ELECTRONIC DEVICES AND CIRCUITS

UNIT I Diode

Diode:

Diode - Static and Dynamic resistances, Equivalent circuit, Diffusion and Transition Capacitances, V-I Characteristics, Diode as a switch- switching times.

1.1 Basics

Atom:

- The smallest particle of an element that can exist either alone or in combination.
- Atoms consist of a heavy central nucleus surrounded by a cloud of negatively charged particles called electrons.
- The nucleus contains positive particles (protons) and electrically neutral particles (neutrons).

Electronics:

- The branch of science that deals with the study of flow and control of electrons and the study of their behavior and effects in vacuums, gases, and semiconductors.

Passive Components:

- Those devices or components which do not required external source to their operation.
  Examples: Resistor, capacitor and inductor.

Active Components:

- Those devices or components which required external source to their operation.
  Examples: Diode, Transistors, SCR, Integrated Circuits, DIAC, TRIAC, LED etc.

DC (Direct Current):

- The electrons flow in one direction only. Current flow is from negative to positive.

AC (Alternating Current):

- The electrons flow in both directions in a cyclic manner.

Frequency:

- The rate of change of direction determines the frequency, measured in Hertz (cycles per second).

Valence Electrons:

- Valence electrons are the electrons present in the outermost orbit of an atom.

Free Electrons (or) Conduction Electrons:

- Free electrons are electrons that are not attached to an atom.

Energy band:

- The range of energies possessed by an electron in an atom.

Conduction band:

- The range of energies possessed by conduction electrons in an atom.

Valence Band:

- The range of energies possessed by valence electrons in an atom.

Energy band diagram:

- It is a diagram between interatomic spacing and energy

Forbidden Energy Gap:

- The separation between conduction band and valance band of the energy band diagram

1.1.1 Classification of Solid state materials

Insulators:

- Insulators are the materials which are not allowing flow of electric current through them.

  Examples – Glass, Wood, Rubber, Plastic and air.

Conductors:

- Conductors are the materials which are easily allowing flow of electric current through them.

  Examples – Copper, Aluminum, Iron and silver

Semiconductors:

- Semiconductors are the materials whose electrical conductivity lies in between insulators and conductors.

  Examples – silicon, Germanium and Gallium

1.2 Theory of P-N Junction

1.2.1 Types of Semiconductor

- Semiconductors can be classified into two types:
  - Intrinsic Semiconductors or Pure of Semiconductors
  - Extrinsic Semiconductors or Impure of Semiconductors

1.2.1.1 Intrinsic semiconductors:

- The normal silicon and Germanium are intrinsic semiconductors.
- The number of electrons present in the outermost orbit of intrinsic semiconductor is four
- So, intrinsic semiconductors are tetra valent in nature.

1.2.1.2 Doping:

- The process of adding impurities to an intrinsic semiconductor is known as doping.

1.2.1.3 Extrinsic Semiconductors:

- With respect to the type of impurity added, extrinsic semiconductors are classified into two types.
  - N- type semiconductors
  - P- type semiconductors

1.2.1.3.1 N- type semiconductors

- When a small amount of penta valent impurity (e.g. Antimony, Arsenic) is added to a pure semiconductor, we will get N - type semiconductor.
- The addition of penta valent gives a large number of free electrons in the semiconductors crystal.

Tetra valent	+	Penta valent	= N- type Semiconductor
(4 electrons)	+	(5 electrons)	= 9 electrons
			= 9 Negative charges
			= Excess of an electron

- The Majority Carriers in N - type are electrons (Negative charges) and Minority carriers are holes (positive charges).
- N – type semiconductors are known as Donor impurities because they donate free electrons to the semiconductor crystal.

1.2.1.3.2 P - type semiconductors

- When a small amount of trivalent material (e.g. Indium, Gallium) is added to a pure semiconductor, we will get P - type semiconductor.
- The addition of trivalent impurity gives a large number of holes in the semiconductor.
- The hole shows absence of an electron.

Tetra valent	+	Tri valent	= P – type Semiconductor
(4 electrons)	+	(3 electrons)	= 7 electrons
			= Shortage of an electron
			= One positive charge
			= Hole

- In a P - type semiconductor, Majority carriers are holes and Minority carriers are electrons.
- P - type semiconductors are called Acceptor Impurities because the holes created can accept the electrons.

1.3 P-N Junction as a Diode

- A junction is formed by joining P - type semiconductor with N – type semiconductor, the structure is called PN Junction or PN Diode.
- The structure of PN junction diode is shown in figure 1.1.

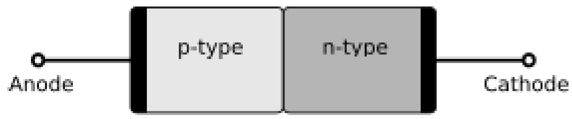


Fig.1.1 PN Junction diode

- Symbol of diode is given in figure 1.2.

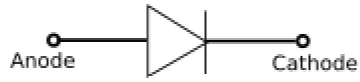


Fig. 1.2 Symbol of PN Junction diode

1.3.1 Parameters used in PN Junction diode

- Figure 1.3 shows the open circuited PN Junction.

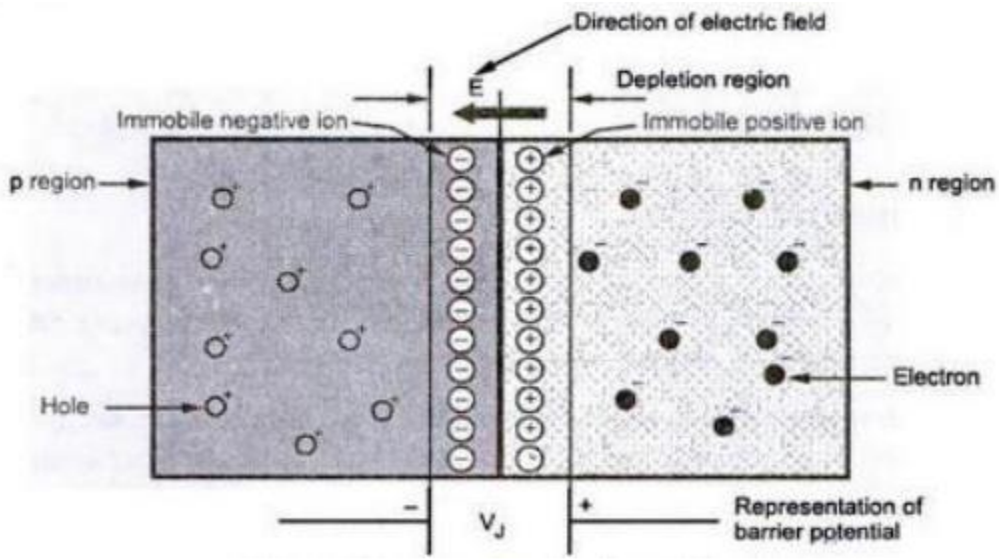


Fig. 1.3 Open circuited (No Biasing) PN Junction

- The free electrons from the n-region start diffusing into the p-region.
- The holes from p-side diffuse across the junction into the n-region.
- As more and more electrons recombine in p-region and holes in n-region, more charges get formed near the junction.
- Hence in equilibrium condition there exists a layer of negative charges in p-region and positive charges in n-region, near the junction.

1.3.1.1 Diffusion:

- Diffusion is the process by which electrons move from high concentration area towards low concentration area.

1.3.1.2 Depletion region:

- A region is formed with empty free charge carriers at both the sides of junctions are called as depletion region (or) depletion layer (or) space charge region.

1.3.1.3 Potential barrier:

- The barrier which does not allow charge flow across the junction is called as potential barrier.

Semiconductor material	Symbol	Barrier potential
Silicon	Si	0.6 V
Germanium	Ge	0.2 V

- The barrier potential depends on,
  - Type of semiconductor
  - The acceptor impurity added
  - The donor impurity added
  - The temperature
  - Intrinsic concentration

1.3.1.4 Biasing:

- Applying external D.C. voltage to any electronic device is called biasing.

1.4 Operation of PN Junction Diode

- Operation of a PN junction diode can be explained in two ways.
  - Forward Biasing
  - Reverse Biasing

1.4.1 Forward Biasing:

- If an external d.c voltage is connected in such a way that the p-region terminal is connected to the positive terminal of the d.c. voltage and the n-region is connected to the negative terminal of the d.c, voltage.

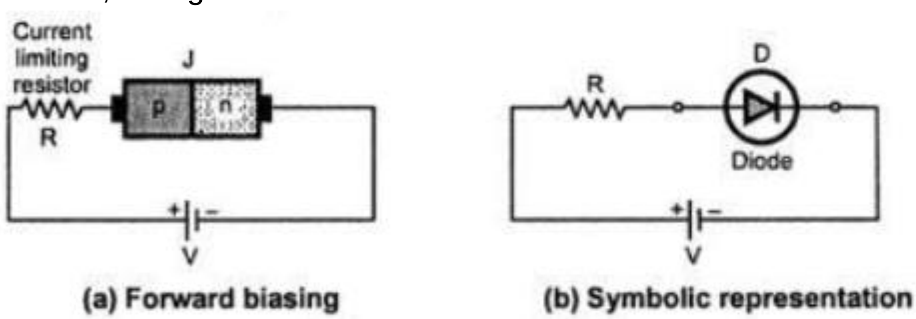


Fig. 1.4 Forward biasing of PN Junction Diode

1.4.1.1 Construction

- The Fig. 1.4 (a) shows the connection of forward biasing of a p-n junction.
- To limit the current, practically a current limiting resistor is connected in series with the p-n junction diode.
- The Fig. 1.4 (b) shows the symbolic representation of a forward biased diode.

1.4.1.2 Operation:

- As long as the applied voltage is less than the barrier potential, there cannot be any conduction.
- When the applied voltage becomes more than the barrier potential, the negative terminal of battery pushes the free electrons against barrier potential from n to p-region, and positive terminal pushes the holes from p to n-region.
- Thus holes get repelled by positive terminal & electrons get repelled by negative terminal and cross the junction against barrier potential.
- Thus the applied voltage overcomes the barrier potential, which reduces the width of depletion region.
- As forward voltage is increased, at a particular value the depletion region becomes very much narrow such that large number of majority charge carriers can cross the junction.
- Hence the overall forward current is due to the majority charge carriers.

1.4.1.3 Forward V-I Characteristics of PN Junction Diode

- The Fig. 1.5 shows the forward biased diode.

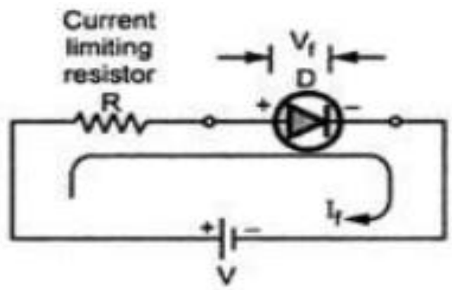


Fig. 1.5 Forward biased diode

- The applied voltage is V while the voltage across the diode is V_f and the current flowing in the circuit is the forward current I_f.
- The graph of forward current I_f against the forward voltage V_f across the diode is called forward characteristics of a diode and is shown in fig. 1.6.

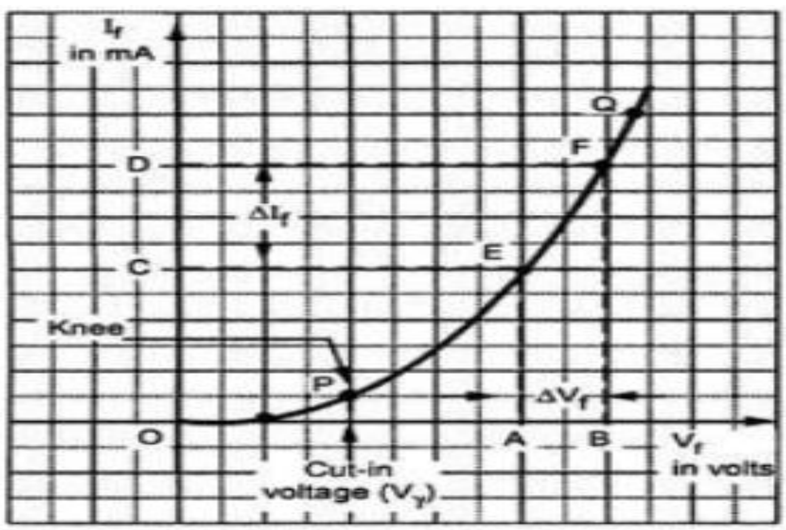


Fig. 1.6 Forward characteristics of a diode

Cut-in voltage:

- Minimum forward voltage required to conduct the diode.

Knee:

- The point P, after which the forward current starts increasing exponentially is called knee of the curve

1.4.1.4 Operation of forward characteristics

- **Region O to P (From Fig. 1.6):**
  - As long as V_f is less than cut in voltage (V_Y), the current flowing is very small.

- **Region P to Q and onwards (From Fig. 1.6):**
  - As V_f increases towards V_Y the width of depletion region goes on reducing.
  - When V_f exceeds V_Y i.e. cut-in voltage, the depletion region becomes very thin and current I_f Increases suddenly.
  - This increase in the current is exponential as shown in the Fig. 1.6 by the region P to Q.
  - The forward current is treated as positive and the forward voltage V_f is also treated positive.
  - Hence the forward characteristic is plotted in the first quadrant.

1.4.1.5 Forward Resistance of Diode

- The resistance offered by the p-n junction diode in forward biased condition is called forward resistance. The forward resistance is defined in two ways.

1.4.1.5.1 Static forward resistance:

- The resistance offered by the p-n junction under d.c, conditions is called static resistance and it is denoted as R_f
- It is calculated at any particular point on the forward characteristics.
- The static resistance R_f is defined as the ratio of the d.c, voltage applied across the p-n junction to the d.c. current flowing through the p-n junction.

$$R_f = \frac{\text{Forward d.c. voltage}}{\text{Forward d.c. current}} = \frac{OA}{OC} \text{ at point E}$$

1.4.1.5.2 Dynamic forward resistance:

- The resistance offered by the p-n junction under a.c, conditions is called as dynamic resistance and it is denoted as r_f.
- Consider the change in applied voltage from point A to B shown In the Fig. 1.6 and denoted as ΔV_f.
- The corresponding change in the forward current is from point C to D and denoted as ΔI_f.

$$r_f = \frac{\Delta V_f}{\Delta I_f} = \frac{1}{(\Delta I_f / \Delta V_f)} = \frac{1}{\text{Slope of forward characteristics}}$$

1.4.2 Reverse Biasing of P-N Junction Diode

- If an external d.c voltage is connected in such a way that the p-region terminal of a p-n junction is connected to the negative terminal of the battery and the n-region terminal of a p-n junction is connected to the positive terminal of the battery.

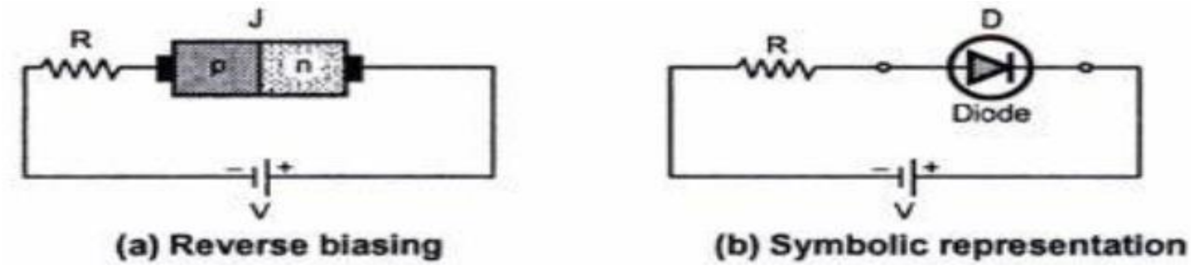


Fig. 1.7 Reverse biasing of PN Junction Diode

1.4.2.1 Construction

- The Fig. 1.7 (a) & 1.7 (b) shows the connection of a reverse biasing and symbolic representation of a p-n junction.

1.4.2.2 Operation:

- When the p-n junction is reverse biased, the negative terminal of battery attracts the holes in the p-region and it is away from the junction.
- The positive terminal of battery attracts the free electrons in the n-region and it is away from the junction.
- No charge carrier is able to cross the junction.
- As electrons and holes both move away from the junction, the depletion region widens.
- As depletion region widens, barrier potential across the junction also increases.
- The electrons on p side and holes on n side are minority charge carriers, which constitute the current in reverse biased condition.
- The current flow due to minority charge carriers alone is called as reverse saturation current (I_O) which are small in number.
- The generation of minority charge carriers depends on the temperature and not on the applied reverse bias voltage.

1.4.2.3 Reverse V-I Characteristics of PN Junction Diode

- The Fig. 1.8 shows the reverse biased diode.
- The reverse voltage across the diode is V_R while the current flowing is reverse current I_R due to minority charge carriers.
- The reverse voltage is taken as negative and reverse saturation current is also taken as negative.

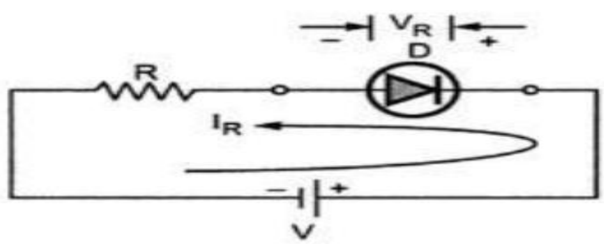


Fig. 1.8 Reverse biased diode

- The graph of I_R against V_R is called reverse characteristics of a diode and is shown in figure 1.9.

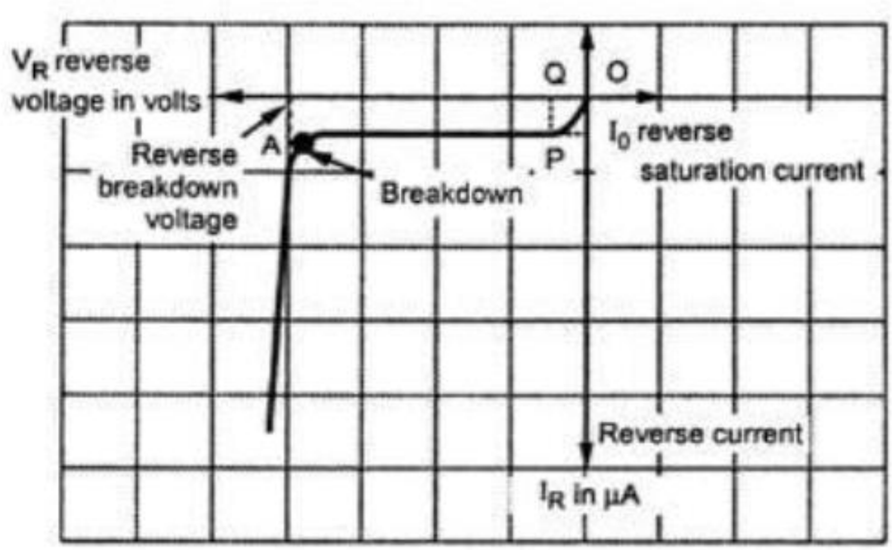


Fig. 1.9 Reverse characteristics of a diode

- As reverse voltage is increased, reverse current increases initially but after a certain voltage, the current remains constant equal to reverse saturation current I_O, though reverse voltage is increased.
- The point A where breakdown occurs and reverse current Increases rapidly is called knee of the reverse characteristics.

Reverse Breakdown Voltage

- The maximum voltage at which breakdown occurs is called as reverse breakdown voltage.

1.4.2.4 Reverse Resistance of Diode

- The p-n junction offers large resistance in the reverse biased condition and is as called reverse resistance.
- This is also defined in two ways.

1.4.2.4.1 Reverse static resistance:

- This is reverse resistance under d.c conditions and it is denoted as R_r.
- It is the ratio of applied reverse voltage to the reverse saturation current I_O.

$$R_r = \frac{OQ}{I_0} = \frac{\text{Applied reverse voltage}}{\text{Reverse saturation current}}$$

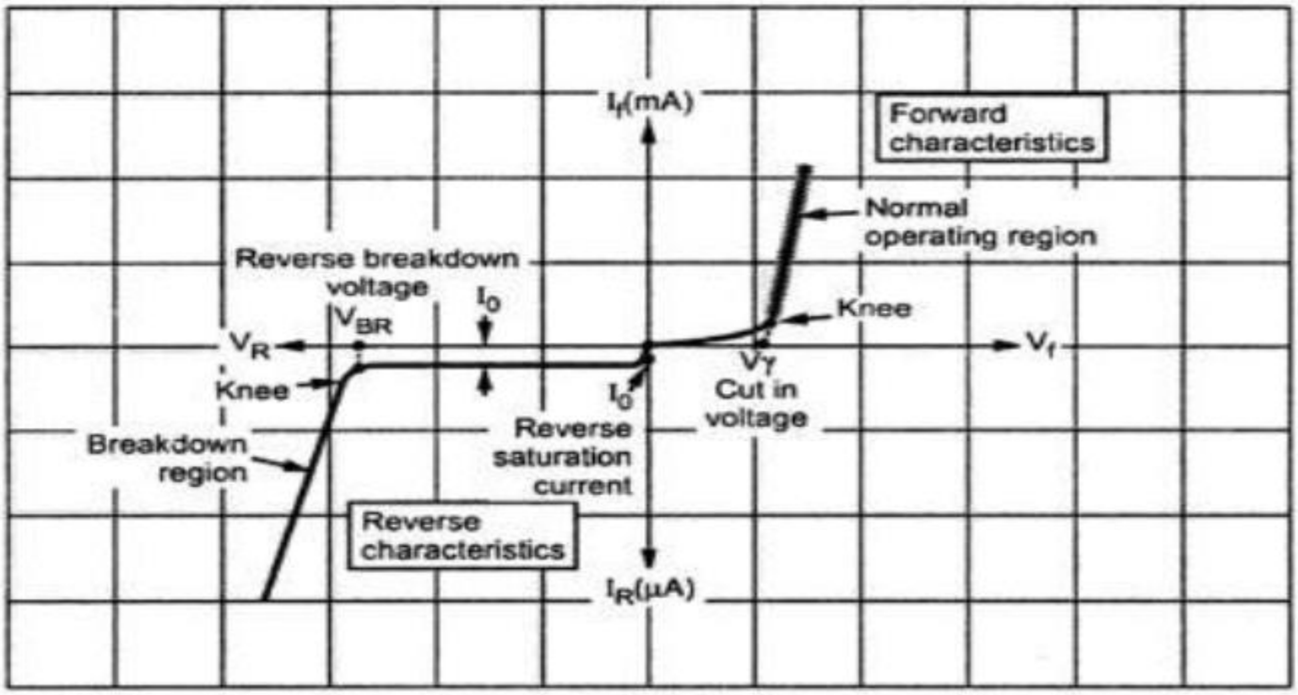
1.4.2.4.2 Reverse dynamic resistance:

- This is the reverse resistance under the a.c. conditions and it is denoted as r_r.
- It is the ratio of incremental change in the reverse voltage applied to the corresponding change in the reverse current.

$$r_r = \frac{\Delta V_R}{\Delta I_R} = \frac{\text{Change in reverse voltage}}{\text{Change in reverse current}}$$

1.4.3 Complete V-I Characteristics of a Diode

- Complete VI characteristics of PN Junction diode under the forward and Reverse bias is shown in single graph.



