ELECTRONIC DEVICES AND CIRCUITS

UNIT V FET Amplifiers & Special Purpose Devices:

FET Amplifiers: Small Signal Model, Analysis of CS, CD, CG JFET Amplifiers. Basic Concepts of MOSFET Amplifiers.
Special Purpose Devices: Zener Diode - Characteristics, Voltage Regulator; Principle of Operation - SCR, Tunnel diode, UJT, Varactor Diode.

5.1 FET Amplifiers

- A FET amplifier is an amplifier which uses one or more field-effect transistors (FETs).
- The main advantage of an FET used for amplification is that it has very high input impedance and low output impedance.
- These are two desirable features for an amplifier.
- FET is replaced by small signal low frequency model and small signal high frequency model.

5.2 Small Signal FET Models

- The small signal FET model is used to relate small changes in FET current and voltages about the quiescent operating point.
- The model is different at low and high frequencies.
- Therefore we shall study the small signal models separately as the low-frequency FET model and high-frequency model.
- In both these models, the FET will be considered in common source configuration.

5.2.1 Small Signal Low Frequency FET Model

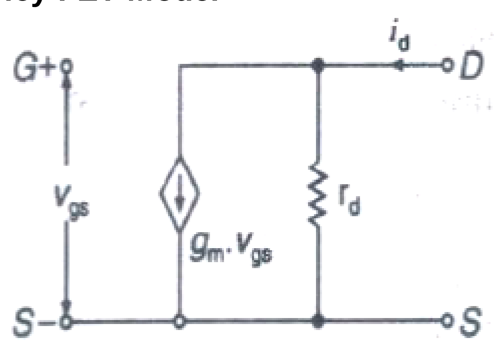

Fig. 5.1 Low-frequency FET model

- Figure 5.1 shows the small signal low-frequency model of a field effect transistor.
- In this model, the gate to source junction is represented by an open circuit and no current is drawn by the input terminal of the field effect transistor.
- It is because of the fact, that the input resistance is very large.
- Its value at d.c. or zero frequency is typically 10^8 to 10^{10} for JFET's and 10^{10} to 10^{14} for MOSFET's.

- It will be interesting to know that although the gate to source junction appears as an open circuit, yet the gate to source voltage affects the value of drain current.
- It is indicated by a voltage controlled current source ($g_m \cdot V_{gs}$) whose value is proportional to the gate to source voltage.
- Typical values of transconductance (g_m) are from 0.5 mA / V to 10 mA / V for JFET's and 0.5 mA / V to 20 mA / V for MOSFET's.
- The FET drain resistance (also called FET output resistance) is represented by the resistance (rd) and its value are from 100 KΩ to 1 MΩ for JFET's and 1 KΩ to 50 KΩ for MOSFET's.

5.2.2 Small Signal High Frequency FET Model

- Figure 5.2 shows the small-signal high-frequency model of a field effect transistor.
- It is identical to the low frequency model, except the addition at capacitances between each pair of terminals.
- The capacitor, (c_{gs}) represents the barrier capacitance between the gate and source. Its typical value is from 1 pF to 10 pF for both JFET's and MOSFET's.
- The capacitor (C_{gd}) represents the barrier capacitance between the gate and drain. Its typical value is also from 1 pF to 10 pF for both JFET's and MOSFET's.
- Similarly, the capacitor (C_{ds}) represents the drain to source capacitance. The typical value of is from 0.1 pF to 1 pF.

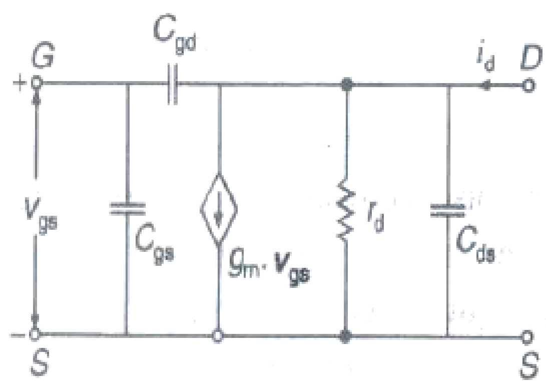

Fig. 5.2 High-frequency FET model

5.3 Field Effect Transistor Amplifier

- The field-effect transistor (FET) has a capability to amplify a.c. signals like a bipolar transistor.
- Depending open the configuration, the FET amplifiers may be studied under the following three heads.
  - ➢ Common source amplifier
  - ➢ Common drain amplifier
  - ➢ Common gate amplifier

5.4 Common Source Amplifier

- Figure 5.3 shows the circuit of a common source N-channel JFET amplifier.
- It is similar to a common emitter amplifier. Here the resistors R_1 and R_2 (called a voltage divider) are used to bias the field effect transistor.
- The capacitor (C_1) and (C_2) are used to couple the a.c. input voltage source and the output voltage respectively, these are known as coupling capacitors.
- The capacitor (C_S) keeps the source of the FET effectively at a.c. ground and is known as bypass capacitor.

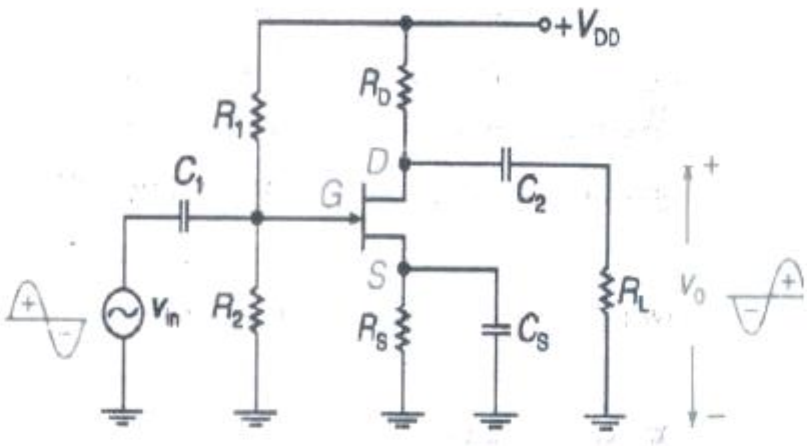

Fig. 5.3 Common Source Amplifier

5.4.1 Operation

- When a small a.c. signal is applied to the gate, it produces variations in the gate to source voltage.
- This produces variations in the drain current.
- As the gate to source voltage increases, the drain current also increases. As a result of this, the voltage drop across the resistor (R_D) also increases.
- This causes the drain voltage to decrease.
- It means that the positive half cycle of the input voltage produces the negative half cycle of the output voltage.
- In other words, the output voltage (at the drain) is 180^0 out of phase with the input voltage (at the gate).
- This phenomenon of phase inversion is similar to that exhibited by a common emitter bipolar transistor amplifier.

5.4.2 Analysis of Common Source Amplifier

- Figure 5.4 shows the a.c. equivalent circuit of a common source amplifier.
- This circuit has been obtained from the amplifier circuit shown in Figure 2.32 by short circuiting the capacitors and the d.c. voltage supplies.
- The field effect transistor is also replaced by its low frequency model (or equivalent circuit).

- Now we shall use this circuit to find the expressions for amplifier voltage gain, input resistance and output resistance.

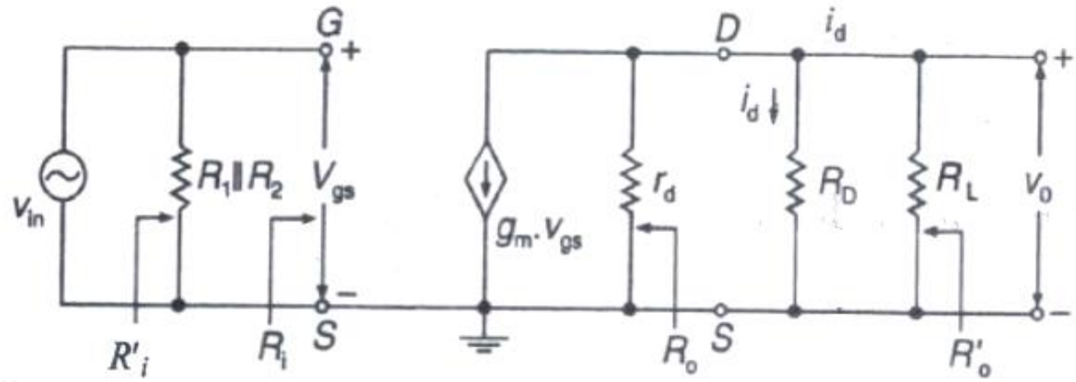

Fig. 5.4 A.C. equivalent circuit of a common source amplifier

5.4.2.1 Voltage gain

- It is the ratio of the output voltage (V_o) to the input voltage (V_{in}).
- Mathematically the voltage gain,

$$A_v = \frac{v_o}{v_{in}}$$

- The output voltage is given by

$$v_o = -i_d \cdot r_L \qquad (\because r_L = (R_D \| R_L) \| r_d)$$

$$= -(g_m \cdot v_{gs})\, r_L \qquad (\because v_{in} = v_{gs})$$

$$= -g_m \cdot r_L \cdot v_{in}$$

- Then the voltage gain is

$$\boxed{A_v = \frac{v_o}{v_{in}} = -g_m \cdot r_L}$$

- The minus sign indicates that the output voltage is 180^0 out of phase with the input voltage.
- If $r_d >> (R_D \text{ II } R_L)$ then,

$$r_L = (R_D \text{ II } R_L)$$

- Then the voltage gain is given as

$$\boxed{A_v = g_m\, (R_D \text{ II } R_L)}$$

5.4.2.2 Input resistance

- It is the ratio of the input voltage (V_{in}) to the input current (i_{in}).
- Mathematically, the input resistance,

$$R_i = \frac{v_{in}}{i_{in}} = \infty$$

- We know that input resistance (R_i) of a field effect transistor is very high and hence can be considered to be infinity (i.e. open circuit).
- However, the input resistance of the amplifier stage (R_i') is equal to the parallel combination of resistors R_1 and R_2 and the FET input resistance (R_i).
- Thus

$$\begin{aligned} R'_i &= (R_1 \| R_2) \| R_i \\ &= R_1 \| R_2 \qquad \text{... (When } R_i \text{ is infinite)} \end{aligned}$$

5.4.2.3 Output resistance

- It is the ratio of the output voltage (V_o) to the output current (i_d).
- Mathematically, the output resistance,

$$R_o = \frac{v_o}{i_d} = r_d$$

- But for the amplifier stage, the output resistance is the parallel combination of resistors R_L R_D and r_d.

$$R'_o = (R_D \| R_L \| r_d)$$

- However, if rd >> (R_D II R_L) then the output resistance of amplifier stage,

$$R'_o = (R_D \| R_L)$$

Example *A certain JFET has a g_m of 4 mS. With an external drain resistance of 1.5 kΩ, find the value of ideal voltage gain.*

Solution. Given: $g_m = 4 \text{ mS} = 4 \times 10^{-3}$ S and $R_D = 1.5 \text{ k}\Omega = 1.5 \times 10^3\ \Omega$.

