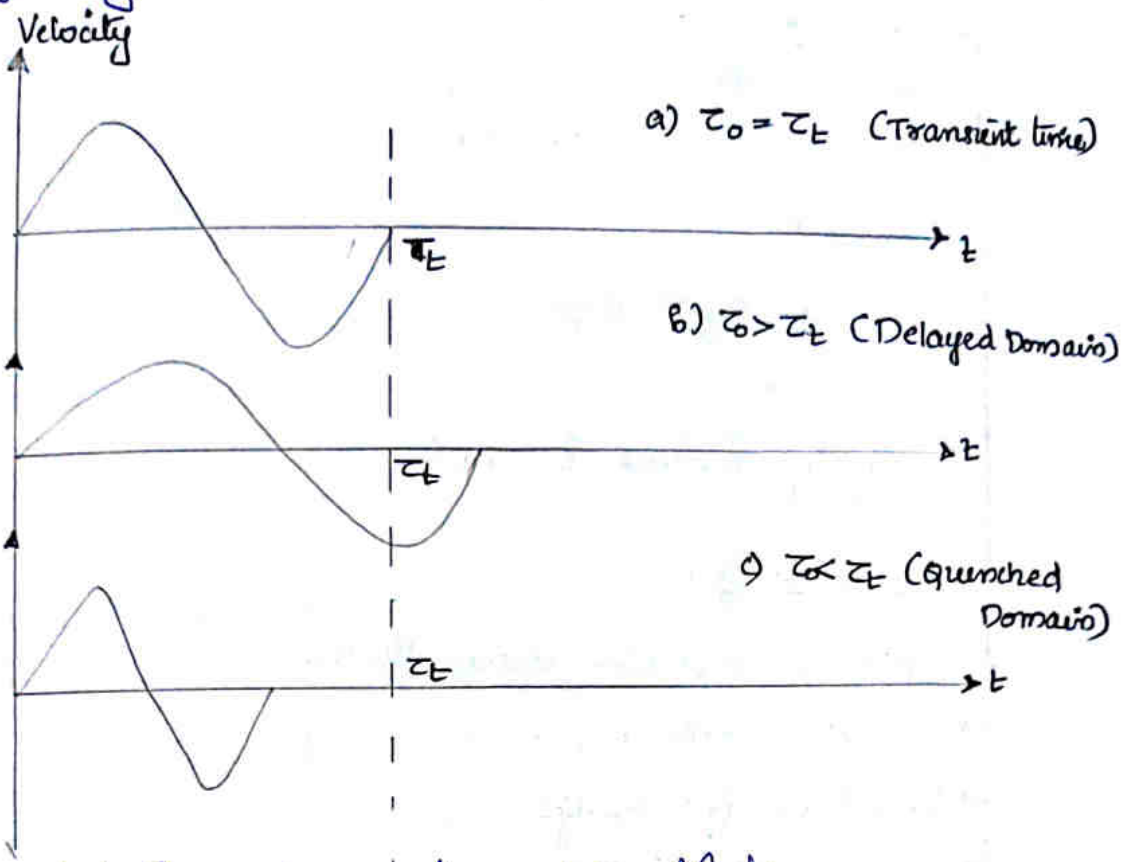
→ Efficiency is about 13%.



2) Limited Space Charge Accumulation Mode

→ When the freq is very high the domains do not have sufficient time to form while the applied electric field is above the threshold value. As a result the charge carriers accumulate near the cathode & collapse with time.

→ Efficiency is about 20%

→ Oscillation time, $\tau_0 = 3 \times \tau_t$.

Gunn Diode Oscillator

One of the main applications of Gunn diode is a Gunn diode Oscillator. It is used to generate & control microwave frequencies. They are mainly applied in relays, radars etc.

When the gunn diode is biased in -ve resistance region it will produce oscillations these oscillations can be in the range of GHz. The nature of oscillations depend on the diode area.

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Advantages of Gunn Diode.

i) highly Stable
ii) higher BW & reliability
iii) Small Size
iv) low Supply Voltage
v) low cost
vi) highly immune to noise.

Disadvantages.

→ Efficiency decreases below 10 GHz
→ Poor temp Stability.
→ Small tunning range.
→ More power dissipation.

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