1.10 Complete V-I Characteristics of a Diode

1.5 Diode Equation

- The mathematical representation of V-I characteristics of diode is called V-I characteristics equation or diode current equation.
- It gives the mathematical relationship between applied voltage V and the diode current I and is given by,

$$\boxed{I = I_0\left[e^{V/\eta V_T} - 1\right] \ A} \qquad \dots (1)$$

where

I_0 = Reverse saturation current in amperes

V = Applied voltage

η = 1 for germanium diode

= 2 for silicon diode

V_T = Voltage equivalent of temperature in volts.

- The factor η is called an emission coefficient or Ideality factor.
- This factor takes into account the effect of recombination taking place in the depletion region.
- The voltage equivalent of temperature indicates dependence of diode current on temperature.
- The voltage equivalent of temperature V_T for a given diode at temperature T is calculated as,

$$V_T = kT \text{ volts} \qquad \dots (2)$$

where k = Boltzmann's constant = 8.62×10^{-5} eV/°K

T = temperature in °K.

At room temperature of 27 °C i.e. T = 27 + 273 = 300 °K and the value of V_T is 26 mV,

- The value of V_T also can be expressed as,

$$V_T = \frac{T}{\left(\frac{1}{k}\right)} = \frac{T}{\left(\frac{1}{8.62 \times 10^{-5}}\right)} = \frac{T}{11600} \qquad \dots (3)$$

- The diode current equation is applicable for all the conditions of diode i.e, unbiased, forward biased and reverse biased.
- When unbiased V=0 tends to I=0
- For forward bias V=Positive value tends to I=Positive value
- For Reverse bias V=Negative value tends to I=Negative value

Example : *The voltage across a silicon diode at room temperature of 300°K is 0.71 V when 2.5 mA current flows through it. If the voltage increases to 0.8 V, calculate the new diode current.*

Solution : The current equation of a diode is

$$I = I_0 \left(e^{V/\eta V_T} - 1\right)$$

At 300 °K, $V_T = 26 \text{ mV} = 26 \times 10^{-3}$ V

$V = 0.71$ V for I = 2.5 mA

and η = 2 for silicon

$$\therefore \quad 2.5 \times 10^{-3} = I_0 \left[e^{(0.71/2 \times 26 \times 10^{-3})} - 1 \right]$$

$$\therefore \quad I_0 = 2.93 \times 10^{-9} \text{ V}$$

Now V = 0.8 V, I_0 remains same.

$$\therefore \quad I = 2.93 \times 10^{-9} \left[e^{(0.8/2 \times 26 \times 10^{-3})} - 1 \right] = 0.0141 \text{ A} = \mathbf{14.11 \text{ mA}}$$

1.6 Diode Equivalent Circuits

- The diode is required to be replaced by the equivalent circuit in many practical electronic circuits, for the analysis purpose. Such an equivalent circuit of a diode is called circuit model of a diode.
- There are three methods of replacing diode by its circuit model, which are,
    - ➢ Practical diode model
    - ➢ Ideal diode model
    - ➢ Piecewise linear model

- When the diode is forward biased, the total voltage drop across the diode is V_f which is equal to sum of the drop due to barrier potential (cut-in voltage V_Y) and the drop across the internal forward dynamic resistance r_f of the diode.
- When the diode is reverse biased, reverse saturation current is very small and practically neglected. Hence reverse biased diode is practically assumed to be open circuit.

1.6.1 Practical Diode Model

- In forward bias, the practical diode model consists of a battery equal to cut-in voltage and the forward resistance in series with an ideal diode which is shown in fig.1.11 (a).
- In reverse bias, it is open circuited and is shown in fig. 1.11 (b).
- While the Fig. 1.11 (c) shows the corresponding V-I characteristics.

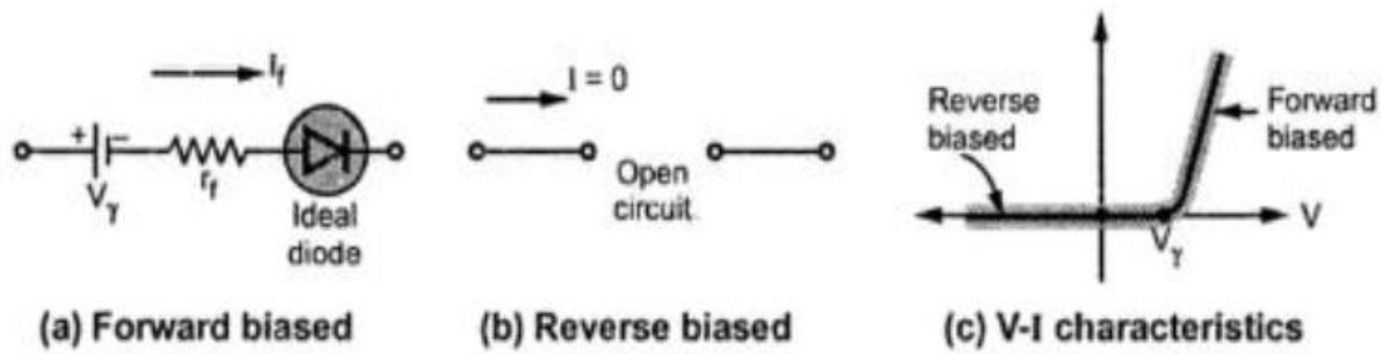


Fig. 1.11 Practical diode model

1.6.2 Ideal Diode Model

- In many cases, as the forward resistance of diode is small and cut-in voltage is also small, the diode is assumed to be an ideal diode.
- In case of ideal diode, it is assumed that it starts conducting instantaneously when applied voltage V_D is just greater than zero and the drop across the conducting diode is zero.
- So conducting diode can be ideally replaced by a short circuit, for the analysis of various diode circuits.
- The Fig. 1.12 shows the ideal diode characteristics.

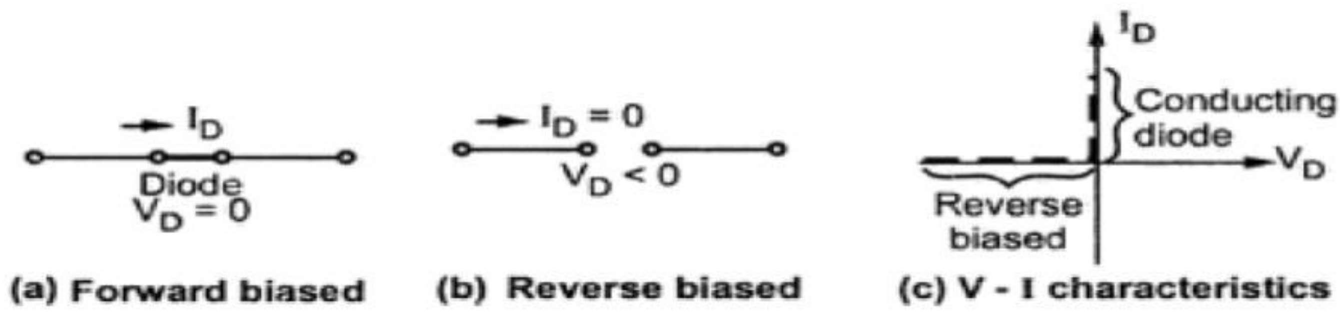


Fig. 1.12 Ideal diode model

1.6.3 Piecewise linear Model of Diode

- Another way to analyze the diode circuits is to approximate the V-I characteristics of a diode using only straight lines i.e. linear relationships.
- In such approximation, the diode forward resistance is neglected and the diode is assumed to conduct instantaneously when applied forward biased voltage V_D is equal to cut-in voltage V_γ and is shown in the fig. 1.13 (a).
- When the diode is in reverse biased condition i.e $V_D < 0$, the diode does not conduct at all and is shown in the Fig. 1.13 (b).
- As the diode conducts at $V_D = V_\gamma$, the V-I characteristics with straight lines is as shown in the Fig. 1.13 (c).

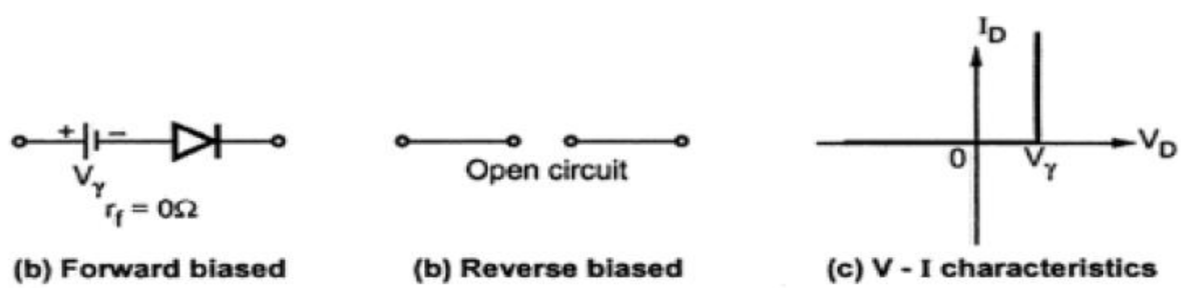


Fig. 1.13 Linear piecewise model of diode when $r_f = 0$

- If forward resistance is considered to be finite, then forward biased characteristic is a straight line with a slope equal to reciprocal of r_f and is shown in the fig. 1.14 (a).
- In reverse bias, the diode is still assumed to be open circuited and is shown in the fig. 1.14 (b).
- The linear piecewise model with finite forward resistance r_f is shown in the Fig. 1.14 (c).

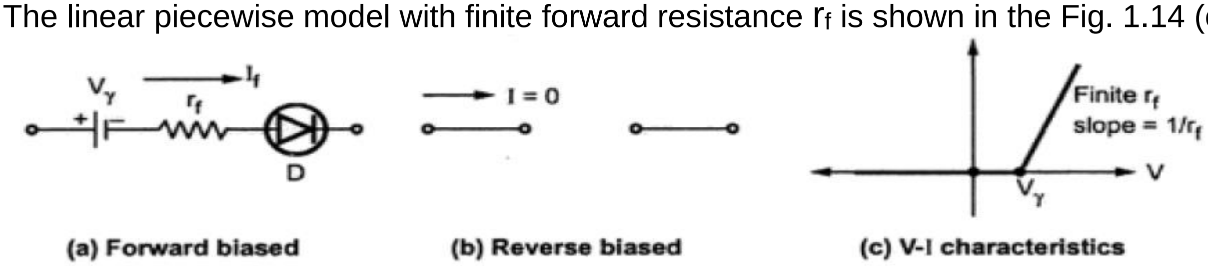


Fig. 1.14 Linear piecewise model of diode with finite r_f

1.7 Junction Capacitances

- Depending upon the biasing condition, two types of capacitive effects exist in the diodes. These are.
    - Transition capacitance (C_T) under reverse biased condition.
    - Diffusion capacitance (C_D) under forward biased condition.

1.7.1 Transition Capacitance (C_T or C_{pn})

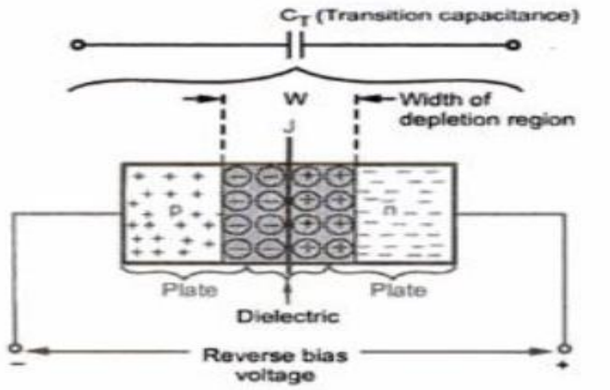


Fig. 1.15 Transition Capacitance

- 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 as transition capacitance.
- It is denoted as C_T and is shown in figure 1.15.
- Mathematically it is given by the expression,

$$\boxed{C_T = \frac{\varepsilon A}{W}}$$

where

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

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

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

A = area of cross section

W = width of depletion region

- As the reverse bias applied to the diode increases, the width of the depletion region (W) increases. Thus the transition capacitance C_T 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. 1.16.

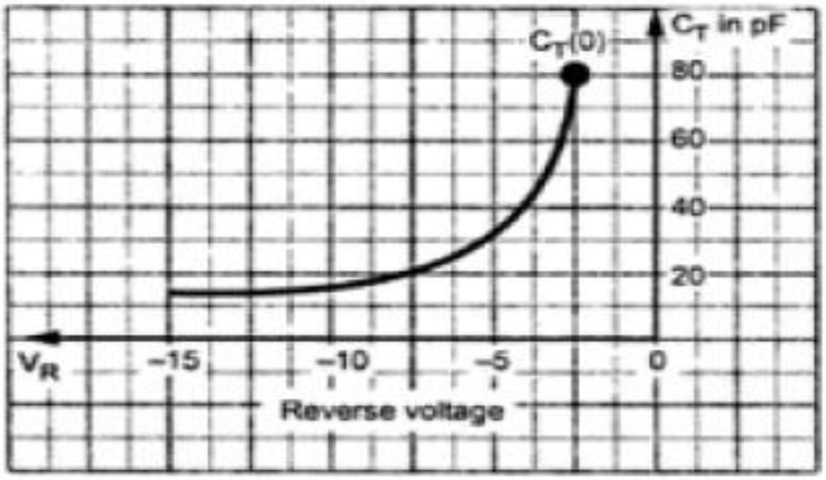


Fig. 1.16 Variation of C_T versus Reverse voltage

- As reverse voltage is negative, graph is shown in the second quadrant.
- The value of transition capacitance is of the order of pico farads.
- 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.

1.7.2 Diffusion Capacitance (C_D)

- During forward biased condition, another capacitance comes into existence called diffusion capacitance (or) storage capacitance and denoted as C_D.
- In forward biased condition, the width of the depletion region decreases and holes from p side get diffused in n side while electrons from n side move into the p-side.
- As the applied voltage increases, concentration of injected charged particles increases.
- This rate of change of the Injected charge with applied voltage is defined as a capacitance called diffusion capacitance.

$$\boxed{C_D = \frac{dQ}{dV}}$$

- The diffusion capacitance expression can also be given as

$$\boxed{C_D = \frac{\tau I}{\eta V_T}}$$

where

τ = mean life time for holes.

- So diffusion capacitance is proportional to the current.
- For forward biased condition, the value of diffusion capacitance is of the order of nano farads to micro farads while transition capacitance is of the order of pico farads.
- So $C_D >> C_T$.
- The graph of C_D against the applied forward voltage is shown in the Fig. 1.17.
- As the applied forward voltage increases, current I increases hence diffusion capacitance C_D increases.

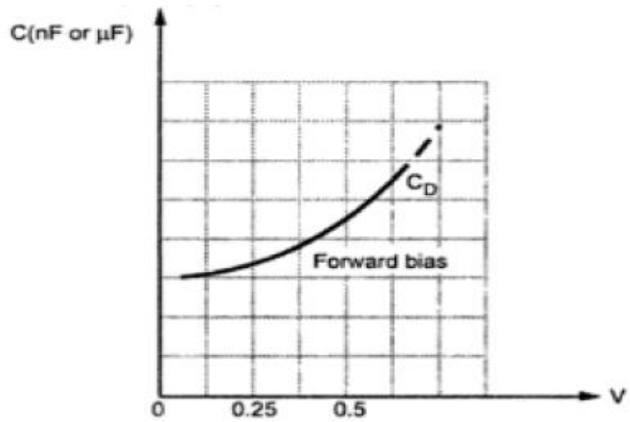


Fig. 1.17 Diffusion capacitance versus applied forward voltage

1.8 PN Junction Diode act as a switch

- The principle of working of a diode as a switch is nothing but the forward and reverse biasing of the diode.
- When a forward voltage is more than the cut-in voltage of the PN junction diode, the current flows through the junction. Thus, the diode junction becomes a short circuit.
- The diode comes in the reverse bias when the voltage at the diode's anode is more negative than the voltage at the cathode. In this condition, the diode junction is an open circuit.
- The figure 1.18 shows the Circuit diagram for diode act as a switch
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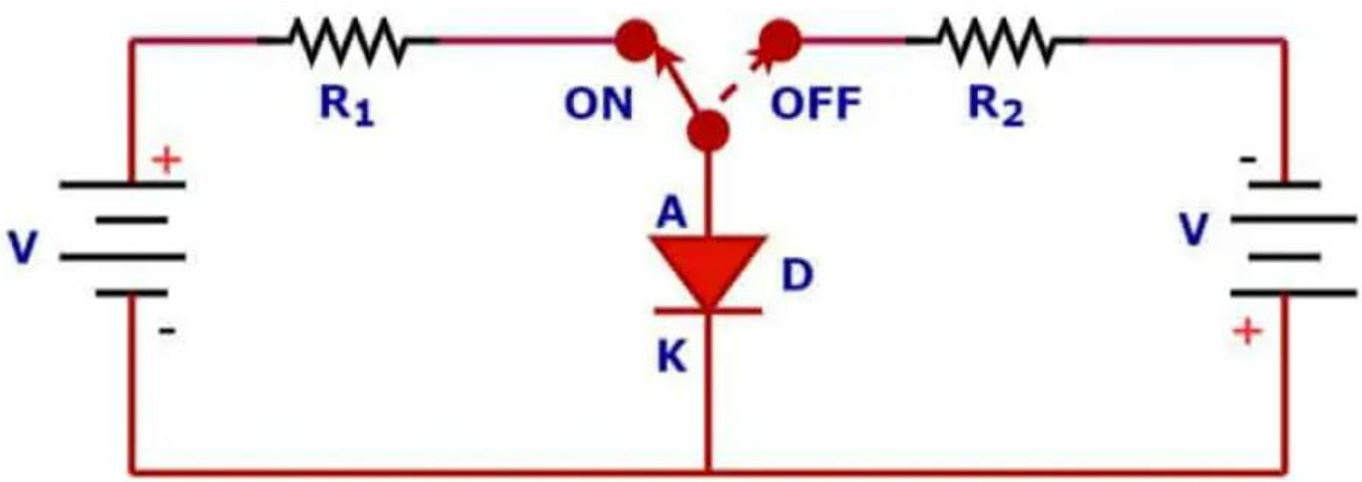


Fig. 1.18 Circuit diagram for diode act as a switch

- A diode has a PN junction.
- In a diode, P-region has lightly doped holes as the majority carriers and N- region has highly doped electrons as the majority carriers.
- When the switch is at the ON position, the anode of diode D gets a positive supply and the cathode of diode D gets a negative supply.
- In this condition, the diode gets forward biasing and it starts conducting.

- Now, when the switch position changes from ON to OFF state, the anode of the diode gets the negative voltage at the anode.
- Under this condition, the current that was flowing in the forward bias state drops to zero, and the diode becomes an open circuit.

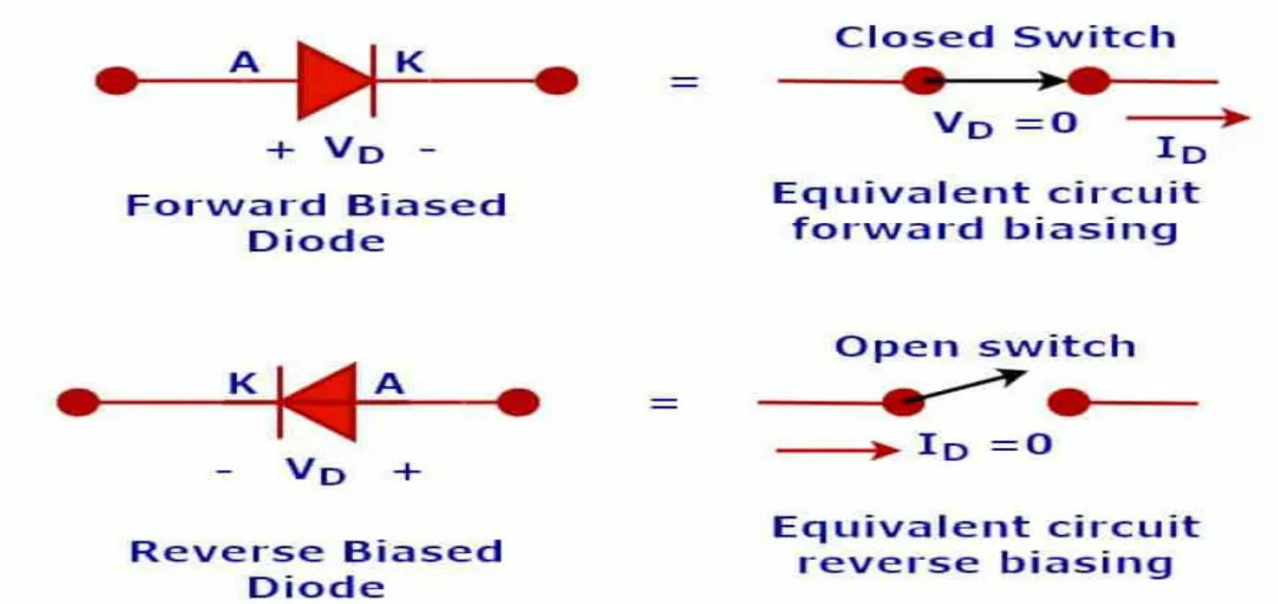


Fig. 1.19 Equivalent circuit for diode act as a switch

1.9 switching times of a PN Junction diode

- When the diode is switched from forward biased to reverse biased or vice versa, it takes finite time to reach the final steady state. The behaviour of diode during this time is called switching characteristics of diode.
- To study the switching characteristics of diode, consider simple diode circuit and an input waveform as shown in the Fig. 1.20.

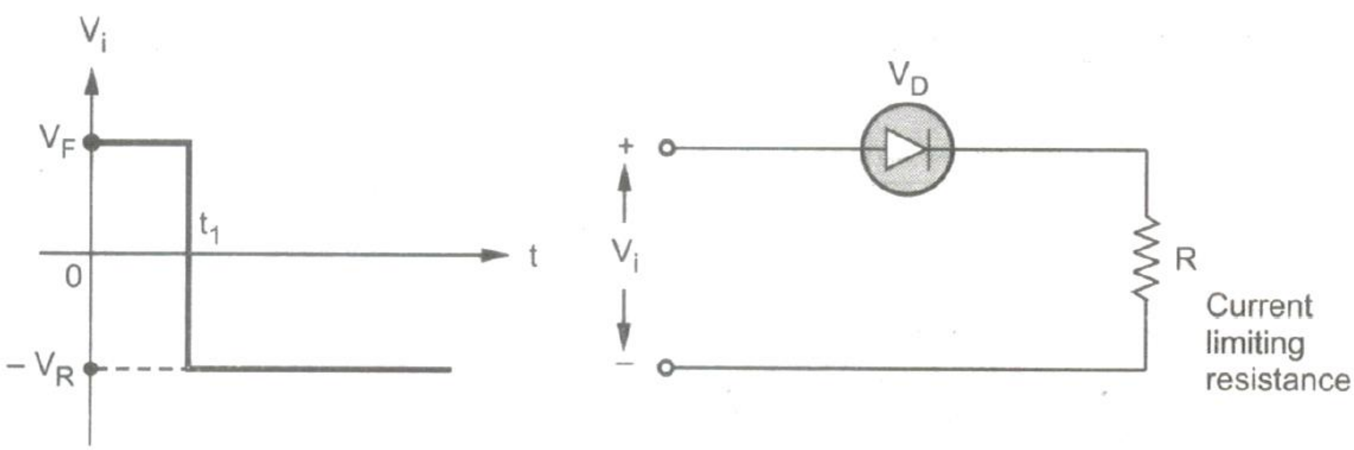


Fig. 1.20 Simple diode circuit

- The following events will take place due to the nature of the applied voltage.