We know that the voltage gain,

$$A_v = -g_m \cdot R_D = -(4 \times 10^{-3}) \times (1.5 \times 10^3) = -6 \textbf{ Ans.}$$

Example *A JFET amplifier has g_m = 2.5 mA/V and r_d = 500 kΩ. The load resistance is 10 kΩ. Find the value of voltage gain.*

Solution. Given: $g_m = 2.5 \text{ mA/V} = 2.5 \times 10^{-3}$ A/V;

$r_d = 500$ kΩ and $R_D = 10$ kΩ.

We know that the a.c. equivalent resistance,

$$r_L = \frac{R_D \times r_d}{R_D + r_d} = \frac{10 \times 500}{10 + 500} \text{ k}\Omega = 9.8 \text{ k}\Omega = 9.8 \times 10^3\ \Omega$$

∴ Voltage gain,

$$\begin{aligned} A_v &= -g_m \cdot r_L = -(2.5 \times 10^{-3}) \times (9.8 \times 10^3) \\ &= -24.5 \textbf{ Ans.} \end{aligned}$$

Example *The input and output resistances of the FET amplifier are shown in Figure Calculate the value of voltage gain. The FET amplifier has $g_m = 2\ mA/V$ and $r_d = 40\ k\Omega$.*

Solution. Given: $g_m = 2\ \text{mA/V} = 2 \times 10^{-3}\ \text{A/V}$; $r_d = 40\ \text{k}\Omega$; $R_D = 20\ \text{k}\Omega$ and $R_G = 100\ \text{M}\Omega$.

Voltage gain

We know that the a.c. equivalent resistance,

$$r_L = \frac{R_D \times r_d}{R_D + r_d} = \frac{20 \times 40}{20 + 40} = 13.3\ \text{k}\Omega$$

$$= 13.3 \times 10^3\ \Omega$$

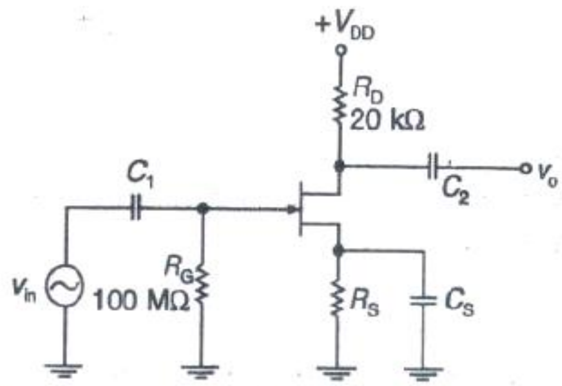

Fig.

$\therefore$ Voltage gain

$$A_v = -g_m \cdot r_L = -(2 \times 10^{-3}) \times (13.3 \times 10^3) = -26.7 \textbf{ Ans.}$$

Input resistance

We know that the input resistance,

$$R'_i = R_G = 100\ \text{M}\Omega \textbf{ Ans.}$$

Outpur resistance

We also know that the output resistance,

$$R_o' = r_L = 13.3\ \text{k}\Omega \textbf{ Ans.}$$

5.5 Common Drain Amplifier

- Figure 5.5 shows the circuit of a common drain amplifier.

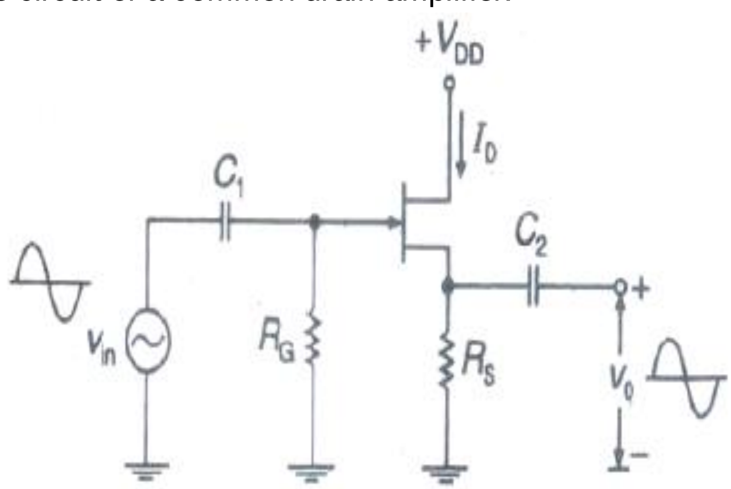

Fig. 5.5 Common Drain Amplifier

- It is similar to common collector (or emitter follower) amplifier.

- Self-biasing is used in the circuit.
- The input signal is applied to the gate through a coupling capacitor (C_1).
- The output is taken from the source terminal through the coupling capacitor (C_2).

5.5.1 Operation

- When a small a.c. signal is applied to the gate, it produces variations in the gate to source voltage.
- This further produces the variations in dram current (I_D).
- As the gate-to-source voltage increases, the drain current also increases.
- As a result of this, the voltage drop across the source resistor (R_s) also increases.
- Thus the output voltage (V_o) increases.
- It may be noted that the output voltage of a common drain amplifier is approximately equal to and in phase with the input voltage.
- Because of this fact, the circuit is known as source follower.

5.5.2 Analysis of a Common Drain Amplifier

- Figure 5.6 shows the a.c. equivalent circuit of a common drain amplifier.
- This circuit has been obtained from the amplifier circuit shown in Figure 5.5 by short circuiting the capacitors and d.c. voltage supply.
- The field-effect transistor is also replaced by its low-frequency model.
- Now we shall use this circuit to find the expressions for voltage gain, input resistance and output resistance.

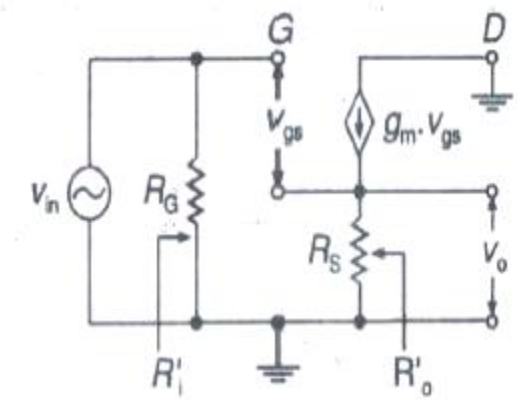

Fig. 5.6 A.C. equivalent Circuit of a common drain amplifier

5.5.2.1 Voltage gain

- It is the ratio of output voltage (V_o) to the input voltage (V_{in}).
- Mathematically, the voltage gain,

$$A_v = \frac{v_o}{v_{in}}$$

- For the common drain amplifier, the input voltage,

$$v_{in} = v_{gs} + i_d \cdot R_s$$

- The output voltage,

$$v_o = i_d \cdot R_S$$

- Then, Voltage gain,

$$A_v = \frac{v_o}{v_{in}} = \frac{i_d \cdot R_s}{v_{gs} + i_d \cdot R_s}$$

- Substituting the value of $i_d = g_m \cdot v_{gs}$ in the above expression,

$$A_v = \frac{(g_m \cdot v_{gs})\, R_s}{v_{gs} + g_m \cdot v_{gs} \cdot R_s}$$

$$= \frac{g_m \cdot v_{gs} \cdot R_s}{v_{gs}\,(1 + g_m \cdot R_s)}$$

$$= \frac{g_m \cdot R_s}{1 + g_m \cdot R_s} = \frac{R_s}{R_s + \dfrac{1}{g_m}}$$

- It may be noted that when $R_s >>> 1/g_m$, the value of voltage gain approaches unity.

5.5.2.2 Input resistance

- It is the ratio of the input voltage (V_{in}) to the input current (i_{in}).
- Mathematically, the input resistance,

$$R_i = \frac{v_{in}}{i_{in}} = \infty$$

- We know that input resistance (R_i) of a field effect transistor is very high and hence can be considered to be infinity (i.e. open circuit).
- However, the input resistance of the amplifier stage (R_i') is equal to the parallel combination of resistors R_G and the FET input resistance (R_i).
- Thus

$$R'_i = R_G \parallel R_i$$

$$R'_i = R_G \qquad \text{... (When } R_i \text{ is infinite)}$$

5.5.2.3 Output resistance

- We know that voltage gain of the common drain amplifier,

$$A_v = \frac{v_o}{v_{in}} = \frac{R_s}{R_s + \dfrac{1}{g_m}}$$

- Output voltage,

$$v_o = \left(\frac{R_s}{R_s + \frac{1}{g_m}} \right) \times v_{in}$$

- The above expression is a voltage-divider equation.
- It implies that the input voltage (V_{in}) drives two resistors R_s and $1/g_m$ with output voltage taken across resistor R_s.
- It means that the output side of the amplifier appears as shown in Figure 5.7(a).
- It is evident from this figure, that the source resistor is driven by an a.c. source with an output resistance i.e.,

(*a*) A.C. equivalent circuit of output side of the amplifier.

(*b*) Thevenin's equivalent circuit of the amplifier.

Fig. 5.7

- It may be noted that output resistance R_o is the value of resistance looking back into the source terminal of the JFET.
- Now let us thevenize the output circuit.
- The resulting circuit is as shown in Figure 5.7(b).
- It is evident from this figure, that the resistance R_s is in parallel with $1/g_m$ and the output resistance of the amplifier stage,

$$R'_o = R_s \,||\, \frac{1}{g_m}$$

- If the value of source resistance $R_s >> 1/g_m$, then the output resistance of the amplifier stage,

$$R'_o = \frac{1}{g_m}$$

Example *Figure shows the circuit of a source follower. Determine the voltage gain of the amplifier.*

Also determine the input and output resistance of the amplifier. Assume g_m = 800 μS, infinite input resistance and neglect FET output resistance.

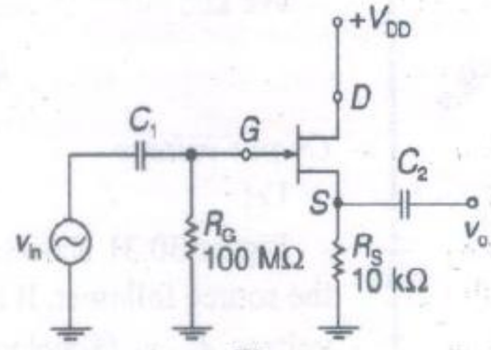

Fig.

Solution. Given: $g_m = 8000\ \mu S = 8000 \times 10^{-6}$ S; $R_G = 10\ k\Omega = 10 \times 10^3\ \Omega$ and $R_G = 100\ M\Omega$.