- **Event 1:**
  - Till time t_1, the forward voltage applied is V_F and diode is forward biased.
  - The value of R is large enough such that drop across forward biased diode is very small compared to drop across R.
  - The forward current is then $I_F = V_F / R$, neglecting forward resistance of diode.
- **Event 2:**
  - At time t_1, the applied voltage is suddenly reversed and reverse voltage of $-V_R$ is applied to the circuit.
  - Ideally diode also must become OFF from ON state instantly. But this does not happen instantly.
  - The number of minority carriers take time to reduce from $P_n - P_{no}$ to zero at the junction as shown in the Fig. 1.21 (b).

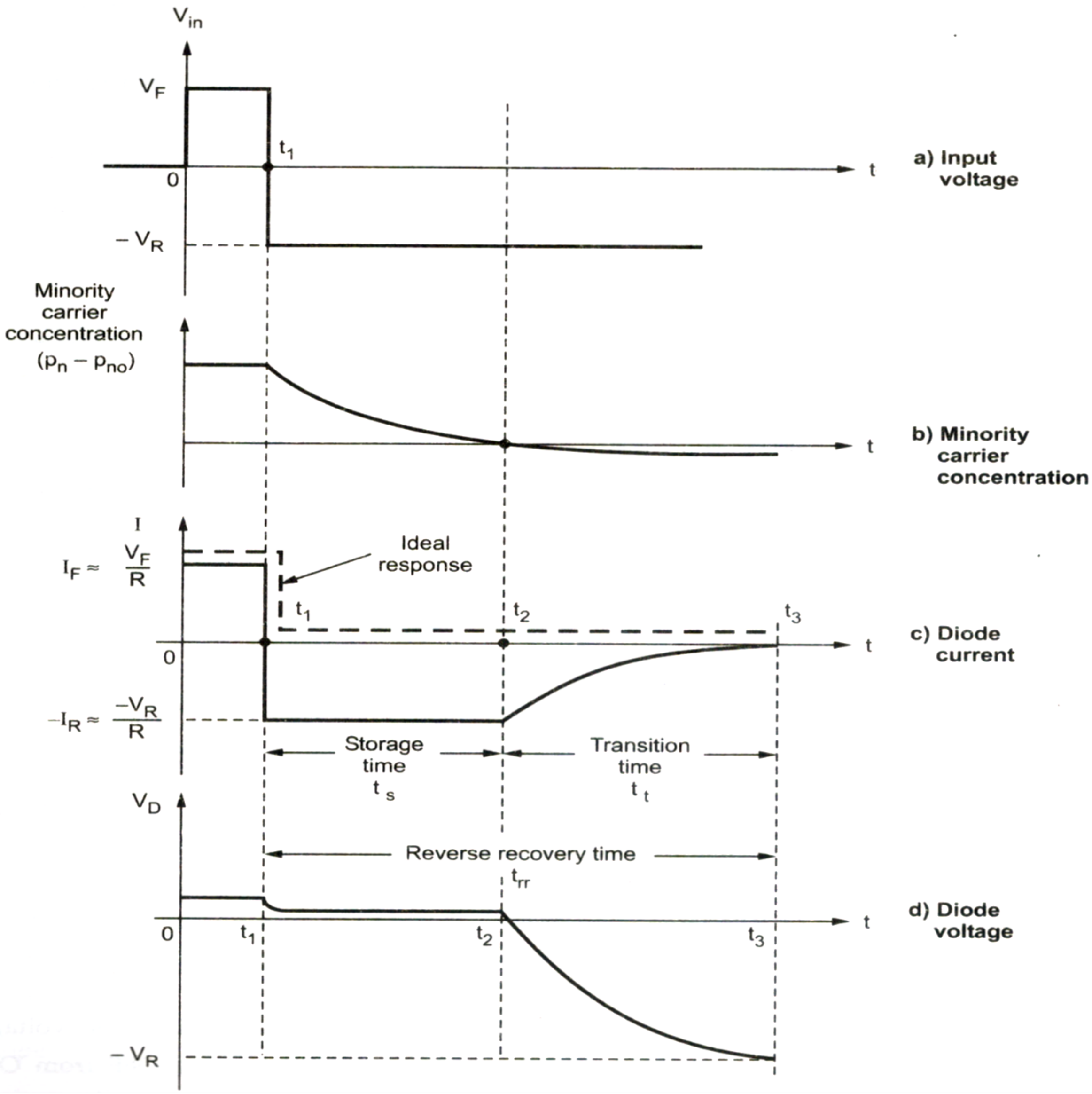


Fig. 1.21 Switching characteristics of diode

- Due to this, at t_1 current just reverses and remains at that reversed value —I_R till the minority carrier concentration reduces to zero.
- This current is given by $-I_R = -V_R/R$. This continues to flow till time t_2.
- **Storage time:**
  - During time t_1 to t_2, the minority charge carriers remain stored and decrease slowly to zero. Hence this time is called storage time denoted as t_s.

- **Event 3:**
  - From t_2 onwards, the diode voltage starts to reverse and the diode current starts decreasing as shown in the Fig. 1.21 (c).
  - At $t=t_3$, the diode state completely gets reversed and attains steady state in reverse biased condition.
  - **Transition time:**
    - The time from t_2 to t_3 i.e., time required by the diode current to reduce to its reverse saturation value is called the transition interval or transition time denoted as t_t.
  - **Reverse recovery time:**
    - The total time required by the diode which is the sum of storage time and transition time, to recover completely from the change of state is called reverse recovery time of the diode and denoted as t_{rr}. This is an important consideration in high speed switching applications.
  - For quick switching from ON to OFF state, the reverse recovery time should be as small as practicable.

$$t_{rr} = t_s + t_t$$

  - The reverse recovery time depends on the RC time constant where C is a transition capacitance of a diode.
  - To have fast switching from ON to OFF of a diode, the transition capacitance should be as small as possible.
- Thus, the transition capacitance plays an important role in the switching circuits using diodes.
- Most commercially available switching diodes have the reverse recovery time ranging from a few nanoseconds to one microsecond.
- However, diodes are specially manufactured having reverse recovery time as small as only a few picoseconds.
- The total switching time t_{rr} puts the limit on the maximum operating frequency of the diode. Hence t_{rr} is an important datasheet specification.
- To minimize the effect of the reverse current, the time period of the operating frequency must be atleast ten times t_{rr}.

$$T = 10\, t_{rr}$$

$$\boxed{f_{max} = \frac{1}{T} = \frac{1}{10\, t_{rr}}}$$

where fmax is the maximum operating frequency.

UNIT II - Diode Applications

Rectifier - Half Wave Rectifier, Full Wave Rectifier, Bridge Rectifier, Rectifiers with Capacitive and Inductive Filters, Clippers-Clipping at two independent levels, Clamper-Clamping Circuit Theorem, Clamping Operation, Types of Clampers.

2.1 Rectifier

- A rectifier is a device which converts a.c. voltage to pulsating d.c. voltage, using one or more p-n junction diode.

2.1.1 Types of Rectifier Circuits

- Using one or more diodes, following rectifier circuits can be designed.
  - Half wave rectifier (HWR)
  - Full wave rectifier (FWR)
  - Bridge rectifier(BR)

2.2 Half Wave Rectifier

- Half wave rectifier circuit uses only one diode.
- During positive half cycle of input a.c. supply, diode conducts and we will get the output at load.
- During negative half cycles of a.c, supply, there is no output at the load.

2.2.1 Construction

- This rectifier circuit consists of a.c. voltage source, rectifying element (p-n junction diode) and resistive load , all are connected in series.
- The circuit diagram is shown in the Fig. 2.1.

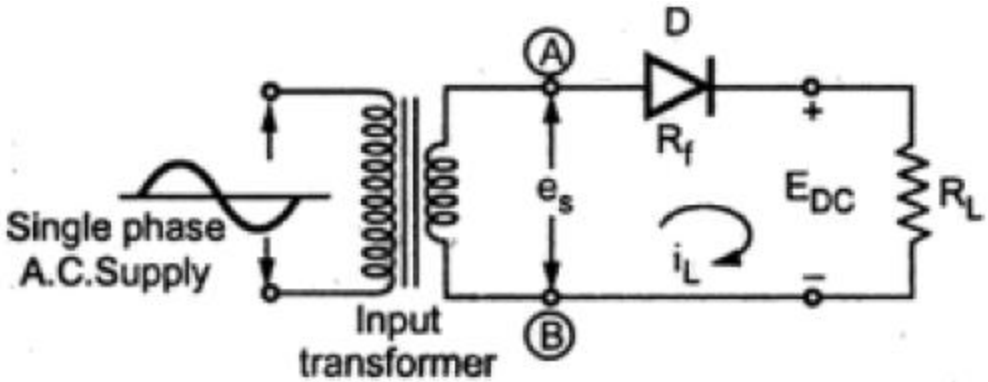


Fig. 2.1 Half wave rectifier

- To obtain the desired d.c voltage across the load, the a.c voltage is applied to rectifier circuit using suitable step-down transformer with necessary turns ratio.
- The input voltage to the half wave rectifier circuit is a sinusoidal a.c voltage, having a supply frequency of 50 Hz and is given by

$$e_s = E_{sm} \sin \omega t$$

Where

$$\omega = 2\pi f$$

$$f = \text{Supply frequency}$$

- The transformer decides the peak value of the secondary voltage.
- If N_1 are the primary number of turns and N_2 are the secondary number of turns and E_{pm} is the peak (or) maximum value of the primary voltage and E_{sm} is the peak (or) maximum value of the secondary voltage then,

$$\frac{N_2}{N_1} = \frac{E_{sm}}{E_{pm}}$$

- R_f represents the forward resistance of the diode.

2.2.2 Operation

- During the positive half cycle of secondary a.c voltage, terminal (A) becomes positive with respect to terminal (B).
- The diode is forward biased and the current flows in the circuit almost full positive half cycle. This current is also flowing through load resistance R_L hence denoted as load current i_L.
- During negative half cycle when terminal (A) is negative with respect to terminal (B), diode becomes reverse biased.
- Hence no current flows in the circuit.

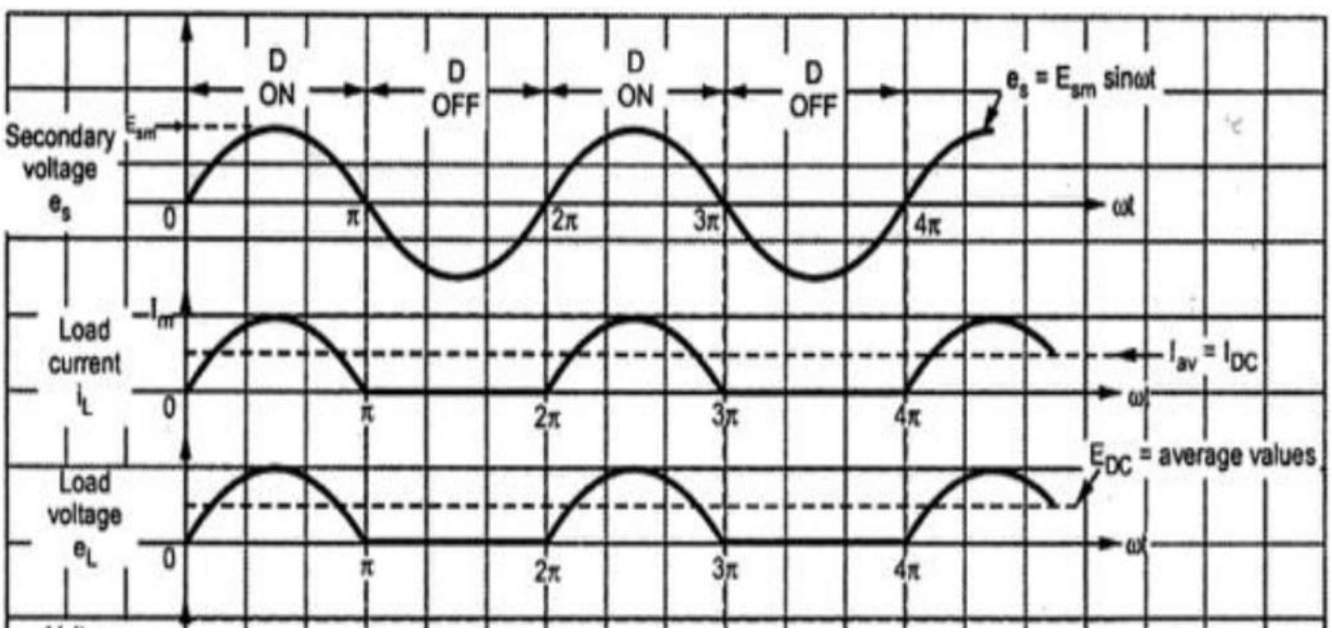


Fig. 2.2 Waveforms of Half wave Rectifier

- Thus the circuit current, which is also the load current, is in the form of half sinusoidal pulses.
- The load voltage, being the product of load current and load resistance, will also be in the form of half sinusoidal pulses.
- The different waveforms are illustrated in Fig. 2.2.

2.2.3 Parameters of Half Wave Rectifier

- Average D.C. Load Current (I_{DC})
- Average D.C. Load Voltage (E_{DC})
- R.M.S. Value of Load Current (I_{RMS})
- D.C. Power Output (P_{DC})
- A.C. Power Input (P_{AC})
- Rectifier Efficiency (η)
- Ripple Factor (ϒ)
- Peak Inverse Voltage (PIV)
- Transformer Utilization Factor (TUF)
- Voltage Regulation

2.2.3.1 Average D.C. Load Current (I_{DC})

- The average d.c value of alternating current is obtained by integration.
- For finding out the average value of an alternating waveform, we have to determine the area under the curve over one complete cycle i.e. from 0 to 2π and then dividing it by the base 2π.
- Mathematically, current waveform can be described as,

$$i_L = I_m \sin \omega t \qquad \text{for } 0 \le \omega t \le \pi$$

$$i_L = 0 \qquad \text{for } \pi \le \omega t \le 2\pi$$

where

$$I_m = \text{Peak value of load current}$$

$$I_{DC} = \frac{1}{2\pi}\int_0^{2\pi} i_L \, d(\omega t) = \frac{1}{2\pi}\int_0^{2\pi} I_m \sin(\omega t)\, d(\omega t)$$

- As no current flows during negative half cycle of a.c, input voltage, i.e. between ωt = π to ωt =2π, we change the limits of integration.

$$I_{DC} = \frac{1}{2\pi}\int_0^{\pi} I_m \sin(\omega t)\, d(\omega t) = \frac{I_m}{2\pi}\left[-\cos(\omega t)\right]_0^{\pi}$$

$$= -\frac{I_m}{2\pi}\left[\cos(\pi) - \cos(0)\right] = -\frac{I_m}{2\pi}[-1-1] = \frac{I_m}{\pi}$$

$$\boxed{I_{DC} = \frac{I_m}{\pi} = \text{Average value}}$$

- Applying Kirchhoff's voltage law we can write,

$$\boxed{I_m = \frac{E_{sm}}{R_f + R_L + R_s}}$$

Where R_S = Resistance of secondary winding of transformer.

2.2.3.2 Average D.C. Load Voltage (E_{DC})

- It is the product of average D.C. load current and the load resistance R_L.

$$E_{DC} = I_{DC} R_L$$

- Substituting value of I_{DC} in the above equation

$$E_{DC} = \frac{I_m}{\pi} R_L$$

$$= \frac{E_{sm}}{(R_f + R_L + R_s)\pi} R_L$$

$$\boxed{E_{DC} = \frac{E_{sm}}{\pi\left[\frac{R_f + R_s}{R_L} + 1\right]}}$$

- The winding resistance R_S and forward diode resistance R_f are practically very small compared to R_L.
- $(R_f + R_S)/R_L$ is negligibly small compared to 1. So we get,

$$\boxed{E_{DC} \approx \frac{E_{sm}}{\pi}}$$

2.2.3.3 R.M.S. Value of Load Current (I_{RMS})

- The R.M.S means squaring, finding mean and then finding square root. Hence R.M.S. value of load current can be obtained as,

$$I_{RMS} = \sqrt{\frac{1}{2\pi}\int_0^{\pi}(I_m \sin \omega t)^2 \, d(\omega t)} = \sqrt{\frac{1}{2\pi}\int_0^{\pi}\left(I_m{}^2 \sin^2 \omega t \, d(\omega t)\right)}$$

$$= I_m \sqrt{\frac{1}{2\pi}\int_0^{\pi}\frac{[1-\cos(2\omega t)]\,d(\omega t)}{2}} = I_m \sqrt{\frac{1}{2\pi}\left\{\frac{\omega t}{2} - \frac{\sin(2\omega t)}{4}\right\}_0^{\pi}}$$

$$= I_m \sqrt{\frac{1}{2\pi}\left(\frac{\pi}{2}\right)} \qquad \text{as } \sin(2\pi) = \sin(0) = 0$$

$$= \frac{I_m}{2}$$

$$\boxed{I_{RMS} = \frac{I_m}{2}}$$

2.2.3.4 D.C. Power Output (P_{DC})

- The d.c. power output can be obtained as,

$$\boxed{P_{DC} = E_{DC} I_{DC} = I_{DC}^2 R_L}$$

- For half wave rectifier, we have $I_{DC} = I_m / \pi$

$$P_{DC} = I_{DC}^2 R_L$$

$$= \left[\frac{I_m}{\pi}\right]^2 R_L$$

$$P_{DC} = \frac{I_m^2}{\pi^2} R_L$$

where

$$I_m = \frac{E_{sm}}{R_f + R_L + R_s}$$

$$\therefore \quad \boxed{P_{DC} = \frac{E_{sm}^2 R_L}{\pi^2 [R_f + R_L + R_s]^2}}$$

2.2.3.5 A.C. Power Input (P_{AC})

- The a.c. power is given by,

$$\boxed{P_{AC} = I_{RMS}^2 [R_L + R_f + R_s]}$$

- For half wave rectifier, we have $I_{RMS} = I_m / 2$

$$\boxed{P_{AC} = \frac{I_m^2}{4} [R_L + R_f + R_s]}$$

2.2.3.6 Rectifier Efficiency (η)

- The rectifier efficiency is defined as the ratio of D.C. output power to A.C. input power.

$$\eta = \frac{\text{D.C. output power}}{\text{A.C. input power}} = \frac{P_{DC}}{P_{AC}}$$

$$\eta = \frac{\frac{I_m^2}{\pi^2} R_L}{\frac{I_m^2}{4} [R_f + R_L + R_s]} = \frac{(4/\pi^2) R_L}{(R_f + R_L + R_s)}$$

$$\therefore \quad \boxed{\eta = \frac{0.406}{1 + \left(\frac{R_f + R_s}{R_L}\right)}}$$

- We know that, $(R_f + R_S) << R_L$. So we get the maximum theoretical efficiency of half wave rectifier as,

$$\boxed{\% \eta_{max} = 0.406 \times 100 = 40.6 \%}$$

- If the efficiency of rectifier Is 40 % then what happens to the remaining 60 % power.
- It is present in terms of ripples in the output which is fluctuating component present in the output.

2.2.3.7 Ripple Factor (ɤ)

- It is seen that the output of half wave rectifier is not pure d.c, but a pulsating d.c.
- The output contains pulsating components called ripples.
- The measure of ripples present in the output is with the help of a factor called ripple factor denoted by ɤ.
- Mathematically ripple factor is defined as the ratio of R.M.S. value of the a.c. component in the output to the average or d.c. component present in the output.

$$\boxed{\text{Ripple factor} \quad \gamma = \frac{\text{R.M.S. value of a.c. component of output}}{\text{Average or d.c. component of output}}}$$

- Now the output current is composed of a.c. component as well as d.c. component.

Let

I_{ac} = r.m.s. value of a. c. component present in output

I_{DC} = d.c. component present in output

I_{RMS} = R.M.S. value of total output current

$$I_{RMS} = \sqrt{I_{ac}^2 + I_{DC}^2}$$

$$I_{ac} = \sqrt{I_{RMS}^2 - I_{DC}^2}$$

- As per definition

$$\boxed{\text{Ripple factor} = \frac{I_{ac}}{I_{DC}}}$$

$$\gamma = \frac{\sqrt{I_{RMS}^2 - I_{DC}^2}}{I_{DC}}$$

$$\boxed{\gamma = \sqrt{\left(\frac{I_{RMS}}{I_{DC}}\right)^2 - 1}}$$

- This is the general expression for ripple factor and can be used for any rectifier circuit.

2.2.3.7.1 Ripple Factor (ɤ) for half wave rectifier

- Now for a half wave circuit, we have

$$I_{RMS} = \frac{I_m}{2} \quad \text{while} \quad I_{DC} = \frac{I_m}{\pi}$$

$$\gamma = \sqrt{\left[\frac{\left(\frac{I_m}{2}\right)}{\left(\frac{I_m}{\pi}\right)}\right]^2 - 1} = \sqrt{\frac{\pi^2}{4} - 1} = \sqrt{1.4674}$$

$$\boxed{\gamma = 1.211} \qquad \text{.. Halfwave}$$

- This indicates that the ripple contents in the output are 1.211 times the d.c. component

2.2.3.8 Peak Inverse Voltage (PIV)

- The Peak Inverse Voltage is the peak voltage across the diode in the reverse direction i.e., when the diode is reverse biased.
- In half wave rectifier, the load current is ideally zero when the diode is reverse biased and hence the maximum value of the voltage that can exist across the diode is nothing but E_{sm}.

$$\therefore \quad \boxed{\text{PIV of diode} = E_{sm} = \text{Maximum value of secondary voltage} = \pi \, E_{DC}\big|_{I_{DC}=0}}$$

2.2.3.9 Transformer Utilization Factor (TUF)

- The factor which indicates how much is the utilization of the transformer in the circuit is called Transformer Utilization Factor (TUF)

$$\text{T.U.F.} = \frac{\text{D.C. power delivered to the load}}{\text{A.C. power rating of the transformer}}$$

- A.C. power rating of transformer = $E_{RMS} \, I_{RMS}$

$$= \frac{E_{sm}}{\sqrt{2}} \cdot \frac{I_m}{2}$$

$$= \frac{E_{sm} \, I_m}{2\sqrt{2}}$$

- D.C. power delivered to the load = $I_{DC}^2 \, R_L$

$$= \left(\frac{I_m}{\pi}\right)^2 R_L$$

$$\text{T.U.F.} = \frac{\left(\frac{I_m}{\pi}\right)^2 R_L}{\left(\frac{E_{sm} I_m}{2\sqrt{2}}\right)}$$

- Neglecting the drop across R_f and R_S we can write,

$$E_{sm} = I_m R_L$$

$$\text{T.U.F} = \frac{{I_m}^2}{\pi^2} \cdot \frac{R_L \cdot 2\sqrt{2}}{{I_m}^2 R_L}$$

$$= \frac{2\sqrt{2}}{\pi^2}$$

$$\boxed{\text{T.U.F} = 0.287}$$

- The value of T.U.F. is low which shows that in half wave rectifier circuit, the transformer is not fully utilized.

2.2.3.10 Voltage Regulation

- The voltage regulation is defined as the change in the d.c output voltage as load changes from no load to full load condition.

$$\text{If } (V_{dc})_{NL} = \text{D.C. voltage on no load}$$

$$(V_{dc})_{FL} = \text{D.C. voltage on full load.}$$

- Then voltage regulation is defined as,

$$\boxed{\text{Voltage regulation} = \frac{(V_{dc})_{NL} - (V_{dc})_{FL}}{(V_{dc})_{FL}}}$$

Where

$$(V_{dc})_{NL} = \frac{E_{sm}}{\pi}$$

$$(V_{dc})_{FL} = I_{DC} R_L = \frac{I_m}{\pi} R_L = \frac{E_{sm}}{\pi[R_f + R_s + R_L]} \times R_L$$

2.2.4 Advantages of Half Wave Rectifier

- Only one diode is required
- Circuit is easy to design
- No centre transformer is necessary

2.2.5 Disadvantages of Half Wave Rectifier

- The ripple factor of half wave rectifier circuit is 1.21, which is quite high
- The maximum theoretical rectification efficiency is found to be 40% which is very low.
- TUF is very low showing that the transformer is not fully utilized.
- To minimize the saturation, transformer size have to be increased which increases the cost

Example : *A half wave rectifier circuit connected to a 230 V, 50 Hz source, through a transformer of turn ratio of 10 : 1. The rectifier circuit is to supply power to a 500 Ω, 1 watt resistor and diode forward resistance is 100 Ω.*

Calculate :

1) Maximum, average and r.m.s. value of current and voltage.

2) Efficiency of rectification.

3) Percentage regulation.

Solution : $E_p(\text{r.m.s.}) = 230$ V, $N_1/N_2 = 10{:}1$, $R_L = 500\ \Omega$, $R_f = 100\ \Omega$

$$\frac{N_2}{N_1} = \frac{1}{10} = \frac{E_{s\,(r.m.s.)}}{E_{p\,(r.m.s.)}}$$

$$\therefore \quad E_{s\,(r.m.s.)} = \frac{1}{10} \times 230 = 23 \text{ V}$$

$$\therefore \quad E_{sm} = \sqrt{2} \times E_{s(r.m.s.)} = \sqrt{2} \times 23 = 32.5269 \text{ V.}$$

1) $\therefore \quad I_m = \dfrac{E_{sm}}{R_f + R_L} = \dfrac{32.5269}{100+500} = \mathbf{54.2115\ mA}$ ...Maximum current

$\therefore \quad I_{av} = I_{DC} = \dfrac{I_m}{\pi} = \mathbf{17.2561\ mA}$ ...Average current

$\therefore \quad I_{R.M.S.} = \dfrac{I_m}{2}$ for half wave $=$ $\mathbf{27.1058\ mA}$

$\therefore \quad E_{DC} = I_{DC}R_L = \mathbf{8.628\ V}$

2) $\therefore \quad P_{DC} = I_{DC}^2 R_L = 0.14888\ W$

$P_{AC} = I_{RMS}^2 (R_L + R_f) = 0.44083\ W$

$\therefore \quad \%\,\eta = \dfrac{P_{DC}}{P_{AC}} \times 100 = \dfrac{0.14888}{0.44083} \times 100 = \mathbf{33.7723\ \%}$

3) $(V_{d.c.})_{NL} = \dfrac{E_{sm}}{\pi} = \dfrac{32.5269}{\pi} = 10.3536\ V$

$(V_{d.c.})_L = E_{DC} = 8.628\ V$

$\therefore \quad \%\,R = \dfrac{(V_{dc})_{NL} - (V_{dc})_L}{(V_{dc})_L} \times 100 = \mathbf{20\ \%}$

Example *A voltage of 200 cos wt is applied to HWR with the load resistance of 5 kΩ. Find the maximum d.c. current component, r.m.s current, ripple factor, TUF and the rectifier efficiency.*

Solution : Comparing input voltage to $E_{sm} \sin(\omega t + \phi)$, $\phi = 90^\circ$

$\therefore \quad E_{sm} = 200\ V, \quad R_L = 5\ k\Omega$

$\therefore \quad I_m = \dfrac{E_{sm}}{R_L + R_f + R_s} = \dfrac{200}{5 \times 10^3} = \mathbf{40\ mA}$ ... $R_f = R_s = 0$

$\therefore \quad I_{RMS} = \dfrac{I_m}{2} = \dfrac{40}{2} = \mathbf{20\ mA}$ ... Half wave

$$\gamma = \sqrt{\left(\frac{I_{RMS}}{I_{DC}}\right)^2 - 1} \quad \text{where} \quad I_{DC} = \frac{I_m}{\pi} = 12.7324\ \text{mA}$$

$$= \sqrt{\left(\frac{20}{12.7324}\right)^2 - 1} = \mathbf{1.21}$$

$$\text{TUF} = \frac{\text{D.C. power output}}{\text{A.C. power rating of transformer}} = \frac{I_{DC}^2 R_L}{\left(\dfrac{E_{sm}}{\sqrt{2}} \dfrac{I_{sm}}{2}\right)}$$

$$= \frac{(12.7324\times 10^{-3})^2 \times 5\times 10^3}{\left(\frac{200}{\sqrt{2}}\right)\left(\frac{40\times 10^{-3}}{2}\right)} = \mathbf{0.2865}$$

Note that for half wave rectifier $I_{RMS} = \frac{I_m}{2}$

$$P_{AC} = I_{RMS}^2 R_L = (20\times 10^{-3})^2 \times 5\times 10^3 = 2\text{ W}$$

$$P_{DC} = I_{DC}^2 R_L = (12.7324\times 10^{-3})^2 \times 5\times 10^3 = 0.8105\text{ W}$$

$$\therefore \quad \%\ \eta = \frac{P_{DC}}{P_{AC}}\times 100 = \frac{0.8105}{2}\times 100 = \mathbf{40.528\ \%}$$

2.3 Full Wave Rectifier

- The full wave rectifier conducts during both positive and negative half cycles of input a.c supply.
- In order to rectify both the half cycles of a.c. input, two diodes are used in this circuit.
- The diodes feed a common load R_L with the help of a centre tap transformer.
- The a.c voltage is applied through a suitable power transformer with proper turns ratio.
- The full wave rectifier circuit is shown in the Fig. 2.3.

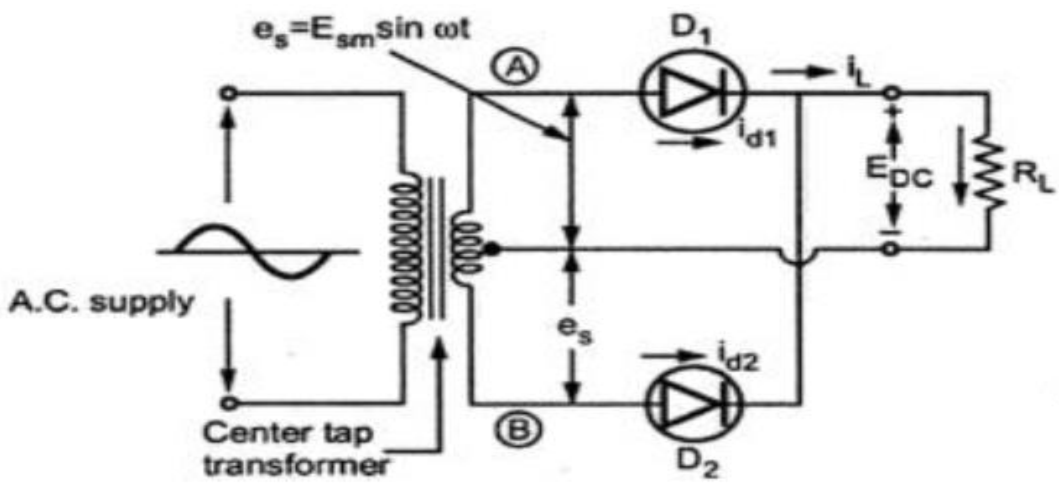


Fig. 2.3 Full wave Rectifier

2.3.1 Operation

- Consider the positive half cycle of a.c input voltage in which terminal (A) is positive and terminal (B) negative.
- The diode D_1 will be forward biased and hence will conduct.
- While diode D_2 will be reverse biased and will act as an open circuit and will not conduct.
- The diode D_1 supplies the load current, i.e. $i_L = i_{d1}$. This current is flowing through upper half of secondary winding.
- The diode current and the load current are illustrated in the Fig. 2.4.

- During negative half cycle of a.c voltage, polarity reverses and terminal (A) becomes negative and (B) is positive.
- The diode D_2 conducts, being forward biased, while D_1 does not, being reverse biased.
- The diode D_2 supplies the load current, i.e. $i_L = i_{d2}$. Now the lower half of the secondary winding carries the current.
- The diode current and the load current are illustrated in the Fig. 2.4.
- It is noted that the load current flows in both the half cycles of a.c voltage and in the same direction through the load resistance.
- Hence we get rectified output across the load.
- The load current is sum of individual diode currents flowing in corresponding half cycles.
- It is also noted that the two diodes do not conduct simultaneously but in alternate half cycles.
- The output load current is still pulsating d.c and not pure d.c.

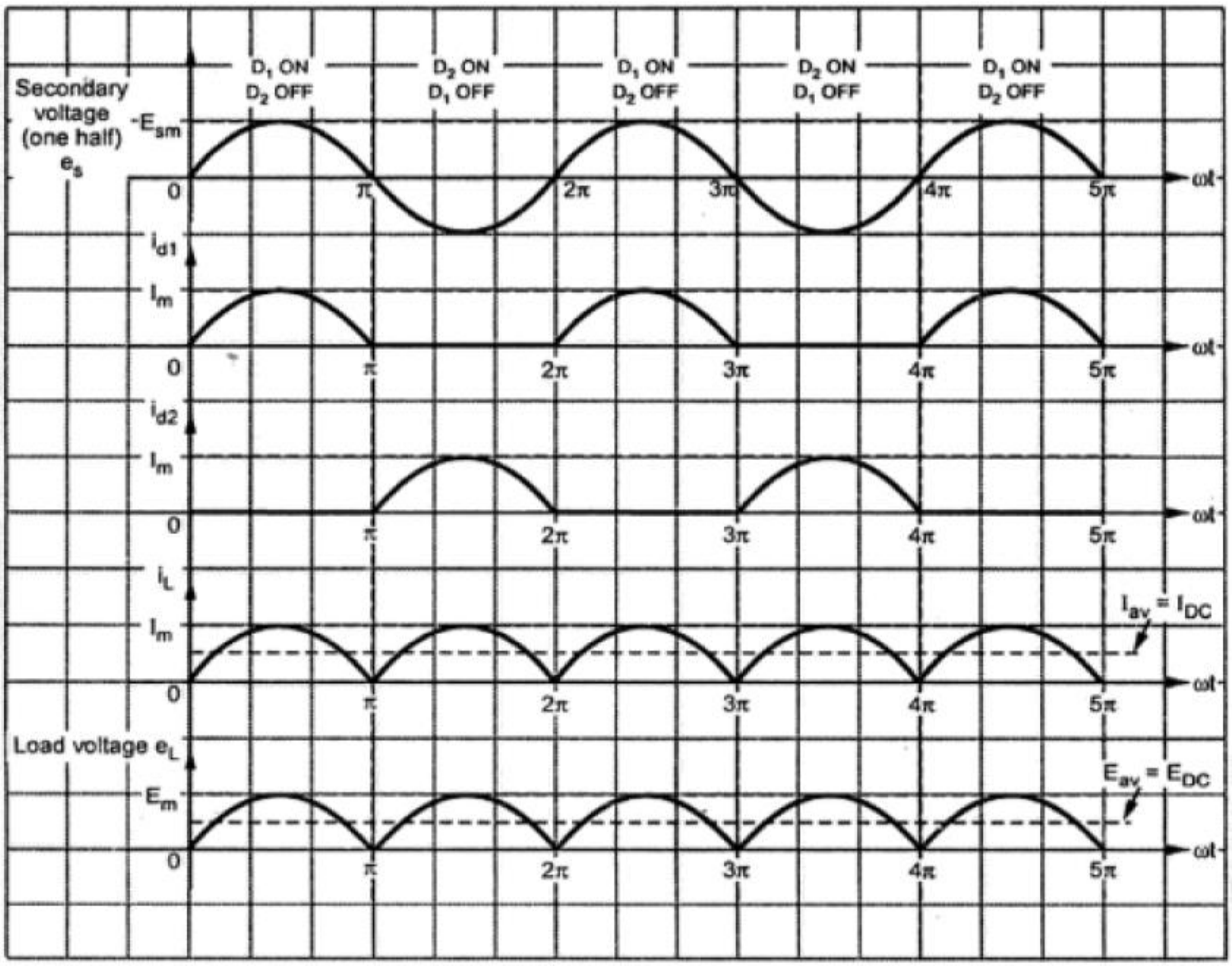


Fig. 2.4 Waveforms for Full wave rectifier

2.3.2 Parameters of FWR

- Average D.C. Load Current (I_{DC})
- Average D.C. Load Voltage (E_{DC})
- R.M.S. Value of Load Current (I_{RMS})
- D.C. Power Output (P_{DC})
- A.C. Power Input (P_{AC})
- Rectifier Efficiency (η)
- Ripple Factor (ϒ)
- Peak Inverse Voltage (PIV)
- Transformer Utilization Factor (TUF)
- Voltage Regulation

2.3.2.1 Average D.C. Load Current (I_{DC})

- The average d.c value of alternating current is obtained by integration.
- For finding out the average value of an alternating waveform, we have to determine the area under the curve over one complete cycle i.e. from 0 to 2π and then dividing it by the base 2π.
- Mathematically, current waveform can be described as,

$$i_L = I_m \sin \omega t \qquad \text{for } 0 \le \omega t \le \pi$$

$$i_L = I_m \sin \omega t \qquad \text{for } \pi \le \omega t \le 2\pi$$

where

$$I_m = \text{Peak value of load current}$$

$$I_{DC} = \frac{1}{2\pi}\int_0^{2\pi} i_L \, d(\omega t) = 2\frac{1}{2\pi}\int_0^{\pi} i_L \, d(\omega t)$$

$$I_{av} = I_{DC} = \frac{1}{\pi}\int_0^{\pi} i_L \, d(\omega t)$$

$$= \frac{1}{\pi}\int_0^{\pi} I_m \sin \omega t \, d\omega t$$

$$= \frac{I_m}{\pi}\left[(-\cos \omega t)_0^{\pi}\right]$$

$$= \frac{I_m}{\pi}[-\cos \pi - (-\cos 0)]$$

$$= \frac{I_m}{\pi}(+1 - (-1))] \qquad \text{... } \cos \pi = -1$$

$$\therefore \quad \boxed{I_{DC} = \frac{2I_m}{\pi}} \qquad \text{for full wave rectifier}$$

2.3.2.2 Average D.C. Load Voltage (E_{DC})

- The d,c. load voltage is,

$$E_{DC} = I_{DC} R_L = \frac{2 I_m R_L}{\pi}$$

- Substituting value of I_m in the above equation

$$E_{DC} = \frac{2\, E_{sm}\, R_L}{\pi\, [R_f + R_s + R_L]}$$

$$= \frac{2\, E_{sm}}{\pi \left[1 + \frac{R_f + R_s}{R_L}\right]}$$

- But as R_f & R_S << R_L hence (R_f & R_S)/ R_L << 1

$$\boxed{E_{DC} = \frac{2 E_{sm}}{\pi}}$$

2.3.2.3 R.M.S. Value of Load Current (I_{RMS})

- The R.M.S value of current can be obtained as follows.

$$I_{R.M.S.} = \sqrt{\frac{1}{2\pi} \int_0^{2\pi} i_L^2\, d(\omega t)}$$

- Since two half wave rectifier are similar in operation we can write

$$I_{R.M.S.} = \sqrt{2\, \frac{1}{2\pi} \int_0^{\pi} [I_m \sin \omega t]^2 d(\omega t)}$$

$$= I_m \sqrt{\frac{1}{\pi} \int_0^{\pi} \left[\frac{1 - \cos 2\omega t}{2}\right] d(\omega t)} \qquad \text{as } \sin^2 \omega t = \frac{1 - \cos 2\omega t}{2}$$

$$\therefore \qquad I_{R.M.S.} = I_m \sqrt{\frac{1}{2\pi}\left[[\omega t]_0^{\pi} - \left(\frac{\sin 2\omega t}{2}\right)_0^{\pi} \right]} = I_m \sqrt{\frac{1}{2\pi} [\pi - 0]}$$

$$= I_m \sqrt{\frac{1}{2\pi}(\pi)} \qquad \text{as } \sin(2\pi) = \sin(0) = 0$$

$$\therefore \qquad \boxed{I_{R.M.S.} = \frac{I_m}{\sqrt{2}}}$$

2.3.2.4 D.C. Power Output (P_{DC})

- D.C. power output $P_{DC} = E_{DC}\, I_{DC} = I_{DC}^2\, R_L$
- For full wave rectifier, we have $I_{DC} = 2I_m / \pi$

$$P_{DC} = I_{DC}^2 R_L = \left(\frac{2I_m}{\pi}\right)^2 R_L$$

$$P_{DC} = \frac{4}{\pi^2} I_m^2 R_L$$

- Substituting value of I_m we get,

$$\boxed{P_{DC} = \frac{4}{\pi^2} \frac{E_{sm}^2}{(R_s + R_f + R_L)^2} \times R_L}$$

2.3.2.5 A.C. Power Input (P_{AC})

- The a.c. power input is given by,

$$\boxed{P_{AC} = I_{RMS}^2 (R_f + R_s + R_L) = \left(\frac{I_m}{\sqrt{2}}\right)^2 (R_f + R_s + R_L)}$$

$$P_{AC} = \frac{I_m^2 (R_f + R_s + R_L)}{2}$$

- Substituting value of I_m we get,

$$P_{AC} = \frac{E_{sm}^2}{(R_f + R_s + R_L)^2} \times \frac{1}{2} \times (R_f + R_s + R_L)$$

$$\boxed{P_{AC} = \frac{E_{sm}^2}{2(R_f + R_s + R_L)}}$$

2.3.2.6 Rectifier Efficiency (η)

- The Rectifier Efficiency is given by

$$\boxed{\eta = \frac{P_{DC} \text{ output}}{P_{AC} \text{ input}}}$$

$$\eta = \frac{\frac{4}{\pi^2} I_m^2 R_L}{\frac{I_m^2 (R_f + R_s + R_L)}{2}}$$

$$\eta = \frac{8 R_L}{\pi^2 (R_f + R_s + R_L)}$$

- But $(R_f + R_S) << R_L$,

$$\eta = \frac{8 R_L}{\pi^2 (R_L)} = \frac{8}{\pi^2}$$

$$\% \eta_{max} = \frac{8}{\pi^2} \times 100$$

$$\boxed{\% \eta_{max} = 81.2 \%}$$

2.3.2.7 Ripple Factor (ɤ)

- As derived earlier, a general expression the ripple factor is given by

$$\text{Ripple factor} = \sqrt{\left[\frac{I_{RMS}}{I_{DC}}\right]^2 - 1}$$

- For full wave rectifier $I_{RMS} = I_m/\sqrt{2}$ and $I_{DC} = 2I_m/\pi$
- Substitute the above values in ripple factor equation

$$\text{Ripple factor} = \sqrt{\left[\frac{I_m/\sqrt{2}}{2I_m/\pi}\right]^2 - 1} = \sqrt{\frac{\pi^2}{8} - 1}$$

$$\boxed{\text{Ripple factor} = \gamma = 0.48}$$

2.3.2.8 Peak Inverse Voltage (PIV)

- The total peak voltage across diode is $2E_{sm}$.

$$\boxed{\text{PIV of diode} = 2\,E_{sm} = \pi E_{DC}|_{I_{DC}=0}}$$

2.3.2.9 Transformer Utilization Factor (TUF)

- In full wave rectifier, the secondary current flows through each half separately in every half cycle while the primary of transformer carries current continuously.
- Hence TUF is calculated for primary and secondary windings separately and then the average TUF is determined.

$$\text{Secondary T.U.F.} = \frac{\text{D.C. power to the load}}{\text{A.C. power rating of secondary}}$$

$$= \frac{I_{DC}^2\,R_L}{E_{RMS}\,I_{rms}} = \frac{\left(\frac{2}{\pi}I_m\right)^2 R_L}{\frac{E_{sm}}{\sqrt{2}} \times \frac{I_m}{\sqrt{2}}}$$

- Neglecting forward resistance R_f of diode, $E_{sm} = I_m R_L$

$$\text{Secondary T.U.F.} = \frac{\frac{4}{\pi^2} \times I_m^2\,R_L}{\frac{I_m^2\,R_L}{2}} = \frac{8}{\pi^2} = 0.812$$

- The primary of the transformer is feeding two half-wave rectifiers separately.

$$\text{T.U.F. for primary winding} = 2 \times \text{T.U.F. of half wave circuit}$$

$$= 2 \times 0.287 = 0.574.$$

- The average T.U.F for full wave rectifier circuit will be

$$\begin{aligned} \text{Average T.U.F. for full wave rectifier circuit} &= \frac{\text{T.U.F. of primary} + \text{T.U.F. of secondary}}{2} \\ &= \frac{0.574 + 0.812}{2} = \mathbf{0.693} \end{aligned}$$

$$\boxed{\text{Average T.U.F. for full-wave rectifier} = 0.693}$$

2.3.2.10 Voltage Regulation

- For a full wave circuit,

$$(V_{dc})_{NL} = \frac{2E_{sm}}{\pi}$$

$$(V_{dc})_{FL} = I_{DC} R_L$$

- The regulation can be expressed as,

$$\% R = \frac{(V_{dc})_{NL} - (V_{dc})_{FL}}{(V_{dc})_{FL}} \times 100$$

2.3.3 Advantages of Full Wave Rectifier

- The d.c load voltage and current are more than half wave.
- No d.c current through transformer windings hence no possibility of saturation.
- T.U.F. is better as transformer losses are less.
- The efficiency is higher.
- The large d.c power output.
- The ripple factor is less.