Voltage gain

We know that the reciprocal of transconductance,

$$\frac{1}{g_m} = \frac{1}{8000 \times 10^{-6}} = 125\ \Omega\ \textbf{Ans.}$$

and the voltage gain,

$$A_v = \frac{R_s}{R_s + \frac{1}{g_m}} = \frac{10 \times 10^3}{(10 \times 10^3) + 125} = 0.988\ \textbf{Ans.}$$

Input resistance

We know that the input resistance

$$R'_i = R_G = 100\ M\Omega\ \textbf{Ans.}$$

Output resistance

We also know that the output resistance,

$$R'_o = \frac{1}{g_m} = \frac{1}{8000 \times 10^{-6}} = 125\ \Omega\ \textbf{Ans.}$$

Example *Find the voltage gain for the source follower shown in Figure*

Also find the input and output resistances. If the input voltage is 2 mV, find the value of the output voltage. Assume g_m = 5500 μS.

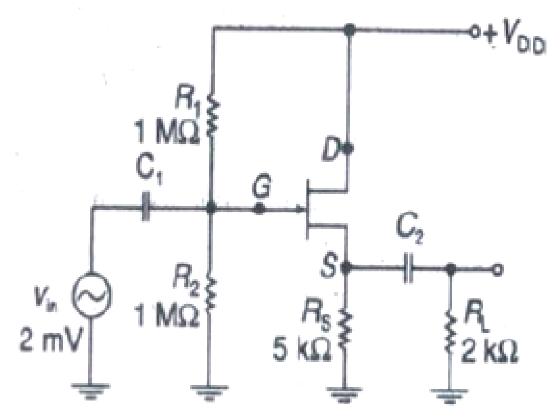

Fig.

Solution. Given: v_{in} = 2 mA; g_m = 5500 μS = 5500 × 10^{-6} S; $R_1 = R_2$ = 1 MΩ; R_S = 5 kΩ = 5000 Ω and R_L = 2 kΩ = 2000 Ω.

Voltage gain

We know that the reciprocal of transconductance,

$$\frac{1}{g_m} = \frac{1}{5500 \times 10^{-6}} = 181.8\ \Omega$$

and the voltage gain,

$$A_v = \frac{R_s}{R_s + \frac{1}{g_m}} = \frac{5000}{5000 + 181.8} = 0.965 \textbf{ Ans.}$$

Input resistance

We know that input resistance,

$$R'_i = R_1 \parallel R_2 = \frac{R_1 \cdot R_2}{R_1 + R_2} = \frac{1 \times 1}{1+1}\ \text{M}\Omega = 0.5\ \text{M}\Omega \textbf{ Ans.}$$

Output resistance

We know that the input resistance,

$$R'_o = R_s \parallel \frac{1}{g_m} = 5000 \parallel 181.8 = 175.4\ \Omega \textbf{ Ans.}$$

Output voltage

Let v_o = Value of the output voltage.

Figure shows the a.c. equivalent circuit of the output side of the source follower. It is evident from this figure, that an a.c. source of voltage $A_v \cdot v_{in}$ (equal to 0.965×2 or 1.93 V) is in series with an output resistance of 175.4 Ω.

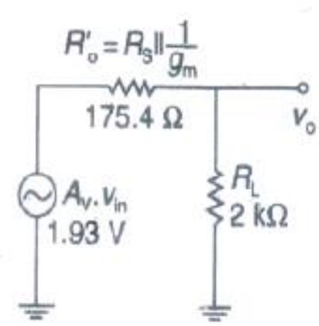

Fig.

We know that the a.c. voltage across the load resistor,

$$= \left(\frac{R_L}{R_L + R'_o}\right) \times A_v.V_{in}$$

$$= \left(\frac{2000}{2000 + 175.4}\right) \times 1.93 \text{ mV}$$

$$= 1.77 \text{ mV } \textbf{Ans.}$$

5.6 Common Gate Amplifier

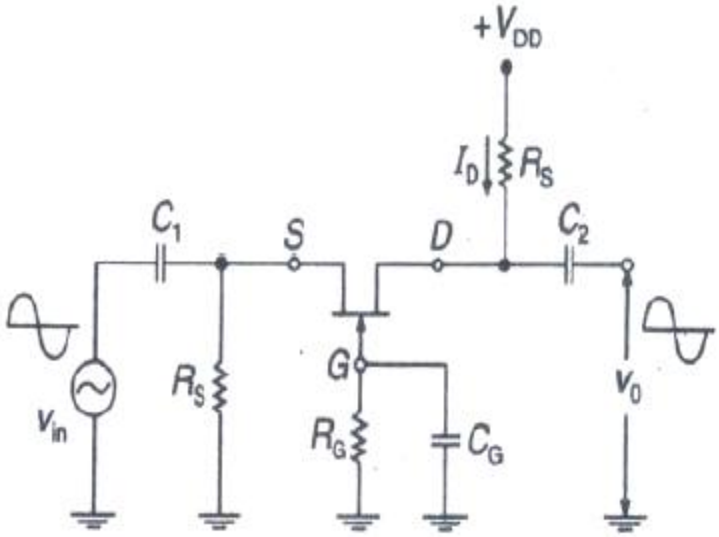

Fig. 5.8 Common gate amplifier

- Figure 5.8 shows the circuit of a common gate amplifier.
- It is similar to a common base amplifier.
- The input signal is applied at the source through a coupling capacitor (C_1) and the output is taken from the drain through the coupling capacitor (C_2).
- The gate is effectively at a.c. ground because of the capacitor, (C_G).

5.6.1 Operation

- When a small a.c. signal is applied to the source, it produces variation in gate to source voltage (V_{GS}).
- This in turn, produces the variations in drain current (I_D).
- As the gate to source voltage increases, the drain current also increases.
- As a result of this, the output voltage also increases.
- Thus output voltage of a common gate amplifier is in phase with the input voltage.

5.6.2 Analysis of a Common Gate Amplifier

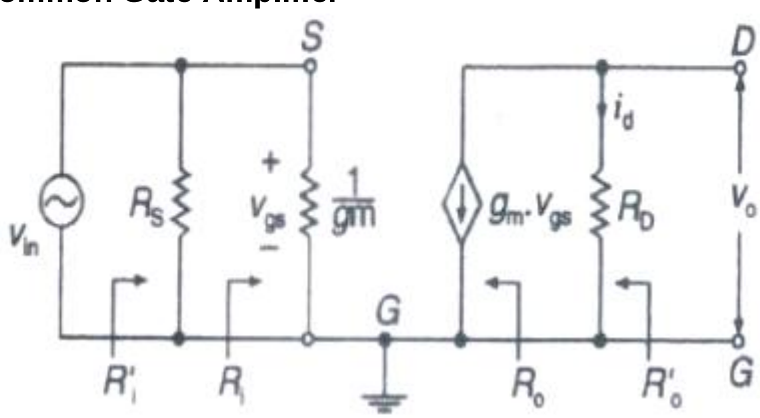

Fig. 5.9 Equivalent circuit of Common gate amplifier

- Figure 5.9 shows an a.c. equivalent circuit of a common gate amplifier.
- This circuit has been obtained from the amplifier circuit shown in Figure 5.8 by short-circuiting the capacitors and the d.c. supply.
- The field effect transistor is also replaced by its low frequency model.
- Now we shall use this circuit to find the expressions for amplifier voltage gain, input resistance and output resistance.

5.6.2.1 Voltage gain

- It is the ratio of a.c. output voltage (V_o) to the a.c. input voltage (V_{in}).
- Mathematically, the voltage gain,

$$A_v = \frac{v_o}{v_{in}}$$

- We know that the a.c. input voltage,

$$v_{in} = v_{gs}$$

- The a.c. output voltage,

$$v_o = i_d \cdot R_\mathrm{D}$$

- Voltage gain,

$$A_v = \frac{i_d \cdot R_\mathrm{D}}{v_{gs}}$$

- Substituting the value of $i_d = g_m . V_{gs}$ in the above expression,

$$A_v = \frac{(g_m \cdot v_{gs}) \cdot R_\mathrm{D}}{v_{gs}} = g_m \cdot R_\mathrm{D}$$

- If there is a load resistor (R_L) connected to the amplifier output, then the voltage gain.

$$A_v = g_m (R_\mathrm{D} \,||\, R_\mathrm{L})$$

5.6.2.2 Input resistance

- It is the ratio of input voltage (V_{in}) to the input current (i_{in}).
- Mathematically, the input resistance,

$$R_i = \frac{v_{in}}{i_{in}}$$

- For a common gate amplifier

$$v_{in} = v_{gs}$$
$$i_{in} = i_d$$

- We have $i_d = g_m v_{gs}$
- Therefore the input resistance

$$R_i = \frac{v_{gs}}{i_d} = \frac{v_{gs}}{g_m \cdot v_{gs}} = \frac{1}{g_m}$$

- The input resistance of the amplifier,

$$R'_i = R_s \parallel \frac{1}{g_m}$$

- If $R_S >> 1/g_m$, then the input resistance of the amplifier,

$$R'_i = R_s$$

5.6.2.3 Output resistance

- It is the ratio of a.c. output voltage (v_o) to the a.c. output current (i_o).
- Mathematically, the output resistance of the amplifier,

$$R'_o = \frac{v_o}{i_o} = \frac{i_d \cdot R_D}{i_d} = R_D \qquad \ldots (\because v_o = i_d \cdot R_D \text{ and } i_o = i_d)$$

- If there is a load resistor (R_L) connected to the amplifier output, then the output resistance of the amplifier,

$$R'_o = R_D \parallel R_L$$

Example *Figure shows the circuit of a common gate JEET amplifier. The JFET has transconductance $g_m = 2500\ \mu S$.*

Determine the amplifier voltage gain and input resistance.

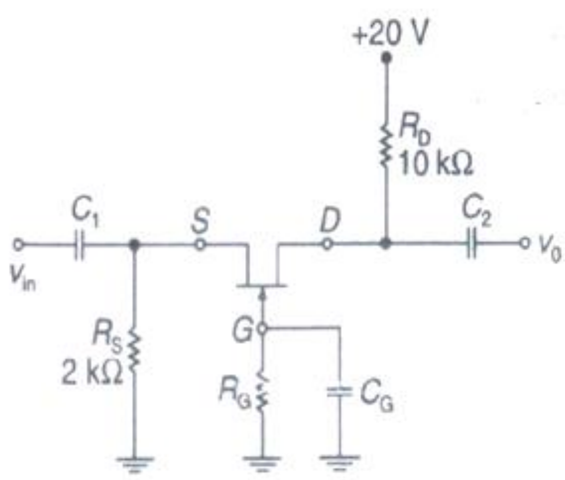

Fig.

Solution. Given: $g_m = 2500\ \mu S = 2500 \times 10^{-6} S$; $R_D = 2\ k\Omega = 2000\ \Omega$ and $R_D = 10\ k\Omega = 10{,}000\ \Omega$.

Voltage gain

We know that voltage gain,

$Av = g_m \cdot R_D = 2500 \times 10^{-6} \times 10{,}000 = 25$

Input resistance

We know that reciprocal of transconductance,

$$\frac{1}{g_m} = \frac{1}{2500 \times 10^{-6}} = 400\ \Omega$$

and the amplifier input resistance,

$$R'_i = R_i \,||\, \frac{1}{g_m} = 2000 \,||\, 400\ \Omega$$

$$= \frac{2000 \times 400}{2000 + 400} = 333\ \Omega \textbf{ Ans.}$$

Example *For a JFET, the transconductance at zero gate-to-source voltage, $g_{mo} = 5$ mS. Determine the amplifier input resistance (R'_i) and a.c. voltage gain (v_o/v_{in}) for the circuit shown in Figure. Assume the capacitors to be short circuit for a.c.*

Solution. Given: $g_{mo} = 5\ \text{mS} = 5 \times 10^{-3}\ S$; $R_D = 1\ \text{k}\Omega = 1 \times 10^3\ \Omega$; $R_s = 200\ \Omega$ and $I_D = 5\ \text{mA} = 5 \times 10^{-3}$ A.

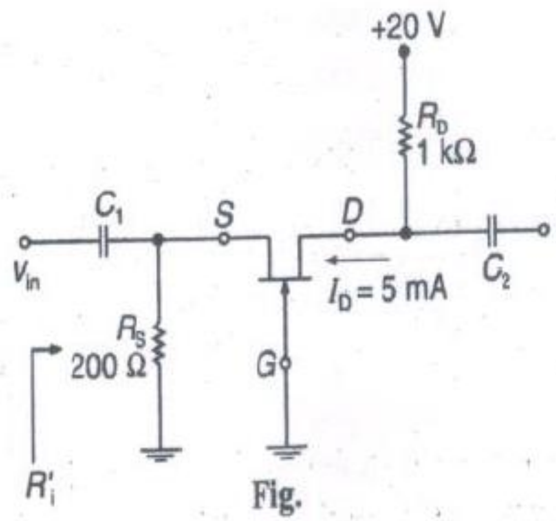

Fig.

Input resistance

We know that reciprocal of transconductance

$$\frac{1}{g_{mo}} = \frac{1}{5 \times 10^{-3}} = 200\ \Omega$$

and the input resistance of the amplifier,

$$R'_i = R_s \,||\, \frac{1}{g_{mo}} = 200 \,||\, 200\ \Omega = 100\ \Omega \textbf{ Ans.}$$

Voltage gain

We know that the d.c. source voltage,

$$V_S = I_D \cdot R_S = (5 \times 10^{-3}) \times 200 = 1\ \text{V}$$

and the gate-to-source voltage,

$$V_{GS} = V_S = 1 \text{ V}$$

We also know that the *maximum value of drain current,

$$I_{DSS} = 2\, I_D = 2 \times (5 \times 10^{-3}) = 10 \times 10^{-3} \text{ A}$$

and gate-to-source cut-off voltage

$$V_{GS(off)} = -\frac{2\, I_{DSS}}{I_D} = -\frac{2 \times (10 \times 10^{-3})}{5 \times 10^{-3}} = -4 \text{ V}$$

and the transconductance (g_m)

$$= g_{mo}\left[1 - \frac{V_{GH}}{V_{GS(off)}}\right]$$

$$= (5 \times 10^{-3})\left[1 - \frac{1}{4}\right]$$

$$= 3.75 \times 10^{-3} \text{ S}$$

5.7 Comparison of CS, CD and CG Amplifiers

S. No.	Parameters	Common Source	Common Drain	Common Gate
1	Voltage Gain	High	Unity	Low
2	Input Resistance	High	High	Low
3	Output Resistance	Low	Low	High
4	Bandwidth	BW varies inversely with gain	High BW	High BW
5	Applications	Voltage amplifier	Voltage buffer circuit, impedance matching, simple output stage.	Current regulator circuit.

5.8 Basic Concepts of MOSFET Amplifiers

- A MOSFET amplifier is an amplifier which uses one or more MOSFET's.
- The main advantage of an MOSFET used for amplification is that it has very high input impedance and low output impedance.
- These are two desirable features for an amplifier.
- MOSFET is replaced by small signal low frequency model and small signal high frequency model.
- Small signal low-frequency model and high frequency model of MOSFET is same as that of FET.

5. 8.1 MOSFET Amplifier

- The MOSFET has a capability to amplify a.c. signals like a bipolar transistor.
- Depending open the configuration, the MOSFET amplifiers may be studied under the following three heads.
    - Common source amplifier
    - Common drain amplifier
    - Common gate amplifier
- Derivations for MOSFET amplifier parameters like voltage gain, Input resistance and Output resistance for Common source, Common Drain and Common Gate amplifier is same as FET.

5.9 Special Purpose Electronic Devices:

There are few diodes which are designed to serve some special purposes.

- Zener Diode
- Tunnel Diode
- Varactor Diode
- Silicon Control Rectifier
- UJT

5.10 Zener Diode

- The zener diode is a silicon p-n junction semiconductor device, which is generally operated in its reverse breakdown region.

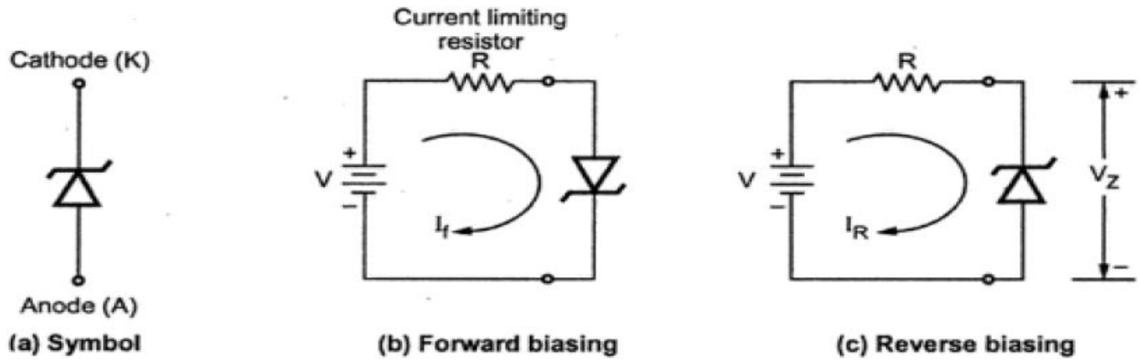

Fig. 5.10 Zener diode

- The zener diodes are fabricated with precise breakdown voltages, by controlling the doping level during manufacturing.
- The zener diodes have breakdown voltage range from 3 V to 200 V.
- The Fig. 5.10 (a) shows the symbol of zener diode.
- The d.c voltage can be applied to the zener diode so as to make it forward biased or reverse biased. This is shown in the Fig. 5.10 (b) and (c).
- Practically zener diodes are operated in **reverse biased mode**.

5.10.1 Characteristics of Zener Diode

- In the forward biased condition, the normal rectifier diode and the zener diode operate in similar fashion.
- But the zener diode is designed to be operated in the reverse biased condition.
- In reverse biased condition the diode carries reverse saturation current till the reverse voltage applied is less than the reverse breakdown voltage.
- When the reverse voltage exceeds reverse breakdown voltage, the current through it changes drastically but the voltage across it remains almost constant.
- Such a breakdown region is a normal operating region for a zener diode.
- VI characteristic of Zener diode is shown in figure 5.11.
- The first quadrant is the forward biased region. Here the Zener diode acts like an ordinary diode. When a forward voltage is applied, current flows through it.
- The third quadrant is the reverse biased region, when we apply a reverse bias to the diode.
- The Zener breakdown voltage (V_Z) is the reverse bias voltage after which a significant amount of current starts flowing through the Zener diode.

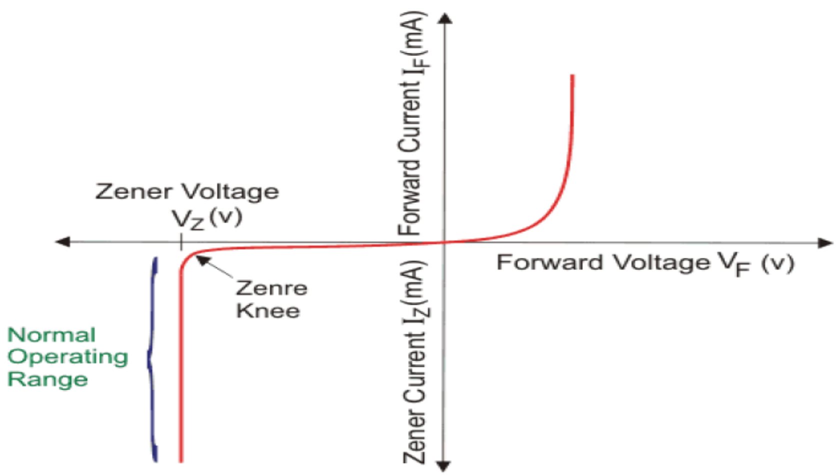

Fig. 5.11 V-I characteristics of Zener diode

- Until the voltage reaches Zener breakdown level, tiny amount of current flows through the diode.
- Once the reverse bias voltage becomes more than the Zener breakdown voltage, a significant amount of current starts flowing through the diode due to Zener breakdown.
- The voltage remains at the Zener breakdown voltage value, but the current through the diode increases when the input voltage gets increased.

5.10.2 Applications of Zener Diode

- Voltage Regulator
- Protection circuits
- Voltage Limiters

5.11 Zener Voltage Regulator

- As the voltage across the zener diode remains constant equal to V_z, it is connected across the load and hence the load voltage V_o is equal to the zener voltage V_z.
- Thus zener diode acts as an ideal voltage source which maintains a constant load voltage, independent of the current

5.11.1 Regulation with Varying Input Voltage

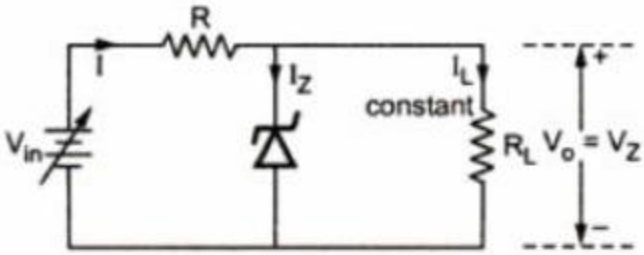

Fig. 5.12 Varying Input condition

- The Fig. 5.12 shows a zener regulator R under varying input voltage condition.
- It can be seen that the output is

$$V_o = V_Z \text{ is constant.}$$

$$\therefore \quad I_L = \frac{V_o}{R_L} = \frac{V_Z}{R_L} = \text{Constant}$$

$$\text{And } I = I_Z + I_L$$

- Now if V_{in} increases, then the total current I increases. But I_L is constant as V_z is constant. Hence the current I_z increases to keep I_L constant. But as long as I_z is between I_{Zmin} and I_{Zmax}, the V_z i.e. output voltage V_0 is constant.
- Similarly if V_{in} decreases, then current I decreases. But to keep I_L constant, I_z decreases. As long as I_z is between I_{Zmin} and I_{Zmax} , the output voltage remains constant.
- Process flow chart for zener regulator under varying V_{in} is,

V_{in} increases	→	$I = I_L + I_Z$ increases	→	I_L is constant (V_Z/R_L)	→	So I_Z increases ($I_Z = I - I_L$)	→	As long $I_Z < I_{Zmax}$, V_Z is constant i.e. output voltage is constant
V_{in} decreases	→	$I = I_L + I_Z$ decreases	→	I_L is constant (V_Z/R_L)	→	So I_Z decreases ($I_Z = I - I_L$)	→	As long $I_Z > I_{Zmin}$, V_Z is constant i.e. output voltage is constant

5.11.2 Regulation with Varying Load

- The Fig. 5.13 shows a zener regulator under varying load condition and constant input voltage.