2.3.4 Disadvantages of Full Wave Rectifier

- The PIV rating of diode is higher.
- Higher PIV diodes are larger in size and costlier.
- The cost of centre tap transformer is higher.

Example : *A full-wave rectifier circuit is fed from a transformer having a centre-tapped secondary winding. The rms voltage from either end of secondary to center tap is 30 V. If the diode forward resistance is 2 Ω and that of the half secondary is 8 Ω, for a load of 1 kΩ, calculate,*

a) Power delivered to load, b) % Regulation at full load,
c) Efficiency of rectification, d) T.U.F. of secondary.

Solution : Given : $E_s = 30\,V,\ R_f = 2\,\Omega,\ R_s = 8\,\Omega,\ R_L = 1\,k\Omega$

$$E_s = E_{RMS} = 30\ V$$

$$E_{sm} = E_s\sqrt{2} = 30\sqrt{2}\ \text{volt} = 42.426\ V$$

$$I_m = \frac{E_{sm}}{R_f + R_L + R_s} = \frac{30\sqrt{2}}{2 + 1000 + 8}\ A$$

$$= 42\ mA$$

$$I_{DC} = \frac{2}{\pi} I_m = 26.74\ mA$$

a) Power delivered to the load $= I_{DC}^2\ R_L = (26.74 \times 10^{-3})^2\ (1\,k\Omega)$

$$= 0.715\ W$$

b) V_{DC}, no load $= \frac{2}{\pi}\ E_{sm} = \frac{2}{\pi} \times 30\sqrt{2} = 27\ V$

V_{DC}, full load $= I_{DC}\ R_L = (26.74\ mA)\ (1\ k\Omega)$

$$= 26.74\ V$$

$$\%\ \text{Regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100 = \frac{27 - 26.74}{26.74} \times 100$$

$$= 0.97\ \%$$

c) Efficiency of rectification $= \frac{\text{D.C. output}}{\text{A.C. input}}$

$$= \frac{8}{\pi^2} \times \frac{1}{1 + \frac{R_f + R_s}{R_L}} = \frac{8}{\pi^2} \times \frac{1}{1 + \frac{(2+8)}{1000}}$$

$$= 0.802 \quad \text{i.e.}\ \ 80.2\ \%$$

d) Transformer secondary rating $= E_{RMS}\ I_{RMS} = [30\ V]\left[\frac{42\ mA}{\sqrt{2}}\right]$

$$= 0.89\ W$$

$\therefore$ $$\text{T.U.F.} = \frac{\text{D.C. power output}}{\text{A.C. rating}}$$

$$= \frac{0.715}{0.89} = 0.802$$

2.4 Bridge Rectifier

- The bridge rectifier circuit is essentially a full wave rectifier circuit, using four diodes, forming the four arms of an electrical bridge and is shown in figure 2.5.
- To one diagonal of the bridge, the a.c voltage is applied through a transformer and the rectified d.c voltage is taken from the other diagonal of the bridge.

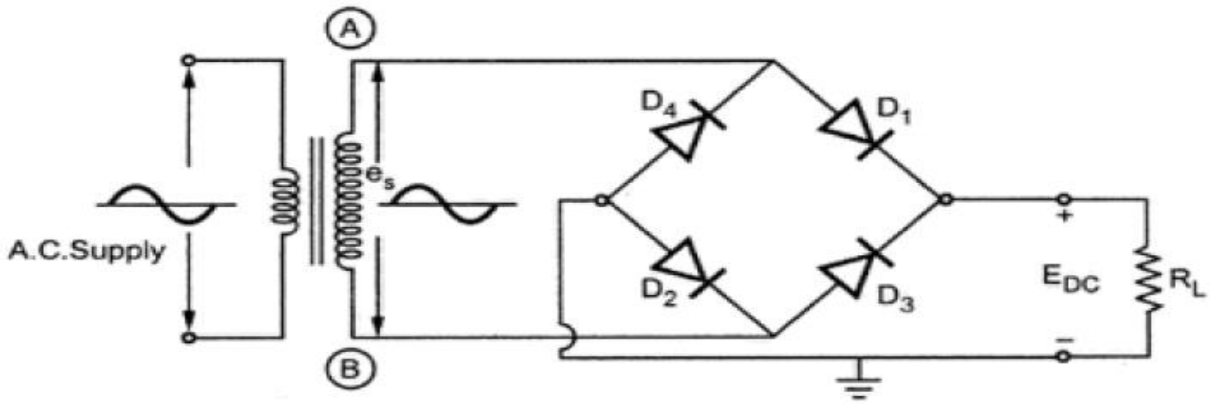


Fig. 2.5 Bridge Rectifier

2.4.1. Operation

- Consider the positive half of ac input voltage.
- The point A of secondary becomes positive. The diodes D_1 and D_2 will be forward biased, while D_3 and D_4 reverse biased.
- The two diodes D_1 and D_2 conduct in series with the load and the current flows as shown in Fig. 2.6.

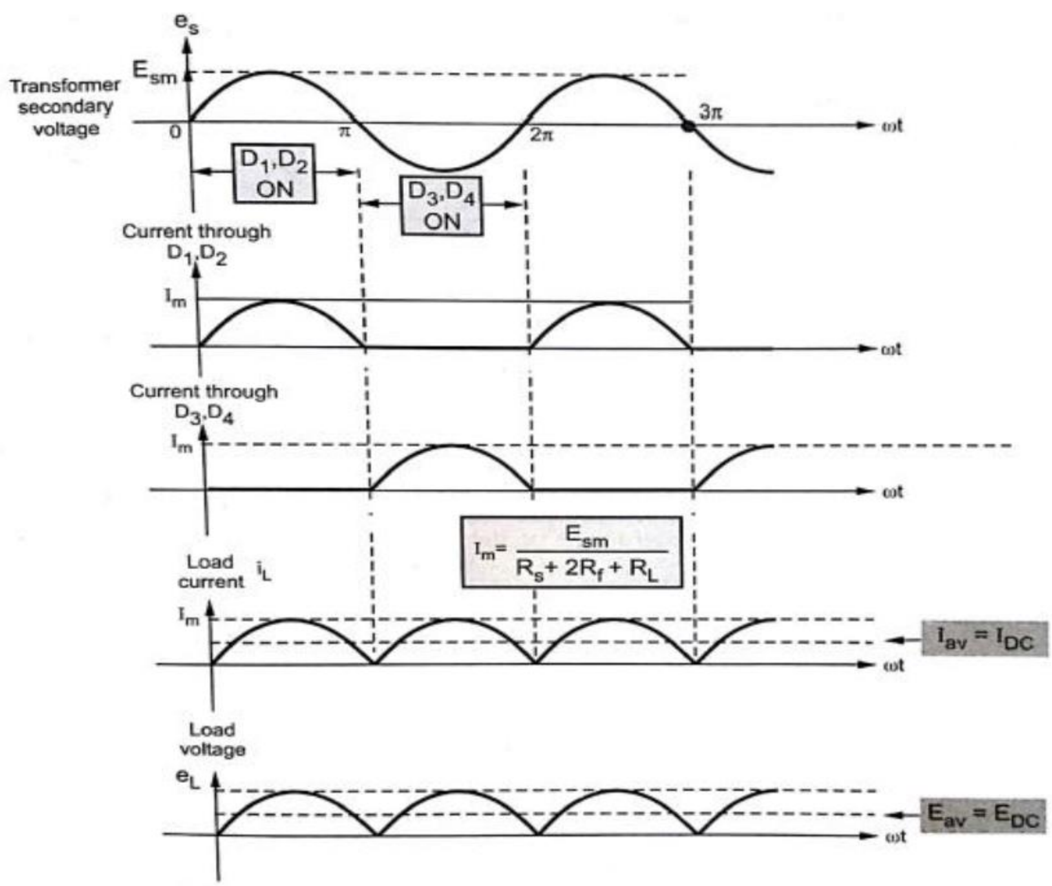


Fig. 2.6 Waveforms of bridge Rectifier

- During negative hall cycle, the polarity of a.c voltage reverses hence point B becomes positive diodes D_3 and D_4 are forward biased, while D_1 and D_2 reverse biased.

- Now the diodes D_3 and D_4 conduct is series with the load and the current flows as shown in Fig. 2.6.
- It is seen that in both cycles of a.c input, the load current is flowing in the same direction.
- The waveforms of load current and voltage remain are shown in figure 2.6.

2.4.2 Expressions for various parameters of Bridge Rectifier

- The bridge rectifier circuit, being basically a full wave rectifier circuit.
- All the derivations discussed previously for a full wave rectifier circuit using two diodes are applicable for a bridge rectifier circuit.
- The relation between I_m the maximum value of load current and I_{DC}, I_{RMS} remains same as derived earlier for the full wave rectifier circuit.

$$\boxed{I_{DC} = \frac{2I_m}{\pi} \quad \text{and} \quad I_{RMS} = \frac{I_m}{\sqrt{2}}}$$

- In each half cycle two diodes conduct simultaneously. Hence maximum value of Load current is,

$$\boxed{I_m = \frac{E_{sm}}{R_s + 2R_f + R_L}}$$

- The remaining expressions are identical to those derived for two diode full wave rectifier and reproduced for the convenience of the reader.

$$\begin{aligned}
E_{DC} &= I_{DC} R_L = \frac{2E_{sm}}{\pi} \\
P_{DC} &= I_{DC}^2 R_L = \frac{4}{\pi^2} I_m^2 R_L \\
P_{AC} &= I_{RMS}^2 (R_s + 2R_f + R_L) \\
&= \frac{I_m^2 (2R_f + R_s + R_L)}{2} \\
\eta &= \frac{8R_L}{\pi^2 (R_s + 2R_f + R_L)} \\
\% \eta_{max} &= 81.2 \% \\
\gamma &= 0.48
\end{aligned}$$

- The transformer utilization factor is 0.812.
- PIV rating of the diode is E_{sm}

2.4.3 Advantages of Bridge Rectifier

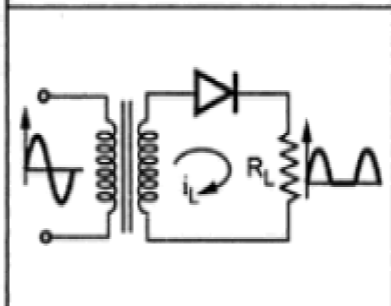
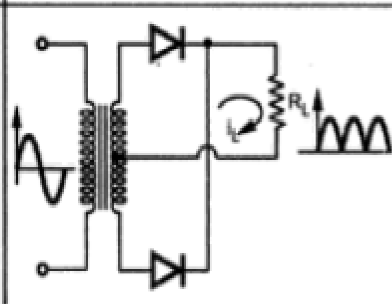
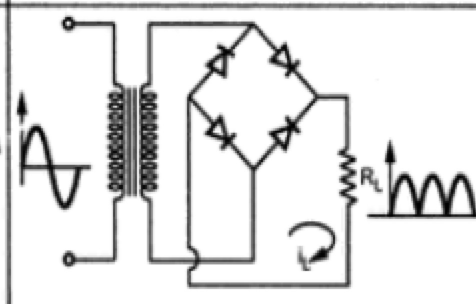
- Power transformer of a small size and less cost may be used.
- No centre tap is required in the transformer secondary.
- The transformer gets utilized effectively
- It is suitable for applications where large powers are required.

- It can be used for high voltage applications.

2.4.4 Disadvantages of Bridge Rectifier

- Use of four diodes
- Due to $2R_f$, this reduces the output voltage

2.5 Comparison of Rectifier Circuits

Circuit diagrams		
Half wave	Full wave	Bridge
		

Sr. No.	Parameter	Half wave	Full wave	Bridge
1.	Number of diodes	1	2	4
2.	Average D.C. current (I_{DC})	$\frac{I_m}{\pi}$	$\frac{2I_m}{\pi}$	$\frac{2I_m}{\pi}$
3.	Average D.C. voltage (E_{DC})	$\frac{E_{sm}}{\pi}$	$\frac{2E_{sm}}{\pi}$	$\frac{2E_{sm}}{\pi}$
4.	R.M.S. current (I_{RMS})	$\frac{I_m}{2}$	$\frac{I_m}{\sqrt{2}}$	$\frac{I_m}{\sqrt{2}}$
5.	D.C. power output (P_{DC})	$\frac{I_m^2 R_L}{\pi^2}$	$\frac{4}{\pi^2} I_m^2 R_L$	$\frac{4}{\pi^2} I_m^2 R_L$
6.	A.C. power input (P_{AC})	$\frac{I_m^2 (R_L + R_f + R_s)}{4}$	$\frac{I_m^2 (R_f + R_s + R_L)}{2}$	$\frac{I_m^2 (2R_f + R_s + R_L)}{2}$
7.	Maximum rectifier efficiency (η)	40.6 %	81.2 %	81.2 %
8.	Ripple factor (γ)	1.21	0.482	0.482
9.	Maximum load current (I_m)	$\frac{E_{sm}}{R_s + R_f + R_L}$	$\frac{E_{sm}}{R_s + R_f + R_L}$	$\frac{E_{sm}}{R_s + 2R_f + R_L}$
10.	PIV rating of diode	E_{sm}	$2\ E_{sm}$	E_{sm}
11.	Ripple frequency	50 Hz	100 Hz	100 Hz
12.	T.U.F.	0.287	0.693	0.812

2.6 Filter Circuits

Definition of filter:

- A **filter circuit** is one which removes the ac component present in the rectified output and allows the dc component to reach the load.

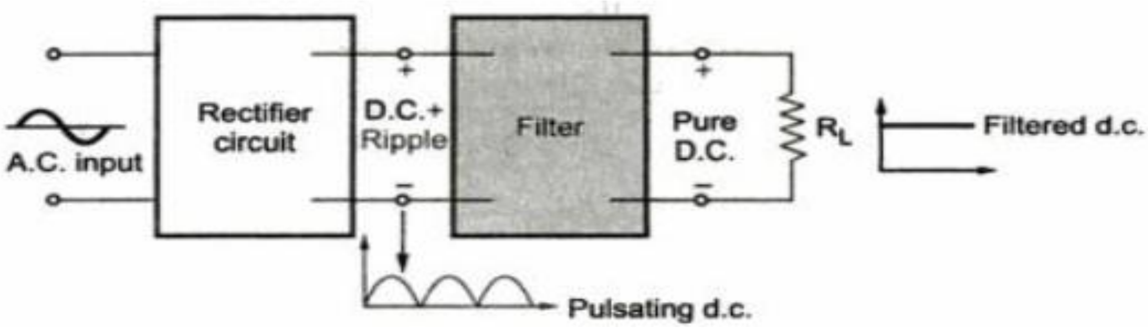


Fig. 2.7 Rectifier and filter

- It is seen that the output of a half wave or full wave rectifier circuit is not pure d.c.
- But it contains fluctuations or ripple, which are undesired.
- To minimize the ripple content in the output of rectifier, filter circuits are used.
- These circuits are connected between the rectifier and load as shown in the Fig. 2.7.
- An a.c input is applied to the rectifier.
- At the output of the rectifier, there will be d.c and ripple voltage present, which is the input to the filter.
- Ideally the output of the filter should be pure d.c.
- Two components which are used in filter circuits are inductance and capacitance.
- An inductor allows dc and blocks ac. A capacitor allows ac and blocks dc.
- In a filter circuit, the inductance is always connected in series with the load.
- In a filter circuit, the capacitance is always connected in parallel with the load.

2.6.1 Types of filter circuits

- Capacitor filter (C Filter)
- Inductor filter (or) Choke filter (L Filter)
- L Section filter (or) LC Filter
- π- Section Filter (CLC Filter)

2.6.2 Capacitor filter (C Filter)

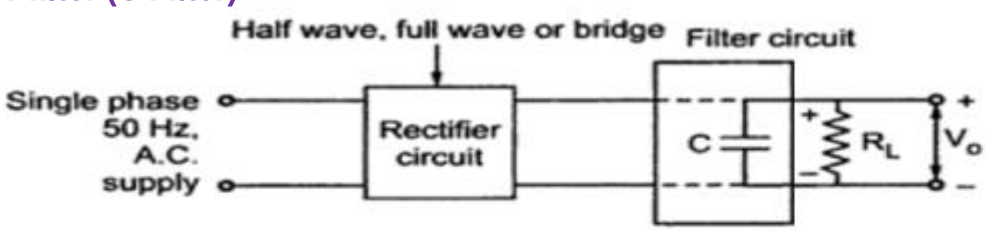


Fig. 2.8 Block Schematic of capacitor filter

- The block schematic of capacitor filter is shown in the Fig. 2.8.
- Looking from the rectifier side the first element in filter is a capacitor.

2.6.2.1 Capacitor filter with Full Wave Rectifier

- The capacitor filter used in full wave rectifier circuit as shown in the Fig. 2.9.

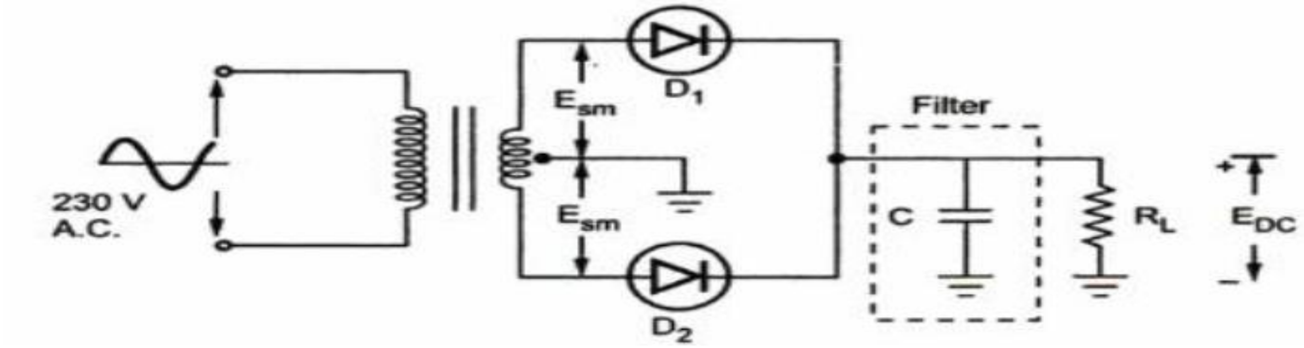


Fig. 2.9 Capacitor input filter with Full wave rectifier

- When power is turned on, the capacitor C gets charged through forward biased diode D_1 to E_{sm}, during first quarter cycle of the rectified output voltage.
- In the next quarter cycle from π/2 to π the capacitor starts discharging through R_L.
- Once capacitor gets charged to E_{sm}, the diode D_1 becomes reverse biased and stops conducting. So during the period from π/2 to π the capacitor C supplies the load current.
- It discharges to point B shown in the Fig. 2.10

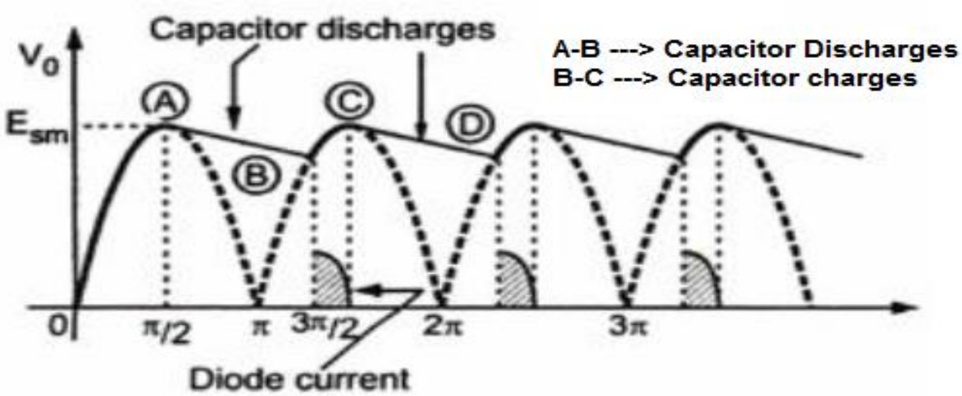


Fig. 2.10 Waveforms of Capacitor input filter with Full wave rectifier

- At point B, lying in the quarter π to 3π/2 of the rectified output voltage, the input voltage exceeds capacitor voltage, making D_2 forward biased. This charges capacitor back to E_{sm} at point C.
- The time required by capacitor C to charge to E_{sm} is quite small and only for this period, diode D_2 is conducting.
- Again at point C, diode D_2 stops conducting and capacitor supplies load and starts discharging upto point D in the next quarter cycle of the rectified output voltage as shown in the Fig. 2.10.
- At this point, the diode D_1 conducts to charge capacitor back to E_{sm}.
- The diode currents are shown shaded in the Fig. 2.11.
- When the capacitor is discharging through the load resistance R_L both the diodes are non-conducting. The capacitor supplies the load current.

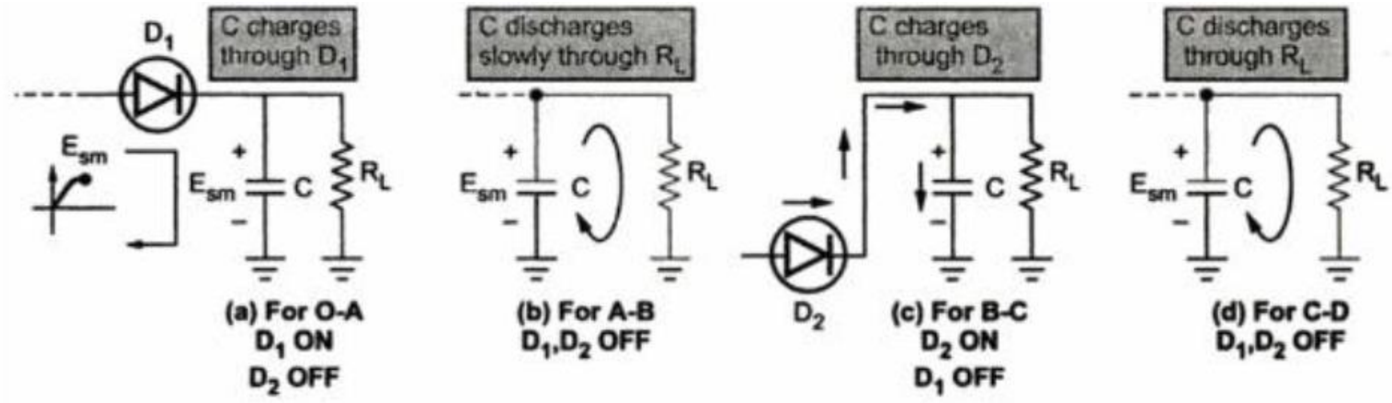


Fig. 2.11 Operation of Capacitor input filter with Full wave rectifier

- Expression for ripple factor of full wave rectifier circuit using a capacitor filter is given below.

$$\boxed{\text{Ripple factor} = \frac{1}{4\sqrt{3}\, f\, C\, R_L} \quad \text{for full wave}}$$

- The product CR_L is the time constant of the filter circuit.
- From the expression of the ripple factor, it is dear that increasing the value of capacitor C, the ripple factor gets decreased.
- Thus the output can be made smoother, reducing the ripple content by selecting large value of capacitor.

2.6.2.2 Advantages of C filter

- Less number of components.
- Low ripple factor hence low ripple voltage.
- Suitable for high voltage at small load currents.

2.6.2.3 Disadvantages of C filter

- Ripple factor depends on load resistance.
- Not suitable for variable loads as ripple content increases as R_L decreases.
- Regulation is poor.
- Diodes are subjected to high surge currents hence must be selected accordingly.

Example : *Calculate the value of 'C ' that has to be used for the capacitor filter of a full wave rectifier to get a ripple factor of 0.01 %. The rectifier supplies a load of 2 kΩ while the supply frequency is 50 Hz.*

Solution : The given values are,

$$\gamma = 0.01\,\%,\ R_L = 2\ \text{k}\Omega \text{ and } f = 50\ \text{Hz}$$

For a capacitor filter with full wave rectifier,

$$\%\,\gamma = \frac{1}{4\sqrt{3}\, f C R_L} \times 100$$

$$\therefore \quad 0.01 = \frac{1}{4\sqrt{3} \times 50 \times C \times 2000} \times 100$$

$$\therefore \quad C = \mathbf{14.433\ mF}$$

2.6.3 Inductor filter with Full Wave Rectifier

- In this type of filter, an inductor (choke) is connected in series with the load.
- The inductor opposes change in the current. So, the ripple which is change in the current is opposed by the inductor and it tries to smoothen the output.
- Consider a full wave rectifier with inductor filter which is also called choke filter.
- Fig. 2.12 shows the circuit diagram while Fig. 2.13 shows the current waveform obtained by using choke filter with full wave rectifier.

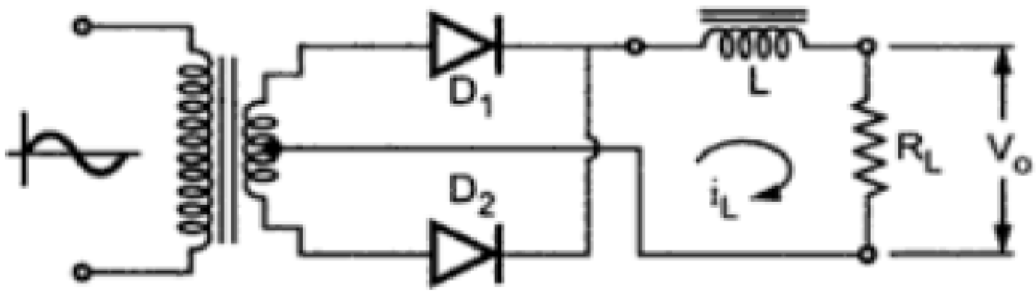


Fig. 2.12 Circuit diagram of Inductor filter

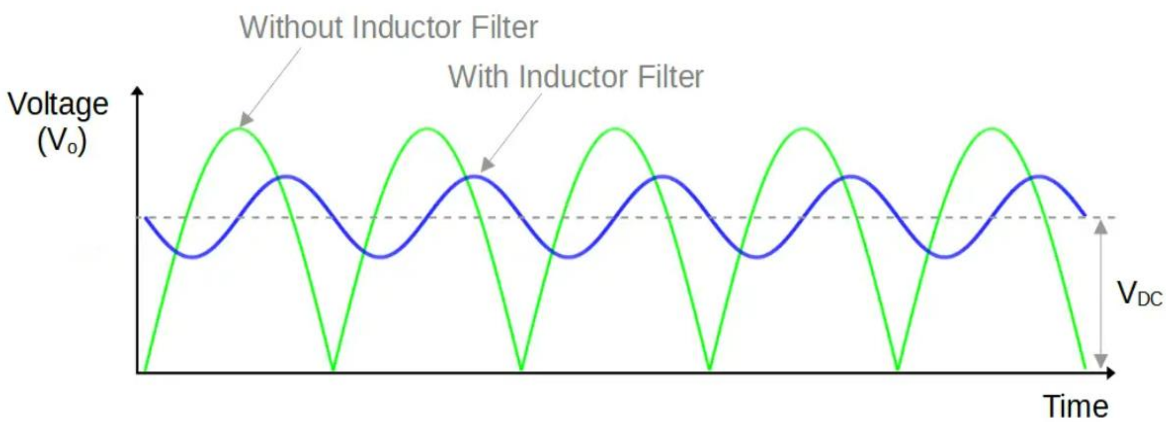


Fig. 2.13 Output Voltage waveform of Inductor filter

- In the positive half cycle of the secondary voltage of the transformer, the diode D_1 is forward biased. Hence the current flows through D_1, L and R_L.
- In the negative half cycle, the diode D_1 is reverse biased while diode D_2 is forward biased. Hence the current flows through D_2, L and R_L.
- Hence, we get unidirectional current through R_L.
- Due to inductor L which opposes change in current, it tries to make the output smooth by opposing the ripple content in the output.
- Expression for ripple factor of full wave rectifier circuit using an Inductor filter is given below.

$$\boxed{\text{Ripple factor} = \gamma = \frac{R_L}{3\sqrt{2}\,.\,\omega L}}$$

- So as load changes, ripple charges which is inversely proportional to the value of the inductor.

2.6.3.1 Advantages of series inductor (L) filter

- The series inductor (L) filter reduces the ripple in the DC output of rectifier circuit.
- It has low ripple factor at heavy load currents i.e. low load resistance.

2.6.3.2 Disadvantages of series inductor (L) filter

- It is bulky and more costly.
- It gives low output DC voltage for larger value of inductance.
- It has poor voltage regulation.
- It has high ripple factor for light loads i.e. small load currents.

2.7 Clipper Circuits (or) Limiters (or) Slicers

- The circuits which are used to clip off unwanted portion of the waveform, without distorting the remaining part of the waveform are called clipper circuits or clippers.
- A diode is most important element of any clipper circuit.

2.7.1 Classification of Clippers

- Series clipper
- Parallel Clipper

2.7.1.1 Series clipper

- When the diode is connected in series with the load, it is called Series clipper.
- A series clipper can be used to clip off the entire positive or negative half cycles of input waveforms.
- It also can be used to clip off the portion above the certain reference voltage or below the certain reference voltage.

2.7.1.2 Parallel (or) Shunt Clipper

- When the diode is connected in parallel to the load, it is called Parallel Clipper.

2.7.2 Types of Series clipper

- Series Negative Clipper
- Series Positive Clipper
- Series Clipping Above Reference Voltage V_R
- Series Clipping Below Reference Voltage V_R

2.7.3 Series Negative Clipper Circuit

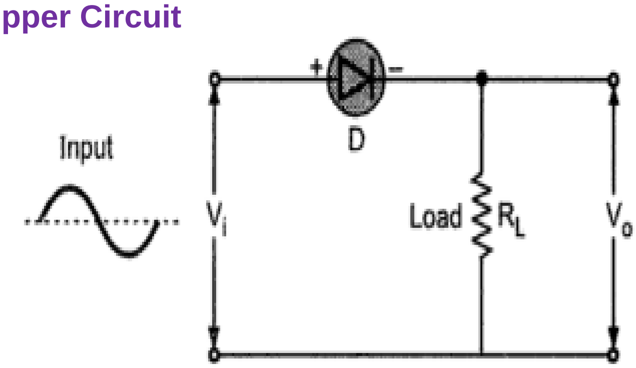


Fig. 2.14 Negative series clipper

2.7.3.1 Operation:

- Consider a circuit shown in the Fig. 2.14 where diode is connected in series with the load.
- For a positive half cycle, the diode D is forward biased and hence the voltage waveform across R_L looks like a positive half cycle of the input voltage.
- While for a negative half cycle, diode D is reverse biased and hence will not conduct at all. Hence there will not be any voltage available across resistance RL.
- Hence the negative half cycle of input voltage gets clipped off.
- The input waveform and the corresponding output voltage waveform is shown in the Fig. 2.15.

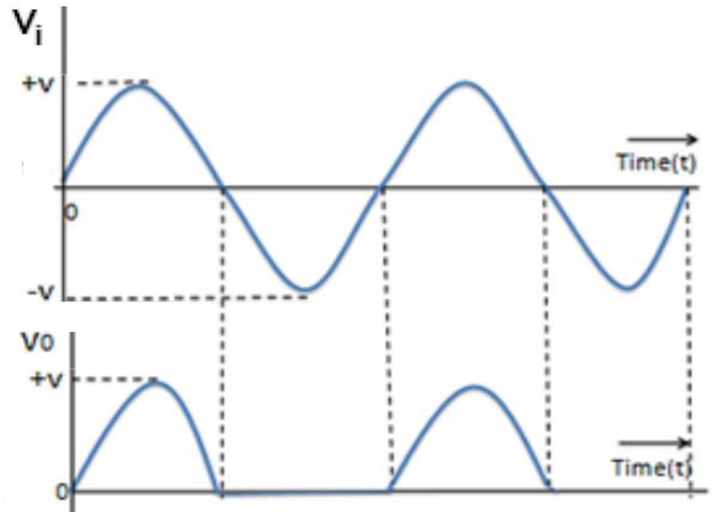


Fig.2.15 Input and Output waveforms

2.7.4 Series Positive Clipper Circuit

- It is similar to series negative clipper, a circuit which clipps off positive part of the input can be obtained.
- The positive series clipper can be obtained by changing the direction of diode in negative clipper circuit.

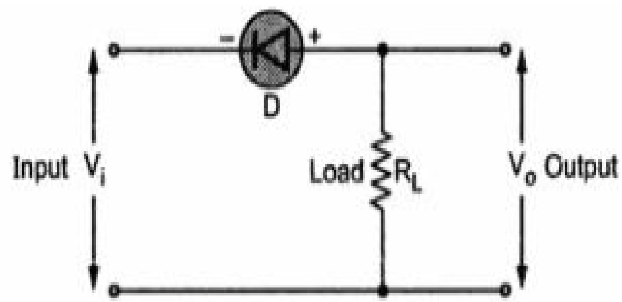


Fig. 2.16 Positive series clipper

- The Fig. 2.16 shows positive series clipper circuit in which diode direction is opposite to that in negative series clipper circuit.

2.7.4.1 Operation:

- For positive half cycle of input, $V_i > 0$ and diode is reverse biased. Hence it acts as open circuit and V_o=0.

- For negative half cycle, when $V_i < 0$, the diode conducts. The output voltage V_o available is same as input voltage.
- Thus, entire negative half cycle of input is available at the output.
- The output waveforms for sinusoidal input waveform is shown in the Fig. 2.17.

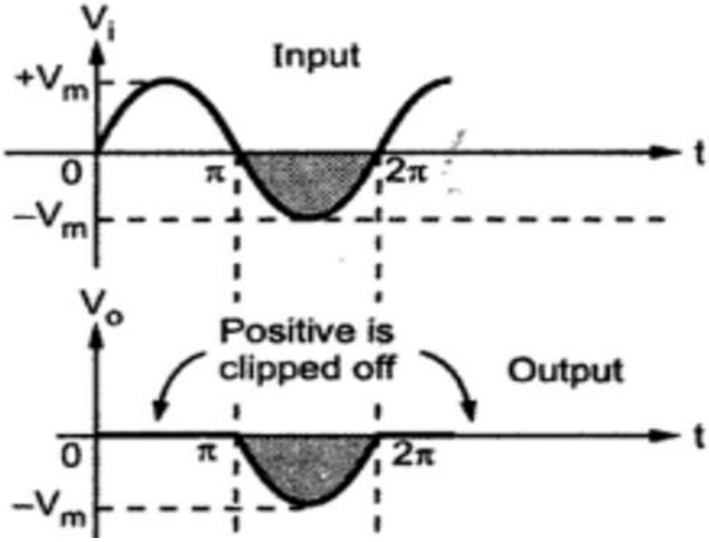


Fig. 2.17 Waveforms of series positive clipper

2.7.5 Parallel (or) Shunt Clippers

- In a parallel clipper circuit, the diode is connected across the load terminals.
- It can be used to clip or limit the positive or negative part of the input signal, as per the requirement.

2.7.5.1 Types of Parallel (or) Shunt clipper

- Shunt Negative Clipper
- Shunt Positive Clipper
- Shunt Clipping Above Reference Voltage V_R
- Shunt Clipping Below Reference Voltage V_R

2.7.6 Parallel Clipper with Positive Clipping

- The Fig. 2.18 shows the basic parallel clipper circuit in which diode D is connected across the load resistance R_L.
- The resistance R1 is current controlling resistance.

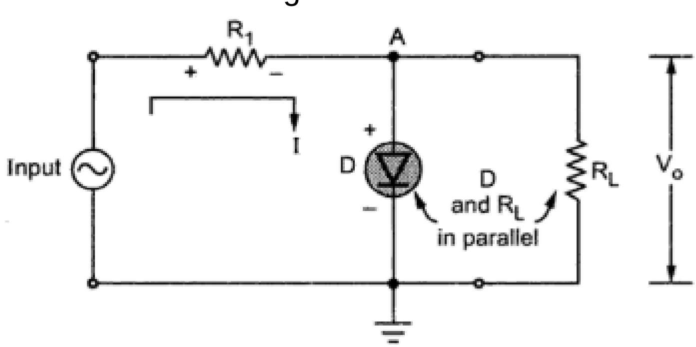


Fig. 2.18 Basic parallel clipper

2.7.6.1 Operation:

- During positive half cycle of the input V_i, the diode D becomes forward biased and remains forward biased for the entire half cycle of the input.
- As R_L is in parallel with diode no current flows through it and output voltage V_o = 0V as shown in the Fig. 2.19.

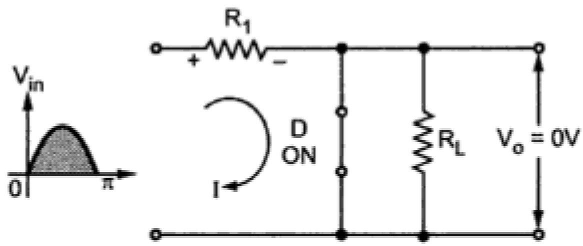


Fig. 2.19 Operation during positive half cycle

- During negative half cycle of input, the diode is reverse biased and acts as open circuit.
- The entire current flows through R_L as shown in the Fig. 2.20.

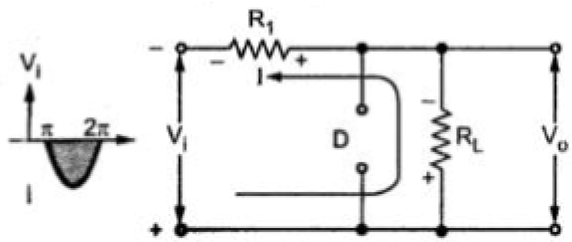


Fig. 2.20 Operation during negative half cycle

- Hence using potential divider rule $V_o = \dfrac{V_i R_L}{R_L + R_1}$.
- Thus, $V_o \propto V_i$ and there exists straight line relationship between the input and output voltage.
- The waveforms are shown in the Fig. 2.21.

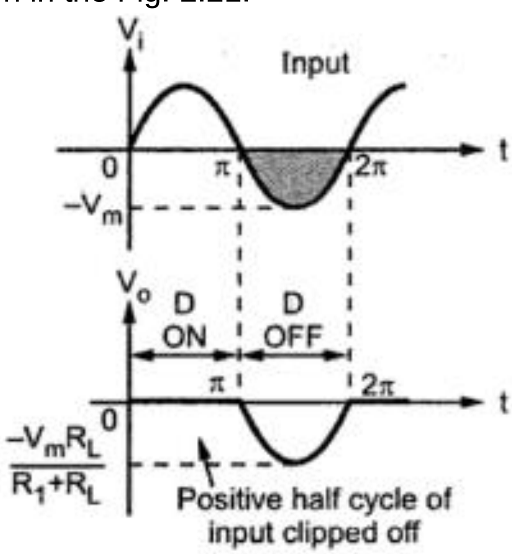


Fig. 2.21 Waveforms for parallel clipper

2.7.7 Clipping at two independent levels

- This type of clipper combines a parallel negative clipper with negative bias (D_2 and V_{R2}) and a parallel positive clipper with positive bias (D_1 and V_{R1}).
- Such a clipper circuit can clip at two independent levels depending upon the bias voltages.
- Fig. 2.22 shows the circuit of a clipping at two independent levels.

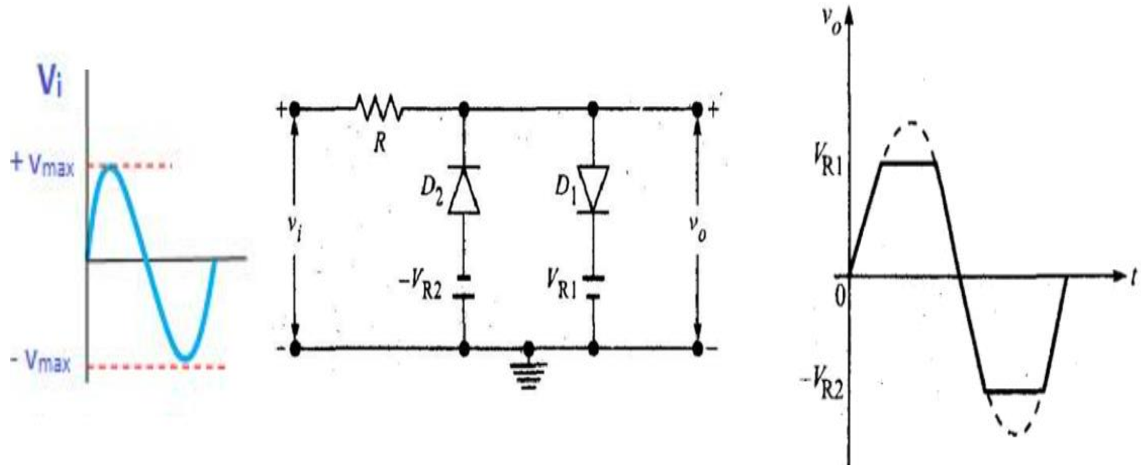


Fig. 2.22 Circuit diagram of a clipping at two independent levels

2.7.7.1 Operation:

- During the positive half cycle of the Input signal, the diode D_1 is forward biased, while diode D_2 is reverse biased.
- Therefore, the diode D_1 will conduct and will acts as a short circuit and the diode D_2 will not conduct and will acts as an open circuit.
- So, the voltage V_{R1} appears across output terminals.
- During the negative half cycle of the Input signal, the diode D_2 acts as a short circuit while the diode D_1 as an open circuit.
- So, the voltage V_{R2} appears across output terminals.
- It may be noted that the clipping levels of the circuit be varied by changing the values of V_{R1} and V_{R2}.
- If the values of V_{R1} and V_{R2} are equal, the circuit will clip both the positive and negative half cycles at the same voltage level.
- In short, the operation of a clipping at two independent levels is given below.

Input v_i	*Output* v_o	*Diode status*
$v_i > V_{R1}$	$v_o = V_{R1}$	D_1 ON, D_2 OFF
$-V_{R2} < v_i < V_{R1}$	$v_o = v_i$	D_1 OFF, D_2 OFF
$v_i < -V_{R2}$	$v_o = -V_{R2}$	D_1 OFF, D_2 ON

2.8 Clamper Circuits

- The circuits which are used to add a d.c. level to the a.c. output signal is called as Clamper circuits.
- The capacitor, diode and resistance are the three basic elements of a clamper circuit.
- The clamper circuits are also called d.c. restorer or d.c. inserter circuits.

2.8.1 Clamping Circuit Theorem

- Clamping Circuit theorem relates the area of the output waveform when diode conducts to the area of the output waveform when diode is OFF.
- It states that, under steady-state conditions, the ratio of area in forward direction A_f to that of reverse direction A_r of output voltage is equal to the ratio of diode forward resistance R_f to resistance R connected across diode.

$$\frac{A_f}{A_r} = \frac{R_f}{R}$$

2.8.2 Types of Clampers

- Depending upon whether the positive d.c. or negative d.c. shift is introduced in the output waveform, the clampers are classified as,

  a) Negative clamper

  b) Positive clamper

2.8.3 Negative Clamper

- A simple negative clamper which adds a negative level to the a.c. output is shown in the Fig. 2.23.
- It consists of a capacitor C, the ideal diode D and the load resistance R_L.

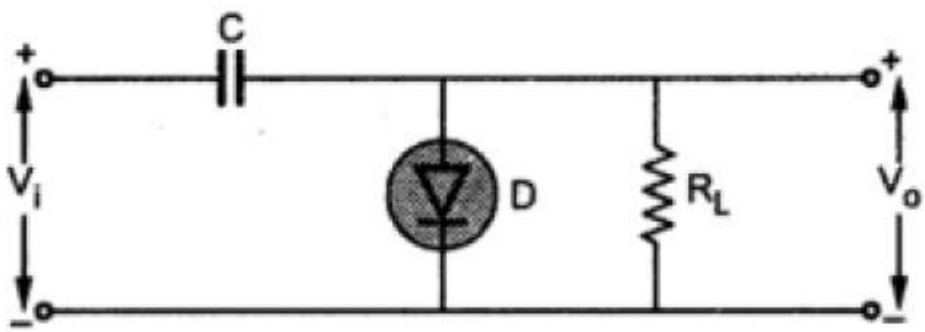


Fig. 2.23 Negative clamper

2.8.3.1 Operation:

- During the first quarter of positive cycle of the input voltage V_i, the capacitor gets charged through forward biased diode D upto the maximum value V_m of the input signal V_i.
- The capacitor charging is almost instantaneous, which is possible by selecting proper values of C and R_L in the circuit.

- The capacitor once charged to V_m, acts as a battery of voltage V_m, as shown in the Fig. 2.24.

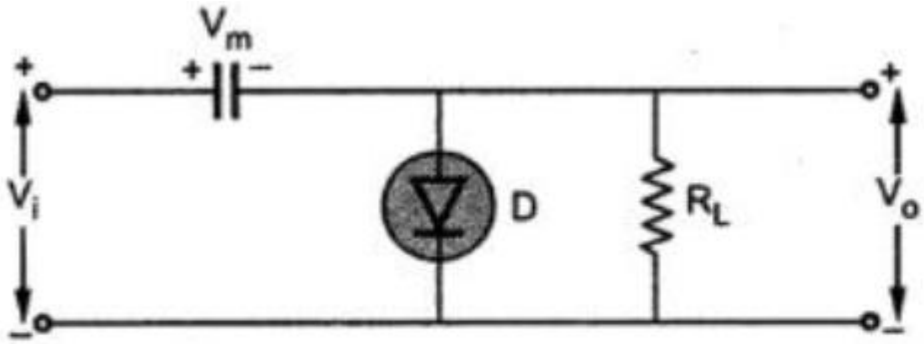


Fig. 2.24 Operation of Negative clamper during first quarter of positive cycle

- Thus, when D is ON, the output voltage V_o is zero.
- As input voltage decreases after attaining its maximum value V_m, the capacitor remains charged to V_m and the diode D becomes reverse biased.
- Due to large RC time constant the capacitor holds its entire charge and capacitor voltage remains as $V_c = V_m$ as shown in the Fig. 2.25.