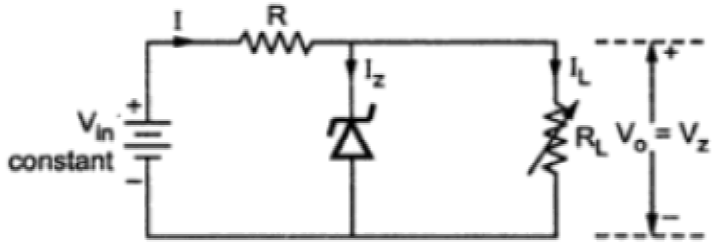

Fig. 5.13 Varying load condition

- The input voltage is constant while the load resistance R_L is variable.
- As V_{in} is constant and $V_o = V_z$ is constant, then for constant R the current I is constant.

$$\therefore I = \frac{V_{in} - V_Z}{R} \text{ constant } = I_L + I_Z$$

- Now if R_L decreases so I_L increases, to keep I constant I_z decreases. But as long as it is between I_{Zmin} and I_{Zmax}, output voltage V_o will be constant.
- Similarly if R_L increases so I_L decreases, to keep I constant I_z increases. But as long as it is between I_{Zmin} and I_{Zmax}, output voltage V_o will be constant.
- Process flow chart for zener regular under varying load is,

R_L increases I_L decreases	→	$I = \frac{V_{in} - V_Z}{R}$ constant	→	$I_Z = I - I_L$ increases	→	As long $I_Z < I_{Zmax}$, V_Z is constant i.e. output voltage is constant
R_L decreases I_L increases	→	$I = \frac{V_{in} - V_Z}{R}$ constant	→	$I_Z = I - I_L$ decreases	→	As long $I_Z > I_{Zmin}$, V_Z is constant i.e. output voltage is constant

5.12 Tunnel Diode (Esaki Diode)

- A Tunnel diode is a heavily doped p-n junction diode in which the electric current decreases as the voltage increases.
- It is used mainly for low voltage high frequency switching applications.
- It works on the principle of Tunneling effect.
- It is also called as Esaki diode

Tunneling

A direct flow of electrons across the small depletion region from n-side conduction band into the p-side valence band.

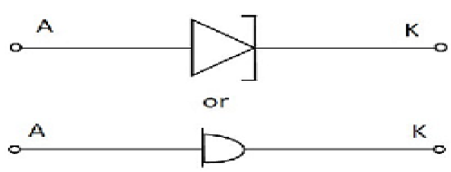

Fig. 5.14 Symbol of tunnel diode

5.12.1 Operation of Tunnel diode

Operation of tunnel diode can be done in three ways

- Under Open Circuit Condition (Unbiasing)
- Forward Biasing

Step 1: Unbiased tunnel diode

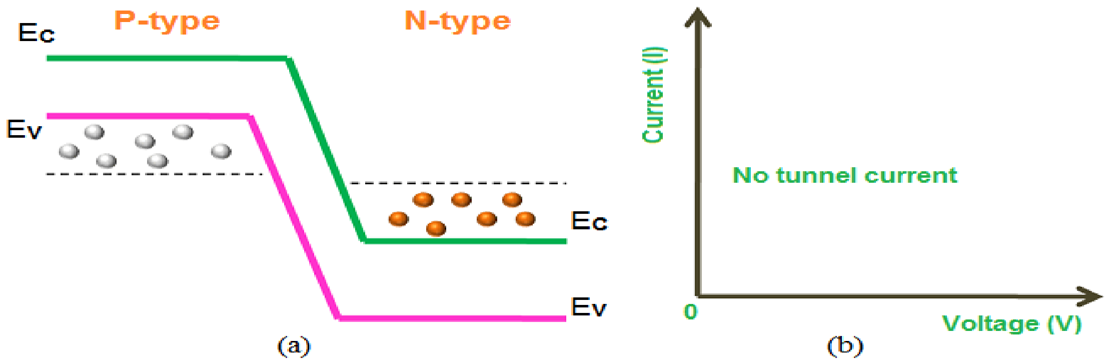

Fig. 5.15 a) Energy Band Diagram b) VI Characteristics

- When no voltage is applied to the tunnel diode, it is said to be an unbiased tunnel diode.
- In tunnel diode, the conduction band of the n-type material overlaps with the valence band of the p-type material because of the heavy doping.
- So when the temperature increases, some electrons tunnel from the conduction band of n-region to the valence band of p-region.
- In a similar way, holes tunnel from the valence band of p-region to the conduction band of n-region.
- However, the net current flow will be zero because an equal number of charge carriers (free electrons and holes) flow in opposite directions.

Step 2: Small voltage applied to the tunnel diode

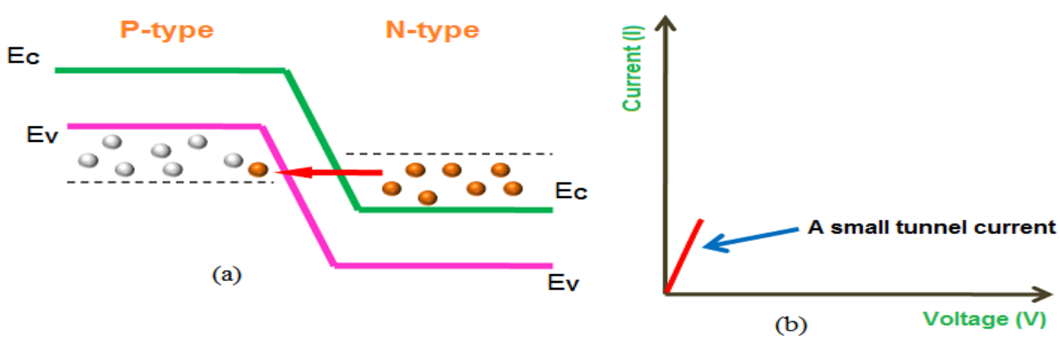

Fig. 5.16 a) Energy Band Diagram b) VI Characteristics

- When a small voltage is applied to the tunnel diode which is less than the built-in voltage of the depletion layer, no forward current flows through the junction.
- However, a small number of electrons in the conduction band of the n-region will tunnel to the empty states of the valence band in p-region.

- This will create a small forward bias tunnel current. Thus, tunnel current starts flowing with a small application of voltage.

Step 3: Applied voltage is slightly increased

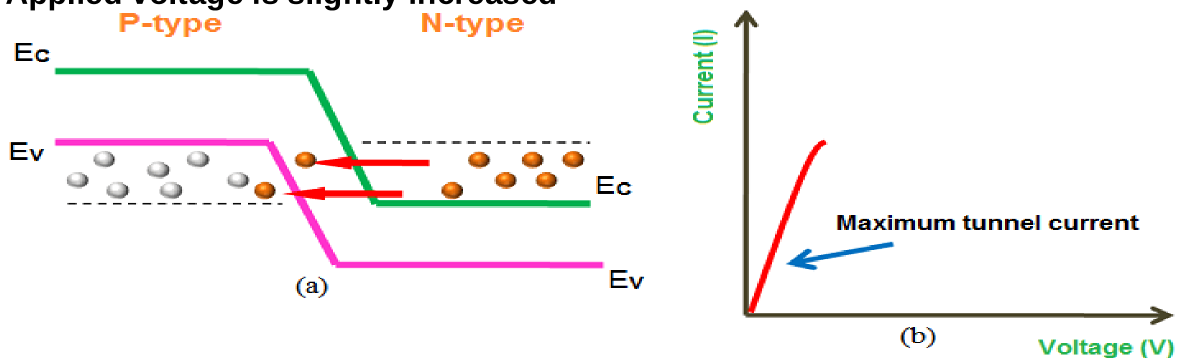

Fig. 5.17 a) Energy Band Diagram b) VI Characteristics

- When the voltage applied to the tunnel diode is slightly increased, a large number of free electrons at n-side and holes at p-side are generated.
- Because of the increase in voltage, the overlapping of the conduction band and valence band is increased.
- In simple words, the energy level of an n-side conduction band becomes exactly equal to the energy level of a p-side valence band. As a result, maximum tunnel current flows.

Step 4: Applied voltage is further increased

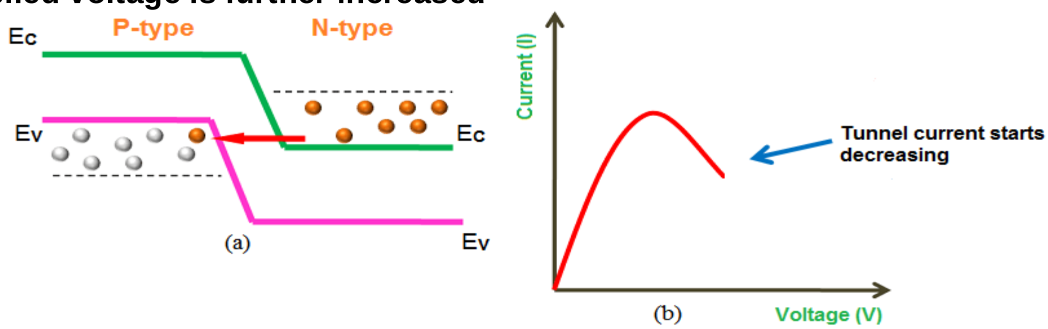

Fig. 5.18 a) Energy Band Diagram b) VI Characteristics

- If the applied voltage is further increased, a slight misalign of the conduction band and valence band takes place.
- Since the conduction band of the n-type material and the valence band of the p-type material sill overlap.
- The electrons tunnel from the conduction band of n-region to the valence band of p-region and cause a small current flow.
- Thus, the tunneling current starts decreasing.

Step 5: Applied voltage is largely increased

- If the applied voltage is largely increased, the tunneling current drops to zero.
- At this point, the conduction band and valence band no longer overlap and the tunnel diode operates in the same manner as a normal p-n junction diode.