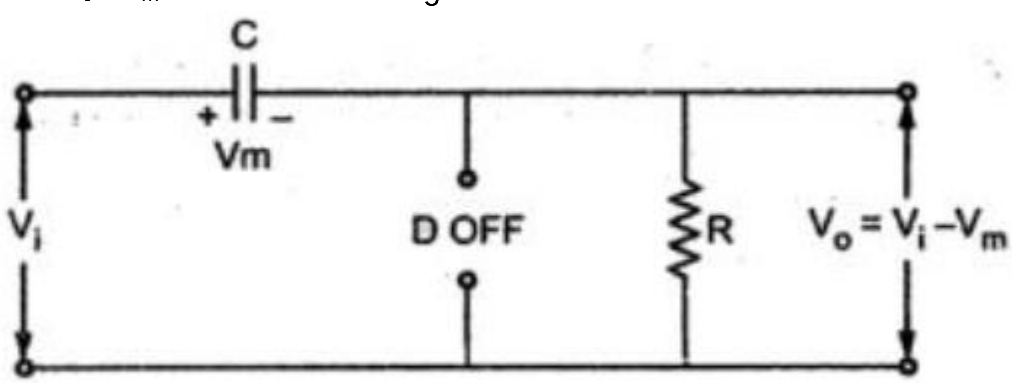


Fig.2.25 Operation of Negative clamper during negative half cycle

- In the negative half cycle of V_i, the diode will remain reverse biased.
- The capacitor starts discharging through the resistance R_L.
- As the time constant R_LC is very large, it can be approximated that the capacitor holds all its charge and remains charged to V_m, during this period also.
- Hence, we can write again that,

$$V_o = V_i - V_c = V_i - V_m \quad \text{for negative half cycle}$$

$$V_o = -V_m, \quad \text{for } V_i = 0$$

$$V_o = 0, \quad \text{for } V_i = V_m$$

$$V_o = -2V_m, \quad \text{for } V_i = -V_m$$

2.8.3.2 Waveforms:

- Assuming ideal diode, the input and output waveforms are shown in the Fig. 2.26.
- The peak to peak amplitude of the input is 2 V_m.
- Similarly, the peak-to-peak amplitude of the output is also 2 V_m.
- Thus, the total swing of the output is always same as the total swing of the input, for a clamper circuit.

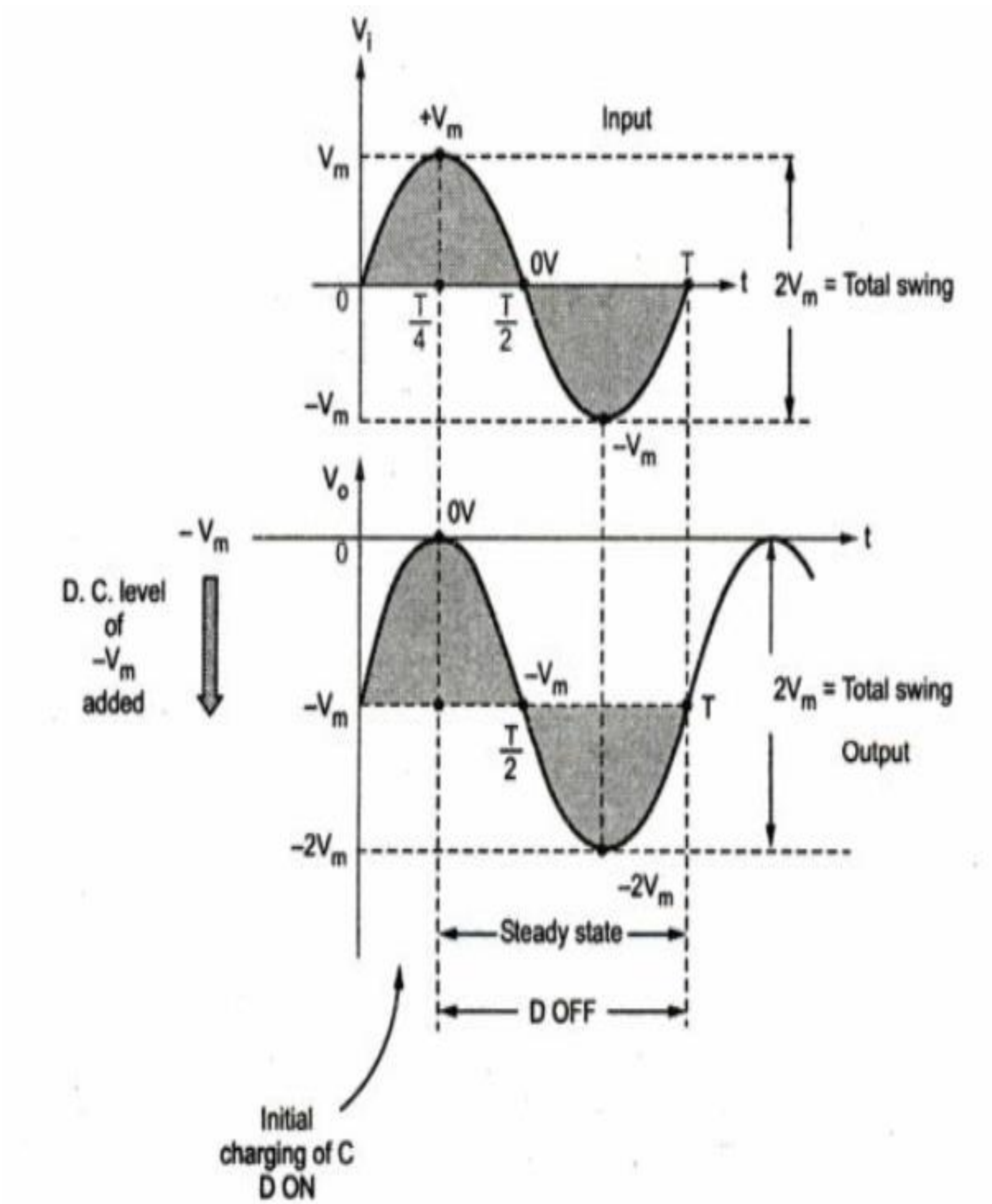


Fig. 2.26 Negative clamper waveforms

2.8.4 Positive Clamper

- By changing the orientation of the diode in the negative clamper, the positive clamper circuit can be achieved.
- The circuit is shown in the Fig. 2.27.

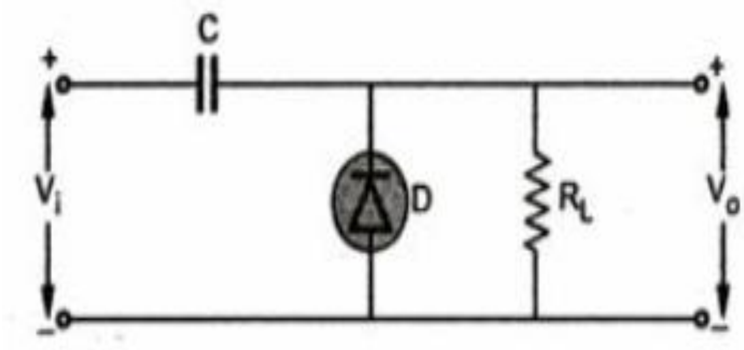


Fig. 2.27 Positive clamper

2.8.4.1 Operation:

- During the first quarter of negative half cycle of the input voltage V_i, diode D gets forward biased and almost instantaneously capacitor gets charged equal to the maximum value V_m of the input signal V_i with the polarities as shown in the Fig. 2.28.

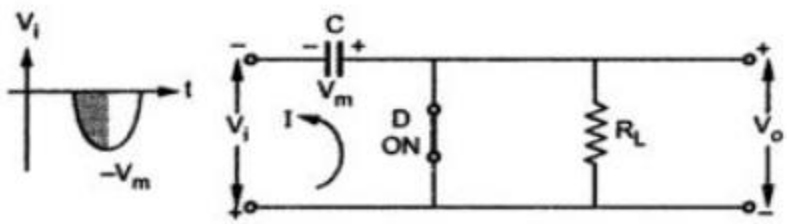


Fig. 2.28 Operation of Positive clamper during first quarter of negative half cycle

- The capacitor once charged to V_m, acts as a battery of voltage V_m with the polarities as shown in the Fig. 2.28.
- This is because RC time constant is very large hence capacitor holds its entire charge all the time.
- Thus when $V_i = V_m$, the output voltage V_o is 2 V_m.
- In the positive half cycle, the diode D is reverse biased.
- The capacitor starts discharging through R_L.
- But due to large time constant, it hardly gets discharged during positive half cycle of V_i. This is shown in the Fig. 2.29.

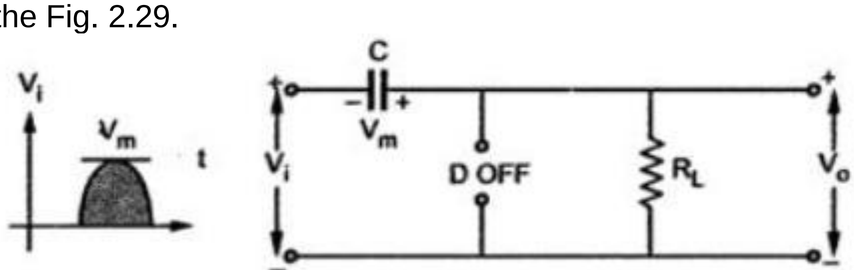


Fig. 2.29 Operation of Positive clamper during Positive half cycle

- Hence, $V_o = V_i + V_m$

$$V_o = V_m, \quad \text{for } V_i = 0$$
$$V_o = 2\,V_m, \quad \text{for } V_i = V_m$$
$$V_o = 0, \quad \text{for } V_i = -V_m$$

2.8.4.2 Waveforms:

- Assuming ideal diode, the input and output waveforms are shown in the fig. 2.30.

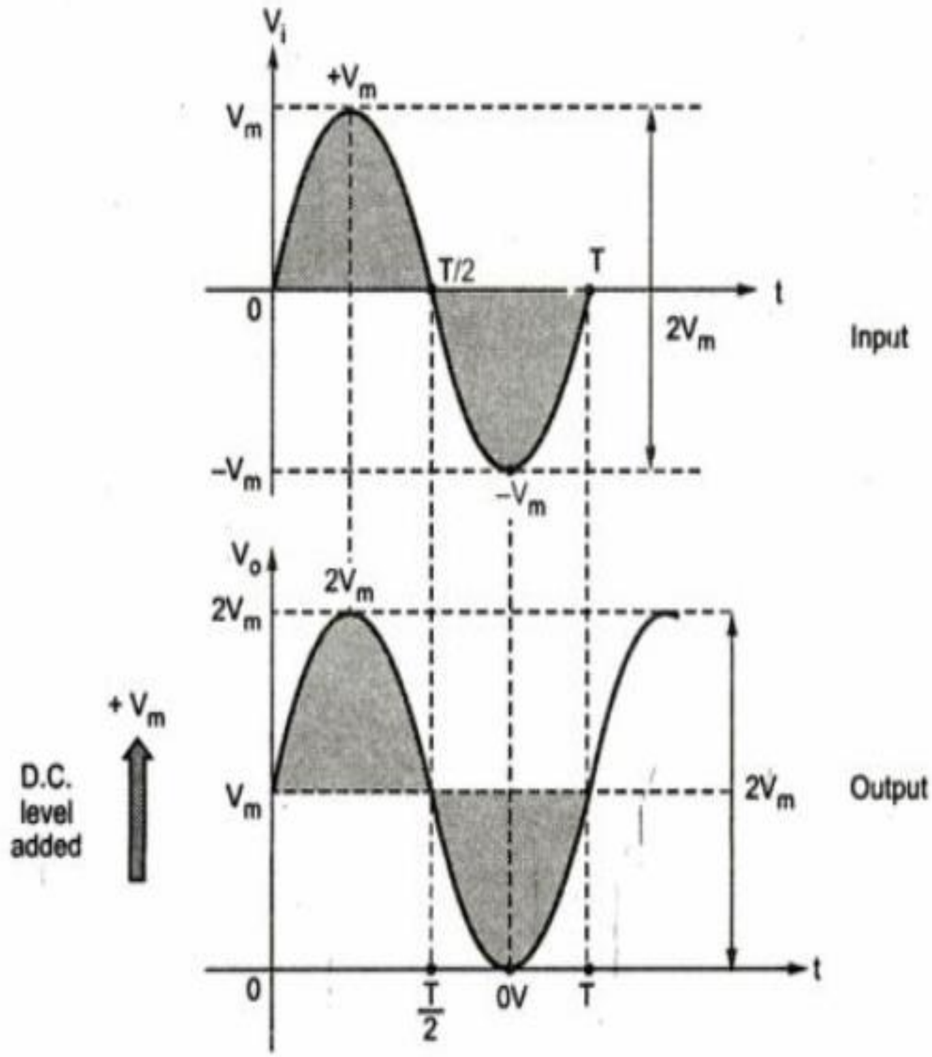


Fig. 2.30 Positive clamper waveforms

UNIT III Bipolar Junction Transistor (BJT):
Principle of Operation, Common Emitter, Common Base and Common Collector Configurations, Transistor as a switch, switching times.

3.1 Introduction

- Transistor is a three terminal device namely Base, emitter and collector, can be operated in three configurations common base, common emitter and common collector.
- According to configuration it can be used for voltage as well as current amplification.
- The input signal of small amplitude is applied at the base to get the magnified output signal at the collector.
- The amplification in the transistor is achieved by passing input current signal from a region of low resistance to a region of high resistance.
- This concept of transfer of resistance has given the name TRANSfer-resISTOR (TRANSISTOR).

3.1.1 Types of transistors

- There are two types of transistors namely unipolar junction transistor and bipolar junction transistor.
- In unipolar transistor the current conduction is only due to one type of carriers, majority carriers.
- In bipolar transistor the current conduction is due to both the types of charge carriers, namely holes and electrons. Hence this is called Bipolar Junction Transistor (BJT).
- In BJT output current is controlled by input current and hence it is a current controlled device.

3.1.2 Types of BJT

- npn type
- pnp type

3.1.3 Advantages of BJT

- Low operating voltage.
- Higher efficiency.
- Small size and ruggedness.
- Does not require any filament power.

3.2 Construction of Bipolar Junction Transistor (BJT)

- When a transistor is formed by sandwiching a single p-region between two n-regions, as shown in the Fig. 3.1 (a), it is an n-p-n type transistor.

- The p-n-p type transistor has a single n-region between two p-regions, as shown in Fig. 3.1 (b).

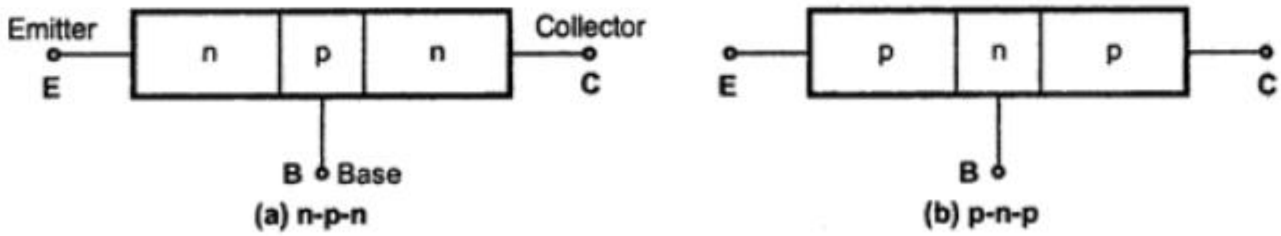


Fig. 3.1 Bipolar Junction transistor construction

- The middle region of each transistor type is called the base of the transistor. This region is very thin and lightly doped.
- The remaining two regions are called emitter and collector. The emitter is heavily doped and collector is moderately doped.
- The collector region area is slightly more than that of emitter.

3.2.1 Biased Transistor

- In order to operate transistor properly as an amplifier, it is necessary to correctly bias the two p-n junctions with external voltages.
- Depending upon external bias voltage polarities used, the transistor works in one of the three regions, Active region, Cut-off region and Saturation region

Region	Emitter base junction	Collector base junction
Active	Forward biased	Reverse biased
Cut-off	Reverse biased	Reverse biased
Saturation	Forward biased	Forward biased

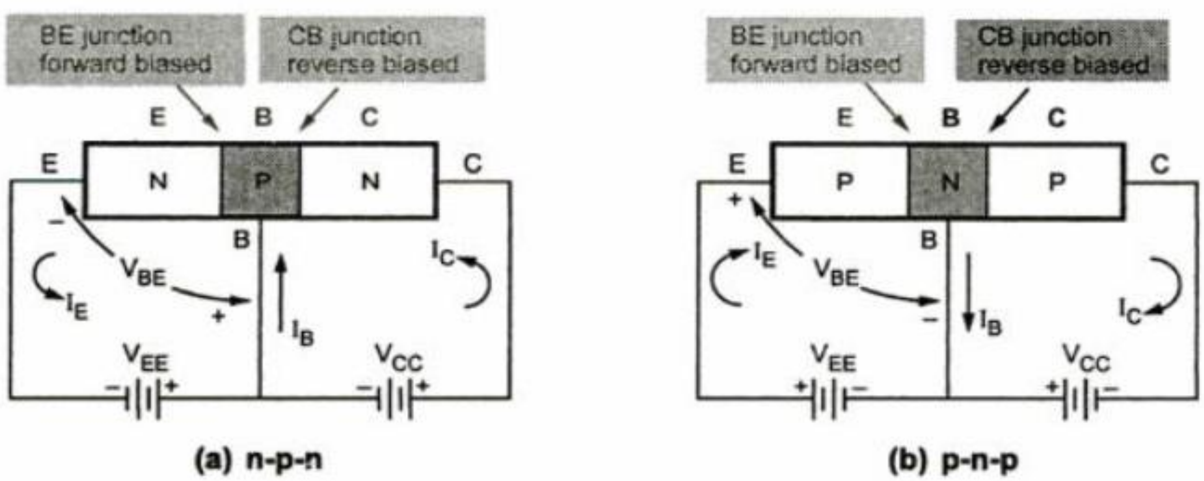


Fig. 3.2 Transistor forward-reverse bias

- To bias the transistor in its active region, the emitter base junction is forward biased while the collector base junction is reverse biased as shown in Fig. 3.2.

- The externally applied bias voltages are V_{EE} and V_{CC}, as shown in Fig. 3.2, which bias the transistor in its active region.

3.3 Operation of BJT

- The operation of the n-p-n is the same as for the p-n-p except that the roles of the electrons and holes, the bias voltage polarities, and the current directions are all reversed.

3.3.1 Operation of npn transistor

- The base to emitter junction is forward biased by the d.c source V_{EE}. Thus, the depletion region at this junction is reduced.
- The collector to base junction is reverse biased, increasing depletion region at collector to base junction as shown in Fig. 3.3.

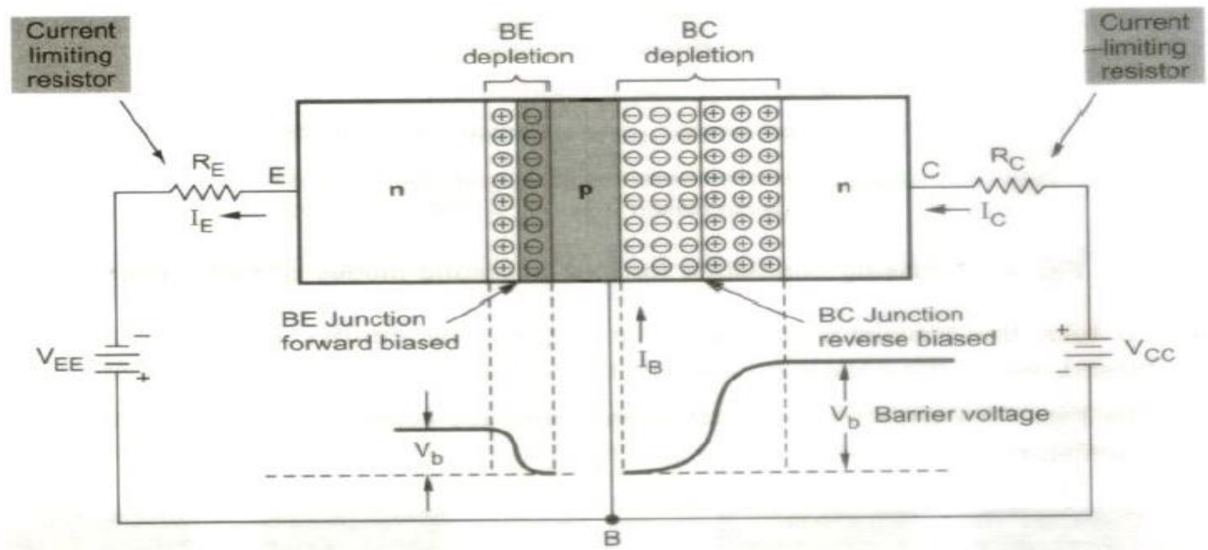


Fig. 3.3 Operation of npn transistor

- The forward biased EB junction causes the electrons in the n-type emitter to flow towards the base. This constitutes the emitter current I_E.
- *As* these electrons flow through the p-type base, they tend to combine with holes in p-region (base).
- Due to light doping, very few of the electrons injected into the base from the emitter recombine with holes to constitute base current, I_B and the remaining large number of electrons cross the base region and move through the collector region to the positive terminal of the external d.c source.
- This constitutes collector current I_C. Thus, the electron flow constitutes the dominant current in an n-p-n transistor.
- Since, most of the electrons from emitter flow in the collector circuit and very few combine with holes in the base.
- Thus, the collector current is larger than the base current.

$$I_E = I_B + I_C$$

3.3.2 Operation of pnp transistor

- The p-n-p transistor has its bias voltages V_{EE} and V_{CC} reversed from those in the n-p-n transistor as shown in Fig. 3.4.