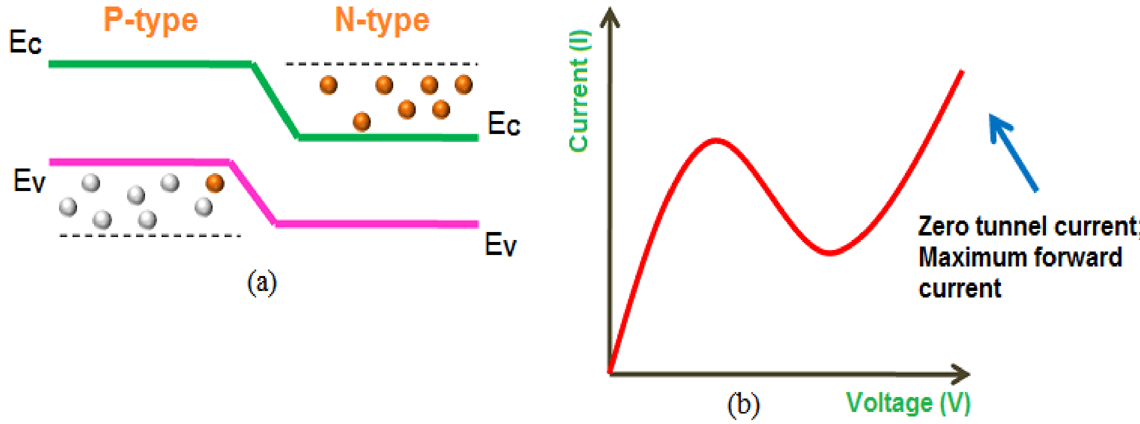

Fig. 5.19 a) Energy Band Diagram b) VI Characteristics

- If this applied voltage is greater than the built-in potential of the depletion layer, the regular forward current starts flowing through the tunnel diode.
- The portion of the curve in which current decreases as the voltage increases is the negative resistance region of the tunnel diode.
- The negative resistance region is the most important and most widely used characteristic of the tunnel diode.

5.12.2 V-I Characteristics of a Tunnel diode

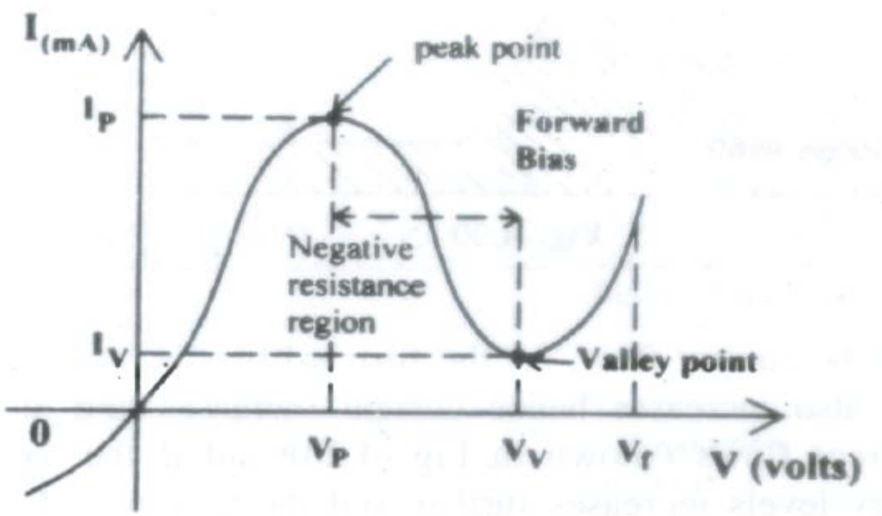

Fig. 5.20 VI characteristics of tunnel diode

- From V-I characteristics in forward bias up to some applied voltage current increases and at one voltage maximum current flows, that point is called peak point and the voltage at that point is called peak Voltage (V_P) and current at that point is called peak current (I_P).
- After this point current decreases with increases in applied voltage and at one voltage nearly zero current flows, that point is called valley point and the voltage at that point is called valley voltage (V_V) and current is called valley current (I_V).
- The region from peak point to valley point is called Negative Resistance Region.
- The tunnel diode is used as an oscillator and switch whenever it is operated in this region.

5.12.3 Advantages of tunnel diode

- High speed operation.
- Ease of operation.
- Low noise.
- Low cost.
- Low power.

5.12.4 Disadvantages of tunnel diode

- It is two terminal device, there is no isolation between the input and output circuit.
- Voltage range over which it can be operated is 1 V or less.

5.12.5 Applications of tunnel diode

1. As a high speed switch.
2. In pulse and digital circuits.
3. In negative resistance and high frequency (microwave) oscillator.
4. In switching networks.
5. In timing and computer logic circuitry.
6. Design of pulse generators and amplifiers.

5.13 Varactor Diode

In practice, special type of diodes is manufactured with transition capacitance. Such diodes are called Varactor diodes, Varicap, VVC (voltage variable capacitance), or tuning diodes.

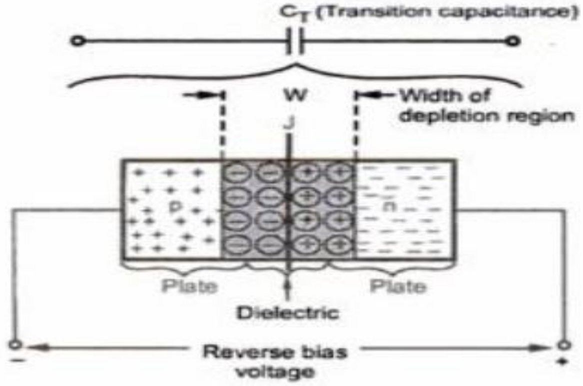

Fig. 5.21 Varactor diode

- When a diode is reverse biased, the width of the depletion region increases.
- So there are more positive and negative charges present in the depletion region.
- Due to this, the p-region and n-region act like the plates of capacitor while the depletion region acts like dielectric.
- Thus there exists a capacitance at the p-n junction called transition capacitance, junction capacitance, space charge capacitance, barrier capacitance or depletion region capacitance.

- It is denoted as C_T and is shown in figure 5.21.
- Mathematically it is given by the expression,

$$C_T = \frac{\varepsilon A}{W} \quad \text{... (1)}$$

where ε = permittivity of semiconductor = $\varepsilon_0 \varepsilon_r$

$$\varepsilon_0 = \frac{1}{36\pi \times 10^9} = 8.849 \times 10^{-12} \text{ F/m}$$

ε_r = relative permittivity of semiconductor = 16 for Ge, 12 for Si

A = area of cross section

W = width of depletion region

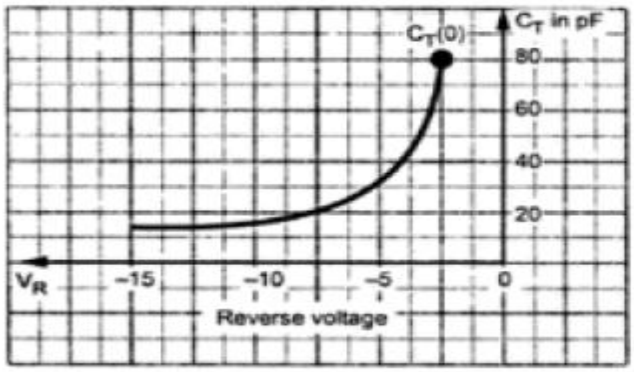

Fig. 5.22 Variation of C_T versus Reverse voltage

- As the reverse bias applied to the diode increases, the width of the depletion region (W) increases. Thus the transition capacitance Cr decreases.
- In short, the capacitance can be controlled by the applied voltage. The variation of C_T with respect to the applied reverse bias voltage is shown in the Fig. 5.22.
- As reverse voltage is negative, graph is shown in the second quadrant.
- For a particular diode shown, C_T varies from 80 pF to less than 5 pF as V_R changes from 2 V to 15 V.

5.13.1 Symbol and Equivalent Circuit of varactor diode

- The Fig. 5.23 (a) shows the symbol of varactor diode while the Fig. 5.23 (b) shows the first approximation for its equivalent circuit in the reverse bias region.

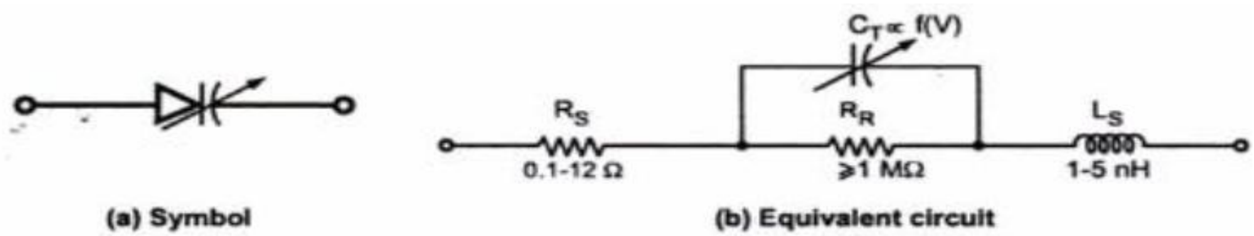

Fig. 5.23 Varactor diode

Where

R_R is the reverse resistance which is very large

R_S is the geometric resistance of diode which is very small.

The inductance L_S indicates that there is a high frequency limits associated with the use of varactor diodes.

- For a varactor diode, the transition capacitance in terms of applied reverse bias voltage is given by,

$$C_T = \frac{K}{(V_J + V_R)^n}$$

where K = Constant depends on semiconductor material and construction technique

V_J = Junction potential

V_R = Magnitude of reverse bias voltage

$n = \frac{1}{2}$ for the alloy junctions

$= \frac{1}{3}$ for the diffused junctions

5.13.2 Applications of varactor diode

- Tuned circuits
- FM modulators
- Automatic frequency control devices
- Adjustable bandpass filters
- Parametric amplifiers
- Television receivers

5.14 Silicon Controlled Rectifier (SCR)

- The SCR is an unidirectional device and it allows the current flow in only one direction.
- It has a built in feature to switch 'ON' and 'OFF'.
- The switching of SCR is controlled by the additional input called gate and biasing conditions.
- This switching property of SCR allows to control the 'ON' periods of the SCR thus controlling average power delivered to the load.
- It can be used as a rectifier element like diode to convert a.c signals to d.c signals.

5.14.1 Construction of SCR

- The SCR is a four layer p-n-p-n device where p and n layers are alternately arranged.
- The outer layers are heavily doped.
- There are three p-n junctions called J_1, J2 and J_3.
- The outer p layer is called anode while outer n layer is called cathode.

- Middle p layer is called gate.
- The three terminals are taken out respectively from these three layers, as shown in the Fig. 5.24.

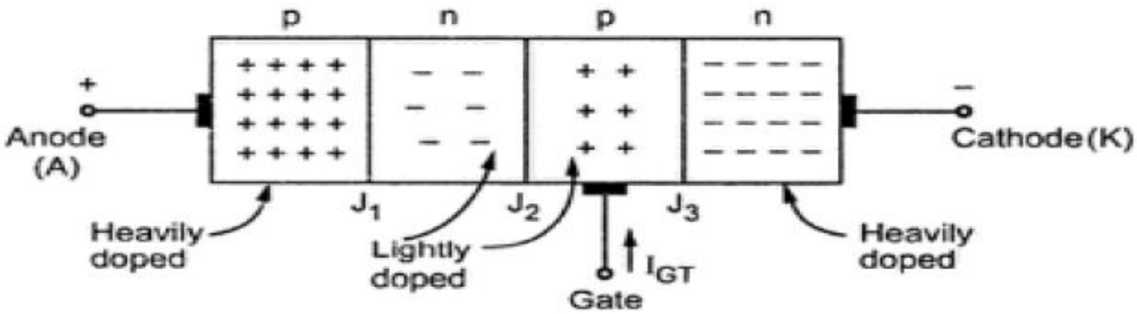

Fig. 5.24 Construction of SCR

- Anode must be positive with respect to cathode to forward bias the SCR But this is not sufficient criterion to turn SCR ON.
- To make it ON, a current is to be passed through the gate terminal denoted as I_{GT}. Thus it is a current operated device.
- The Fig. 5.25 shows the symbol of SCR

Fig. 5.25 Symbol of SCR

5.14.2 Operation of SCR

The operation of SCR is divided into two categories.

- When gate is open
- When gate is closed

5.14.2.1 When gate is open

- Consider that the anode is positive with respect to cathode and gate is open.
- Then junctions J_1 and J_3 are forward biased and junction J_2 is reverse biased.
- There is depletion region around J_2 and only leakage current flows which is negligibly small.
- Practically the SCR is said to be OFF.
- This is called forward blocking state of SCR and voltage applied to anode and cathode with anode positive is called forward voltage.
- This is shown in the Fig. 5.26 (a).
- With gate open, if cathode is made positive with respect to anode, the junctions J_1, J_3 become reverse biased and J_2 forward biased.
- Still the current flowing is leakage current, which can be neglected as it is very small.
- The voltage applied to make cathode positive is called reverse voltage and SCR is said to be in reverse blocking state.

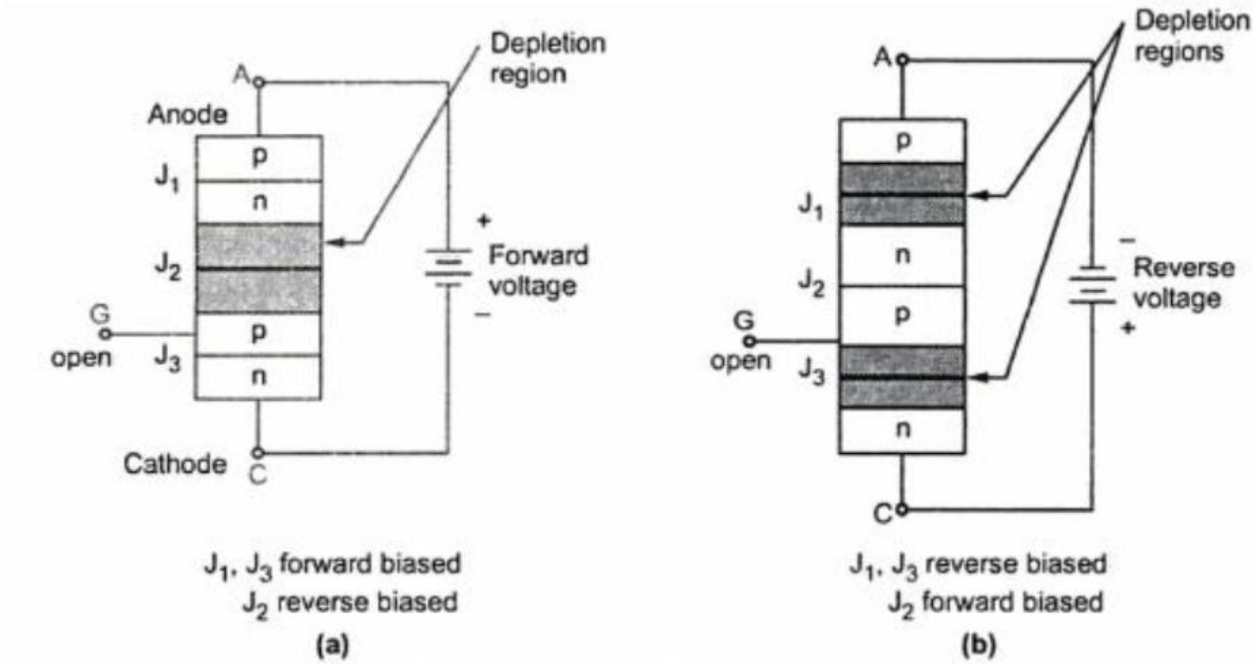

Fig. 5.26 Operation of SCR when Gate is open

- This is shown in the Fig. 5.26 (b).
- In forward blocking state, if the forward voltage is increased, the current remains almost zero upto certain limit.
- At a particular value, the reverse biased junction J_2 breaks down and SCR conducts heavily. This voltage is called forward breakover voltage V_{BO}.
- In such condition SCR is said to be ON or triggered.

5.14.2.2 When gate is closed

- Consider that the voltage is applied between gate and cathode when the SCR is in forward blocking state.
- The gate is made positive with respect to the cathode.
- The electrons from n-type cathode which are majority in number, cross the junction J_3 to reach to positive of battery.

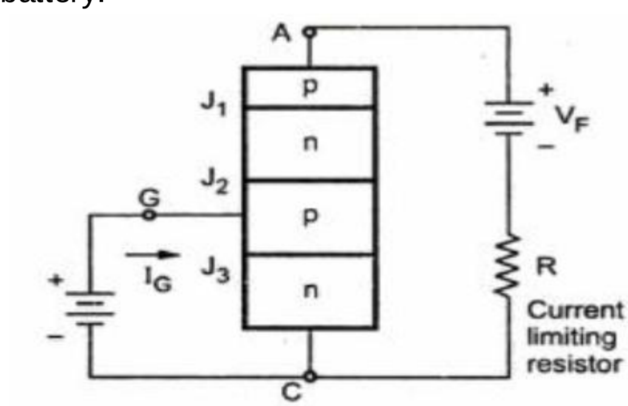

Fig. 5.27 Operation of SCR when Gate is closed

- While holes from p-type move towards the negative of battery, this constitutes the gate current. This current increases the anode current as some of the electrons cross junction J_2.
- As anode current increases, more electrons cross the junction J_2 and the anode current further increases.
- Due to regenerative action, within short time, the junction J_2 breaks and SCR conducts heavily. The connections are shown in the Fig. 5.27.
- The resistance R is required to limit the current.
- Once the SCR conducts, the gate loses its control.

5.14.3 VI Characteristics of SCR

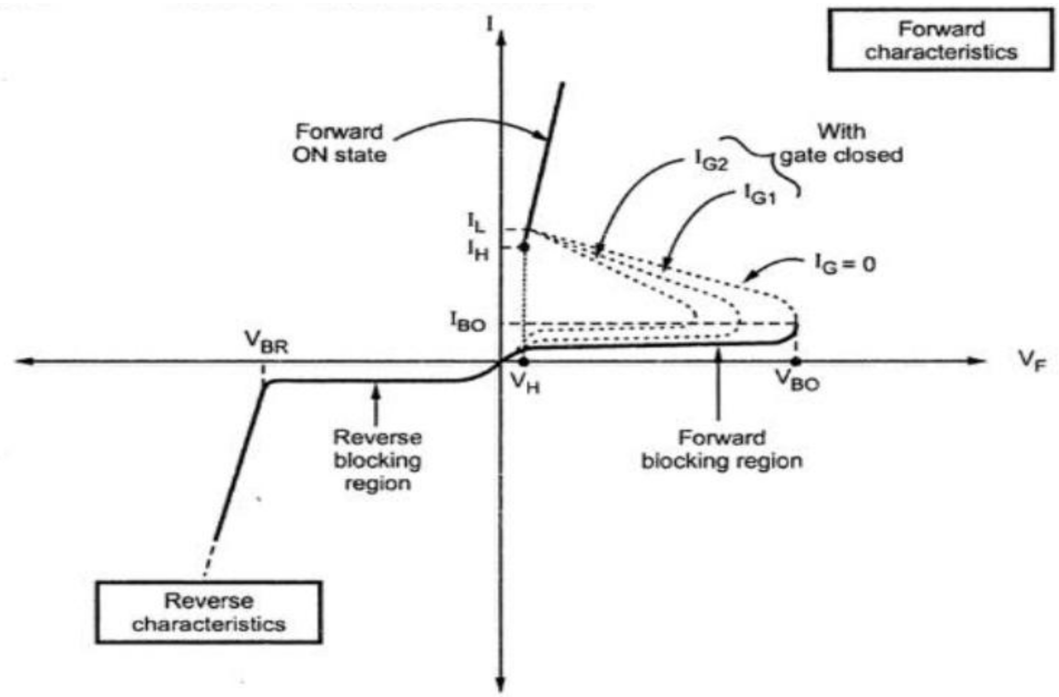

Fig. 5.28 VI Characteristics of SCR

- The Fig. 5.28 shows the characteristics of SCR. The characteristics are divided into two sections.
  - Forward characteristics
  - Reverse characteristics

5.14.3.1 Forward characteristics

- It shows a forward blocking region, when $I_G = 0$.
- It also shows that when forward voltage increases upto V_{BO}, the SCR turns ON and high current results.
- The drop across SCR reduces suddenly which is now the ohmic drop in the four layers.
- The current must be limited only by the external resistance in series with the device.
- It also shows that, if gate bias is used then as gate current increases, less voltage is required to turn ON the SCR.

- If the forward current falls below the level of the holding current I_H, then depletion region begins to develop around J_2 and device goes into the forward blocking region.
- When SCR is turned ON from OFF state, the resulting forward current is called latching current I_L. The latching current is slightly higher than the holding current.

5.14.3.2 Reverse characteristics

- If the anode to cathode voltage is reversed, then the device enters into the reverse blocking region. The current is negligibly small and practically neglected.
- If the reverse voltage is increased, similar to the diode, at a particular value avalanche breakdown occurs and a large current flows through the device. This is called reverse breakdown voltage V_{BR}.

5.14.4 Specifications of SCR

1. Forward breakover voltage (V_{BO}):

It is the voltage above which the SCR enters the conduction region (ON state). The forward breakdown voltage is dependent on the gate bias.

2. Holding current (I_H):

It is that value of current below which the SCR switches from the conduction state (ON state) to the forward blocking state.

3. Latching current (I_L):

This is the minimum current flowing from anode to cathode when SCR goes from OFF to ON state and remains in ON state even after gate bias is removed.

It is greater than, but very close to holding current.

4. Reverse breakdown voltage (V_{BR}):

It is the reverse voltage (Anode-negative and cathode-positive) above which the reverse breakdown occurs, breaking J_1 and J_3 junctions.

Therefore, the forward breakover voltage V_{BO} is greater than the reverse breakover voltage V_{BR}.

5. Minimum gate trigger current (I_{GTmin}):

The minimum value of gate current which can trigger SCR is defined as $I_{GTmin.}$

6. Maximum gate current (I_{GTmax}):

It is the peak value of gate current which must not be exceeded to avoid damage to the SCR.

5.14.5 Merits of SCR

- Very small amount of gate drive is required.
- SCRs with high voltage and current ratings are available.
- On state losses of SCR are less.

5.14.6 Demerits of SCR

- Gate has no control, once SCR is turned on.
- External circuits are required for turning it off.
- Operating frequencies are low.
- Additional protection circuits are required.

5.14.7 Applications of SCR

- Switching
- Power (AC & DC) control
- Over-voltage protection
- Battery charging regulator.

5.15 Unijunction Transistor (UJT)

- A unijunction transistor (UJT) is a device which does not belong to thyristor family but is used to turn ON SCRs.
- It is a three terminal device namely Emitter (E), Base1 (B_1) and base2 (B_2).

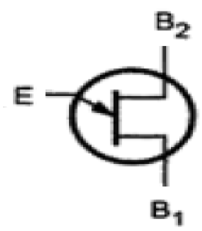

Fig. 5.29 Symbol of UJT

5.15.1 Equivalent Circuit of UJT

- The Fig. 5.30 (a) shows the basic structure of UJT while the Fig. 5.30 (b) shows the equivalent circuit of UJT.

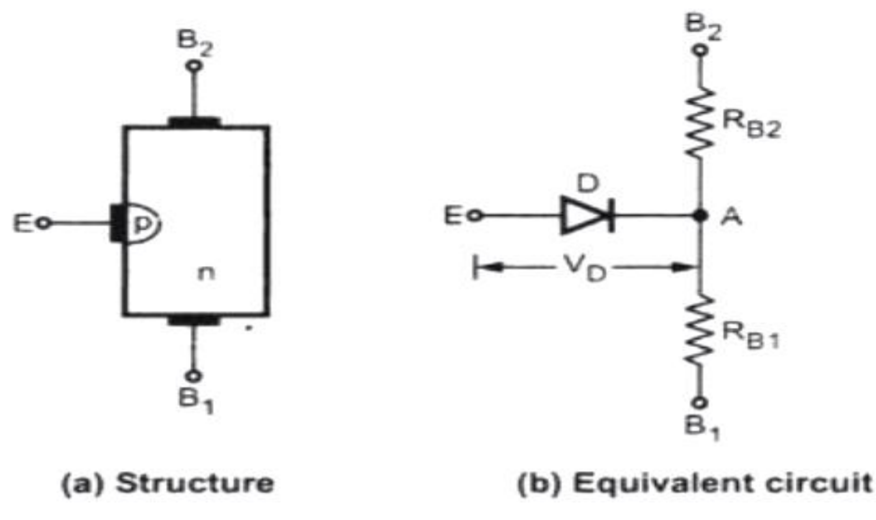

Fig. 5.30 Equivalent Circuit of UJT

- The internal resistances of the two bases are represented as R_{B1} and R_{B2}.
- In the actual construction, the terminal E is closer to B_2 as compared to B_1.

- Hence resistance R_{B1} is more than the resistance R_{B2}.
- The p-n junction is represented by a normal diode with V_D as the drop across it.
- When the emitter diode is not conducting then the resistance between the two bases B_1 and B_2 is called interbase resistance denoted as R_{BB} and its value ranges between 4 KΩ and 12 KΩ.

$$R_{BB}=R_{B1}+R_{B2}$$

5.15.2 Intrinsic Stand off Ratio (η)

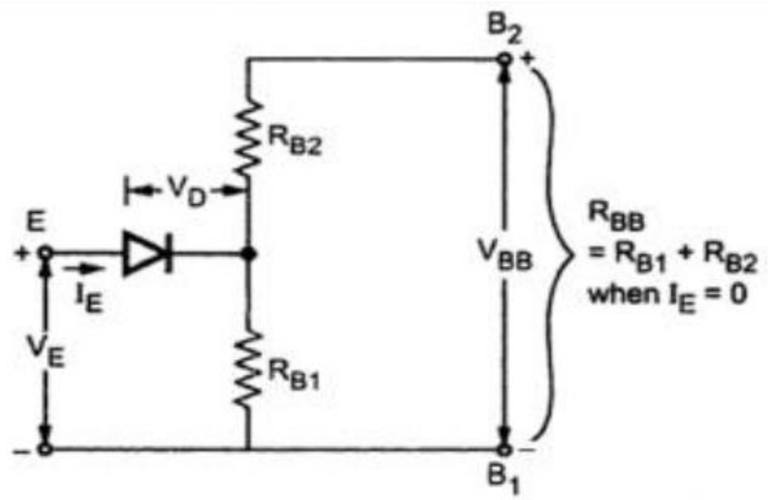

Fig. 5.31 Intrinsic Stand Off Ratio

Then the voltage drop across R_{B1} can be obtained by using potential divider rule.

$$V_{RB1} = \frac{R_{B1}\, V_{BB}}{R_{B1} + R_{B2}} = \eta\, V_{BB} \quad \text{... when } I_E = 0$$

Then $$\eta = \text{Intrinsic stand off ratio} = \left.\frac{R_{B1}}{R_{B1} + R_{B2}}\right|_{I_E=0}$$

$$\eta = \left.\frac{R_{B1}}{R_{BB}}\right|_{I_E=0}$$

- The typical range of η is from 0.5 to 0.8.

5.15.3 Principle of Operation

- The supply V_{BB} is applied between B_2 and B_1, while the variable emitter voltage V_E is applied across the emitter terminals.
- This arrangement is shown in the Fig. 5.32.
- Let us see the effect of change in V_E. The potential of A is decided by η and is equal to ηV_{BB}.

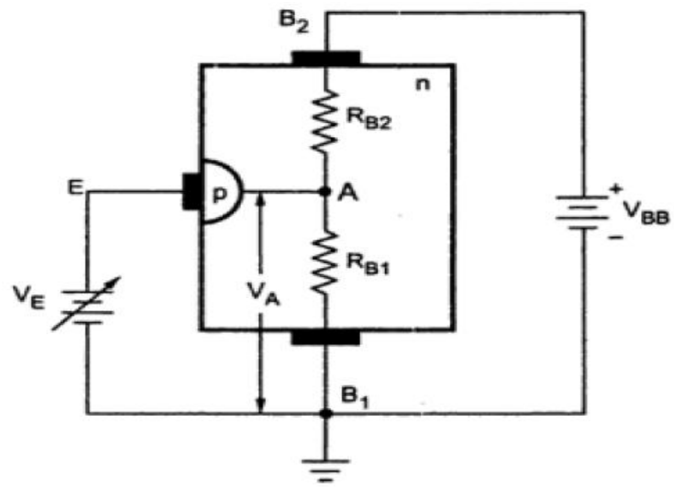

Fig. 5.32 Operation of UJT

Case 1: $V_E < V_A$

- As long as V_E is less than V_A, the p-n junction is reverse biased.
- Hence emitter current I_E will not flow. Thus UJT is said to be OFF.

Case2: VE > V_P

- The diode drop V_D is generally between 0.3 to 0.7 V. Hence we can write,

$$V_P = V_A + V_D = \eta V_{BB} + V_D$$

- When V_E becomes equal to or greater than V_P the p-n junction becomes forward biased and current I_E flows. The UJT is said to be ON.

5.15.4 Characteristics of UJT

- The graph of emitter current against emitter voltage plotted for a particular value of V_{BB} is called the characteristics of UJT.
- For a particular fixed value of V_{BB} such characteristics is shown in the Fig. 5.33.

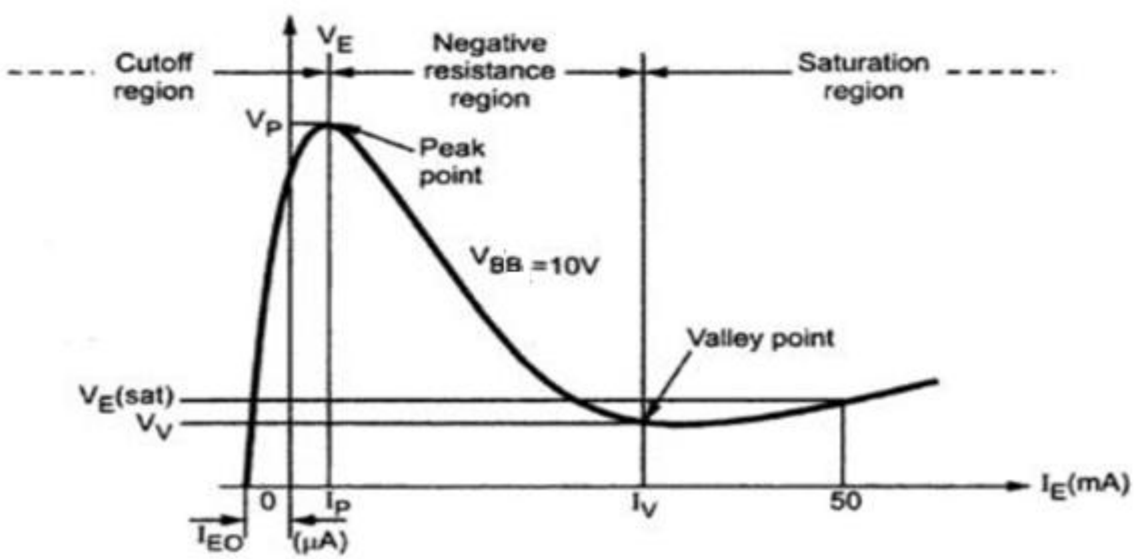

Fig. 5.33 Characteristics of UJT

The characteristics can be divided into three main regions which are,

1. Cut off region:

- The emitter voltage V_E is less than V_P and the p-n junction is reverse biased.
- A small amount of reverse saturation current I_{EO} flows through the device, which is negligibly small of the order of µA.
- This condition remains till the peak point.

2. Negative resistance region:

- When the emitter voltage V_E becomes equal to V_P the p-n junction becomes forward biased and I_E starts flowing.
- The voltage across the device decreases in this region, though the current through the device increases.
- Hence the region is called negative resistance region.
- This decreases the resistance R_{B1}.
- This region is stable and used in many applications.
- This region continues till valley point.

3. Saturation region:

- Increase in I_E further valley point current I_V drives the device in the saturation region.
- The voltage corresponding to valley point is called valley point voltage denoted as V_V.
- In this region, further decrease in voltage does not take place.
- The characteristic is similar to that of a semiconductor diode, in this region.

As the V_{BB} increases, the potential V_P corresponding to peak point will increase.

5.15.5 Applications of UJT

- Triggering of SCR
- Sawtooth Wave Generators
- Relaxation Oscillator