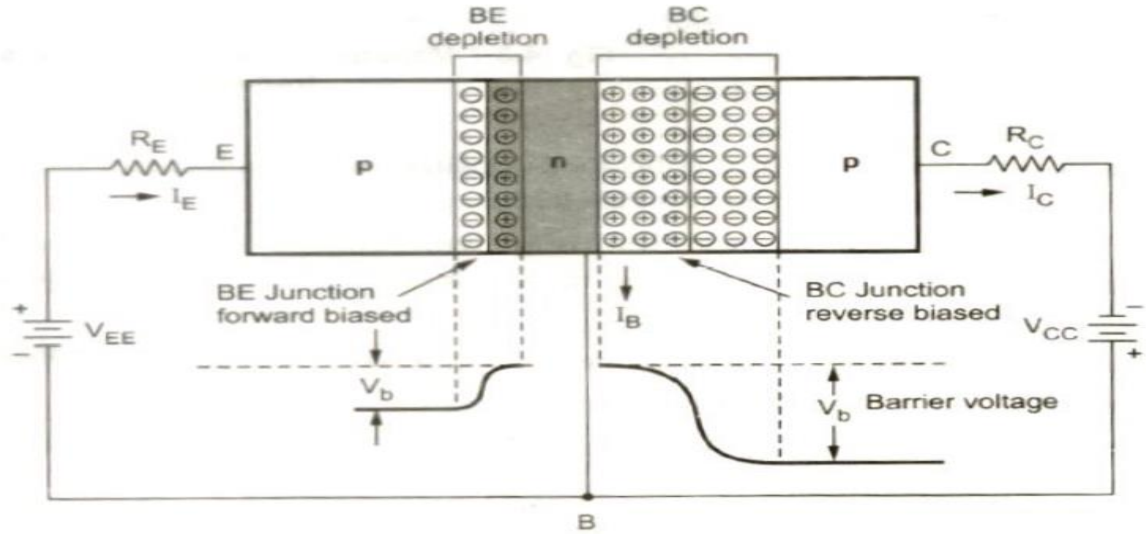


Fig. 3.4 Operation of pnp transistor

- This is necessary to forward bias the emitter base junction and reverse bias the collector base junction.
- The forward biased EB junction causes the holes in the p-type emitter to flow towards the base. This constitutes the emitter current I_E.
- As these holes flow through the n-type base, they tend to combine with electrons in n-region (base).
- As the base is very thin and lightly doped, very few of the holes injected into the base from the emitter recombine with electrons to constitute base current, I_B.
- The remaining large number of holes crosses the depletion region and move through the collector region to the negative terminal of the external d.c source.
- This constitutes collector current I_C.
- Thus, the hole flow constitutes the dominant current in an p-n-p transistor.
- Since, most of the holes from emitter flow in the collector circuit and very few combine with electrons in the base.
- Thus, the collector current is larger than the base current.

$$I_E=I_B+I_C$$

3.4 Transistor Circuit Configurations

- A transistor has three terminals or leads namely emitter (E), base (B) and collector (C).
- However, when a transistor is connected in a circuit, we require four terminals i.e., two terminals for input and two for output.
- This difficulty is overcome by using one of the three terminals as a common terminal to the input and output terminals.

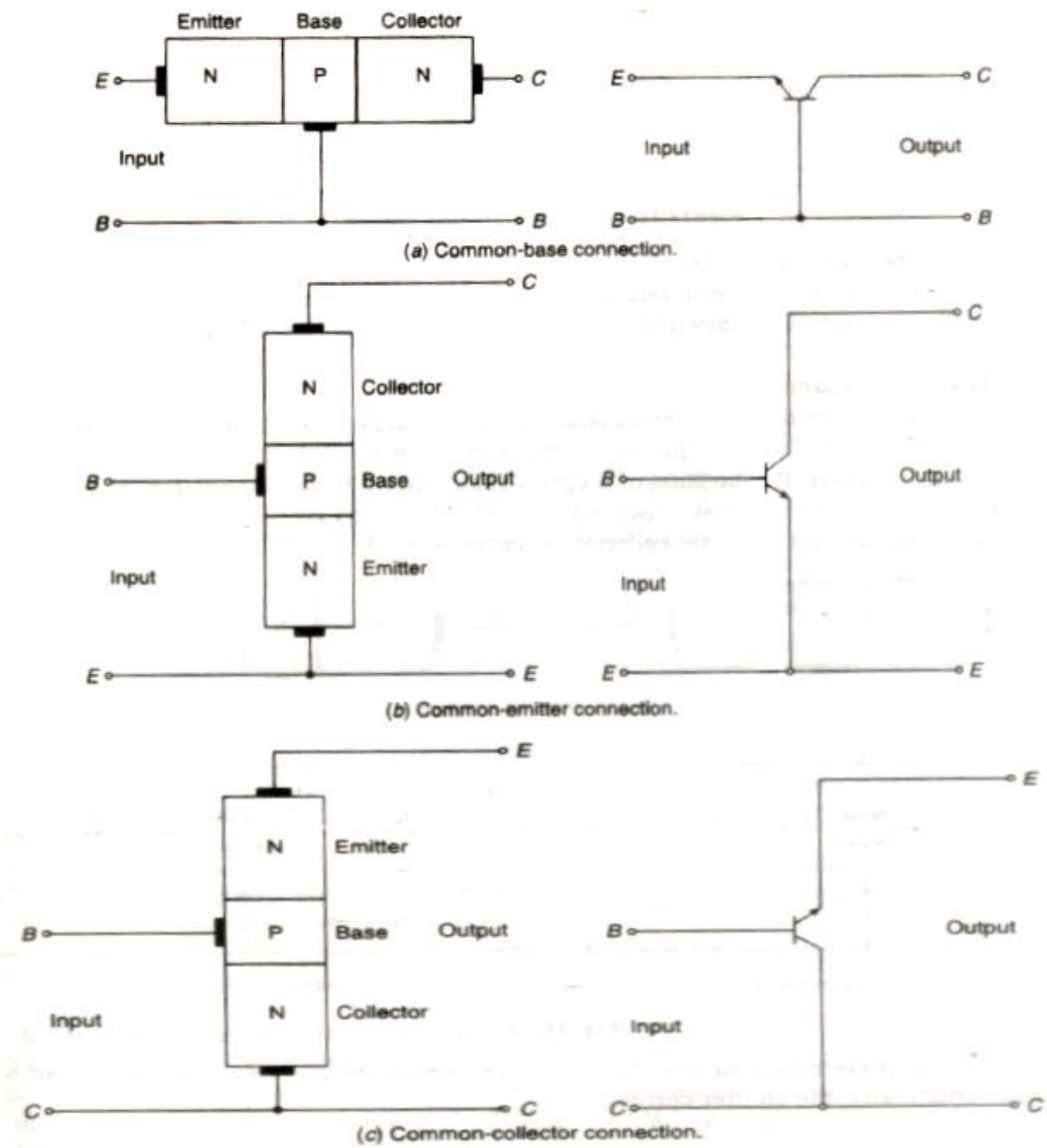


Fig. 3.5 Transistor Circuit Configurations

- Depending upon the terminals, which are used as a common terminal, the transistors can be connected in the following three different connections or configurations.
  - Common Base (CB) connection.
  - Common Emitter (CE) connection
  - Common Collector (CC) connection

Note:

- Regardless of circuit configuration, the base emitter junction is always forward biased while the collector base is always reverse biased to operate the transistor in active region.

3.5 Common Base Configuration

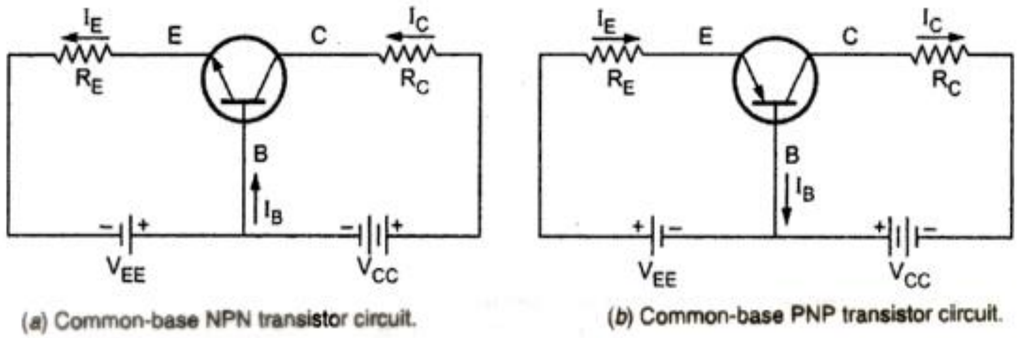


Fig. 3.6 Common Base Configuration

- Consider a transistor (either NPN or PNP) in a common base configuration as shown in Fig. 3.6 (a) or (b).
- Here the emitter current is the input current and collector current is the output current.
- The ratio of the transistor output current to the input current is called current gain of a transistor.
- Since the input current and output current may be either direct current or alternating current.
- Therefore, we define two types of current gains namely d.c current gain and a.c current gain.

3.5.1 Common base d.c current gain (α)

- It is defined as the ratio of collector current (I_C) to emitter current (I_E) and is usually designated by α, α_{DC} or h_{FB}
- Mathematically, the common base d.c current gain,

$$\boxed{\alpha = \frac{I_C}{I_E}}$$

- In a transistor, the collector current is always less than the emitter current.
- Therefore, current gain of a transistor in common base configuration is always less than unity.

3.5.2 Common base a.c current gain (α_0)

- It is defined as the ratio of small change in collector current (ΔI_C) to a small change in emitter current (ΔI_E) for a constant collector to base voltage (V_{CB}).
- It is designated by α_0, α_{ac} or h_{fb}.
- Mathematically, the common base a.c current gain

$$\boxed{\alpha_0 = \frac{\Delta I_C}{\Delta I_E}}$$

3.5.3 Current relations in Common Base configuration

- Hence the total collector current,

$$I_C = \alpha I_E + I_{CO}$$

Example *In a common-base connection, the emitter current is 6.28 mA and the collector current is 6.20 mA. Determine the common-base d.c. current gain.*

Solution. Given: $I_E = 6.28$ mA and $I_C = 6.20$ mA.

We know that common-base d.c. current gain,

$$\alpha = \frac{I_C}{I_E} = \frac{6.20}{6.28} = 0.987 \text{ Ans.}$$

Example *The common-base d.c. current gain of a transistor is 0.967. If the emitter current is 10 mA, what is the value of base current?*

Solution. Given: $\alpha = 0.967$ and $I_E = 10$ mA.

We know that common-base d.c. current gain (α),

$$0.967 = \frac{I_C}{I_E} = \frac{I_C}{10}$$

$$\therefore \quad I_C = 0.967 \times 10 = 9.67 \text{ mA}$$

We also know that emitter current (I_E),

$$10 = I_B + I_C = I_B + 9.67$$

$$\therefore \quad I_B = 10 - 9.67 = 0.33 \text{ mA Ans.}$$

3.5.4 Input and Output Characteristics of a Transistor in a Common Base Configuration

- Following are two important characteristics of a transistor in a common base (CB) configuration.
  - **Input characteristics**
    - These curves give the relationship between the emitter current (I_E) and the emitter to base voltage (V_{EB}) for a constant collector to base voltage (V_{CB}).
  - **Output characteristics.**
    - These curves give the relationship between the collector current (I_C) and the collector to base voltage (V_{CB}) for a constant emitter current (I_E).

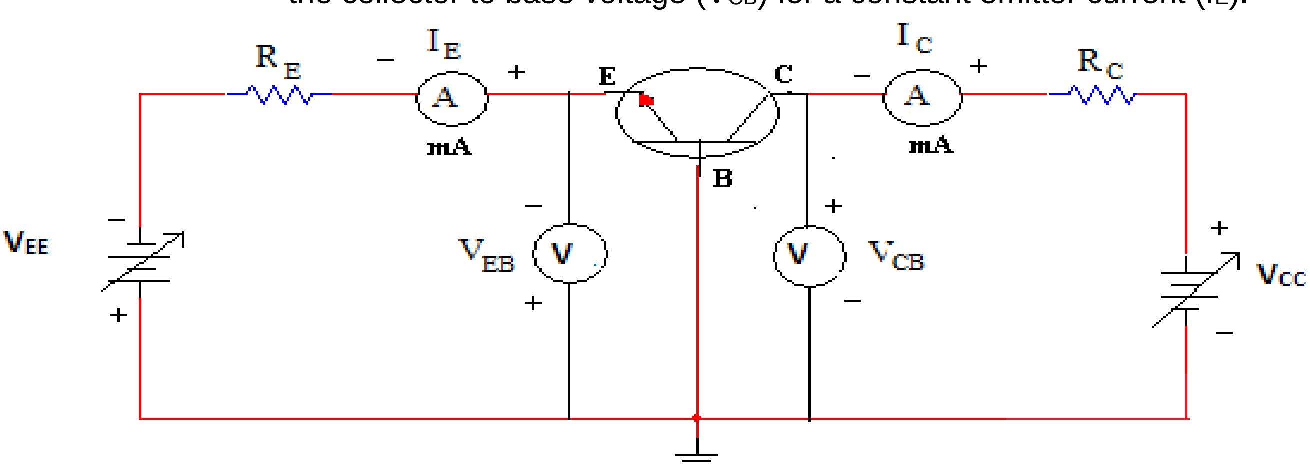


Fig. 3.7 Circuit arrangement for determining common base transistor characteristics

- In this circuit, the NPN transistor is connected in a common-base configuration.

- The d.c milli ammeters and d.c voltmeters are connected in the emitter and collector circuits of a transistor to measure the currents and voltages.

3.5.4.1 Input Characteristics of a Transistor in Common Base Configuration

- These curves may be obtained by using the circuit arrangement as shown in Fig. 3.7.
- First of all, vary the collector to base voltage (V_{CB}) to 1 V.

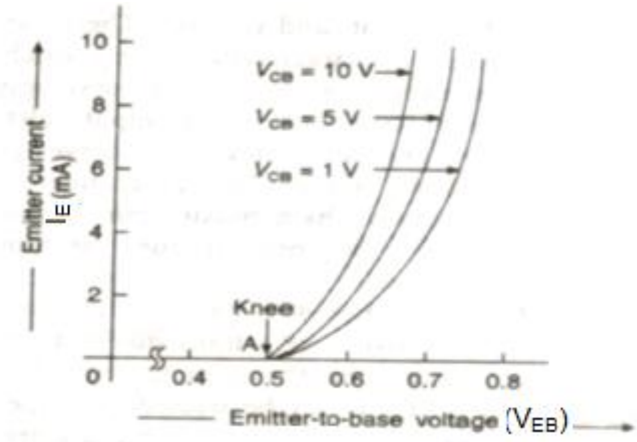


Fig. 3.8 Input characteristics of a common base transistor

- Then increase the emitter to base voltage (V_{EB}) in small suitable steps (i e., of the order of 0.1 V) and record the corresponding values of emitter current (I_E) at each step.
- Now, if we plot a graph with emitter to base voltage (V_{EB}) along the horizontal axis and the emitter current (I_E) along the vertical axis, we shall obtain a curve marked V_{CB} = 1 V as shown in Fig.3.8.
- A similar procedure may be used to obtain curves at different collector to base voltage 5 V and 10 V as shown in the figure 3.8.
- From the input characteristics the following important points are derived.
  - Up to region OA, the emitter current is negligibly small.
  - Beyond the point A, for a fixed collector to base voltage the emitter current (I_E) increases rapidly with a small increase in emitter to base voltage (V_{EB}).
  - The input characteristic may be used to determine the value of a.c input resistance.
  - Its value at any point on the curve is given by the ratio of a change in emitter to base voltage (ΔV_{EB}) to the resulting change in emitter current (ΔI_E) for a constant collector to base voltage (V_{CB}).
  - Mathematically the a.c input resistance,

$$\boxed{R_i = \frac{\Delta V_{EB}}{\Delta I_E}}$$

3.5.4.1.1 Base Width Modulation (or) Early Effect

- When reverse bias voltage V_{CB} increases, the width of depletion region also increases, which reduces the electrical base width.

3.5.4.2 Output Characteristics of a Transistor in Common Base Configuration

- These characteristics may be obtained by using the circuit shown in Fig. 3.7.

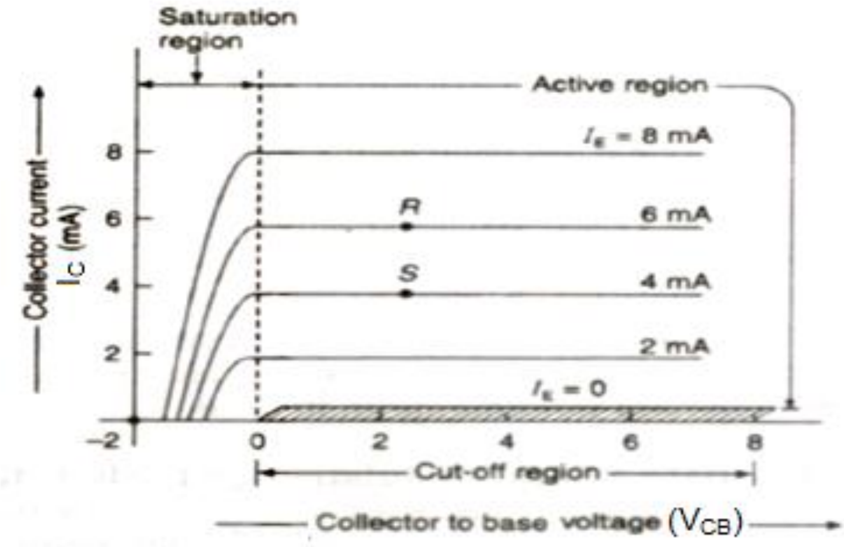


Fig. 3.9 Output characteristics of a common base transistor

- First of all, vary the emitter to base voltage (V_{EB}) to get a suitable value of emitter current (I_E) say 2 mA.
- Keeping the emitter current (I_E)constant, we increase the collector to base voltage (V_{CB}) from zero in a number of suitable steps and record the corresponding values of the collector current (I_C) at each Step.
- If we plot a graph with collector to base voltage (V_{CB}) along the horizontal axis and the collector current (I_C) along the vertical axis, we shall obtain a curve marked I_E = 2 mA as shown in Fig. 3.9.
- A similar procedure may be used to obtain the characteristics at different values of emitter current *i.e.,* I_E = 4, 6, and 8 mA.
- From the output characteristics the following important points are derived.
  - The curve may be divided into three important regions namely saturation region, active region and cut off region.

  Saturation Region

    - The saturation region is the region to the left of the vertical dashed line.
    - It may be noted that in this region, collector to base voltage (V_{CB}) is negative for a NPN transistor.
    - In this region, a small change in V_{CB} results in a large value of collector current.

  Active Region

    - The active region is the region between the vertical dashed line and the horizontal axis.
    - In the active region, the collector current is constant and is equal to the emitter current.

Cut off Region

- ➢ The cut off region is the region along the horizontal axis as shown by a shaded region in the figure. It corresponds to the curve marked $I_E = 0$.
- ➢ The collector current flows even when the collector to base voltage (V_{CB}) is zero.
- ➢ A small collector current flows even when emitter current (I_E) is zero.

- The collector current is practically independent of collector to base voltage (V_{CB}) in the active region.
- The output characteristic may be used to determine the value of a.c. output resistance.
- Its value at any point is given by the ratio of a change in collector to base voltage (ΔV_{CB}) to the resulting change in collector current (ΔI_C) for a constant emitter current (I_E)
- Mathematically, the a.c output resistance,

$$\boxed{R_o = \frac{\Delta V_{CB}}{\Delta I_C}}$$

3.6 Common Emitter Configuration

- Consider a transistor (either NPN or PNP) in a common emitter configuration as shown in Figure 3.10 (a) and (b).

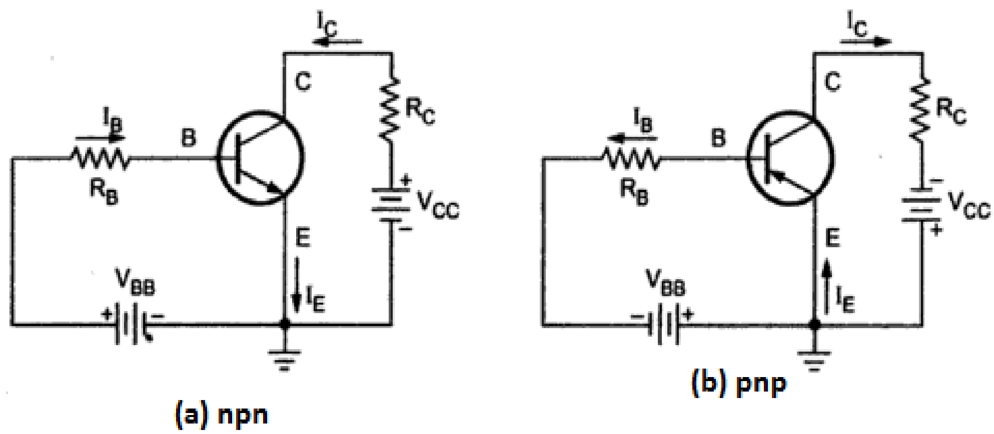


Fig. 3.10 Common Emitter Configuration

- Here, the base current is the input current and the collector current is the output current.
- The current gain is the ratio of collector current to the base current.
- Since the base current and collector current may be direct or alternating current.
- Therefore, we define two types of current gains namely d.c current gain and a.c current gains.

3.6.1 Common emitter d.c current gain (β)

- It is defined as the ratio of collector current (I_C) to base current (I_B) and is usually designated by β, β_{DC} or h_{FE}
- Mathematically, the common base d.c current gain,

$$\boxed{\beta = \frac{I_C}{I_B}}$$

- Collector current of a transistor is much larger than the base current.
- Therefore, current gain β is always greater than unity.

3.6.2 Common emitter a.c current gain (β_0)

- It is defined as the ratio of small change in collector current (ΔI_C) to a small change in base current (ΔI_B) for a constant collector to emitter voltage (V_{CE}).
- It is designated by β, β_{ac} or h_{fe}.
- Mathematically, the common emitter a.c current gain

$$\boxed{\beta_0 = \frac{\Delta I_C}{\Delta I_B}}$$

3.6.3 Relation between current gain α and β

- We know that emitter current (I_E) of a transistor is the sum of its base current (I_B) and collector current (I_C).

$$I_E = I_B + I_C$$

- Dividing the above equation on both sides by I_C,

$$\frac{I_E}{I_C} = \frac{I_B}{I_C} + 1$$

- We have $I_C / I_E = \alpha$, $I_C / I_B = \beta$ and apply it in above equation

$$\frac{1}{\alpha} = \frac{1}{\beta} + 1 = \frac{1+\beta}{\beta}$$

$$\boxed{\alpha = \frac{\beta}{\beta + 1}}$$

- The above expression may be written as

$$\alpha(\beta + 1) = \beta$$

$$\alpha \cdot \beta + \alpha = \beta$$

$$\alpha = \beta - \alpha \cdot \beta$$

$$= \beta(1 - \alpha)$$

$$\boxed{\beta = \frac{\alpha}{1 - \alpha}}$$

3.6.4 Current relations in Common emitter configuration

- The total leakage current flowing through the transistor with base open is given by

$$I_{CEO} = I_{CO} + \beta . I_{CO} = (1+\beta)\, I_{CO}$$

- The total collector current in a transistor consists of the injected current (βI_B) and the leakage current (I_{CEO}).
- Thus, the total collector current is given by

$$\boxed{I_C = \beta I_B + I_{CEO} = \beta I_B + (1+\beta)\, I_{CO}}$$

Example *(a) A transistor has an α of 0.975. What is the value of β; (b) if β = 200, what is the value of α?*

Solution. Given: $\alpha = 0.975$ and $\beta = 200$

Value of β when α is 0.975

We know that

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.975}{1-0.975} = 39 \textbf{ Ans.}$$

Value of α when β is 200

We also know that

$$\alpha = \frac{\beta}{\beta+1} = \frac{200}{200+1} = 0.995 \textbf{ Ans.}$$

Example *A transistor has a typical β of 100. If the collector is 40 mA, what is the value of emitter current?*

Solution. Given: $\beta = 100$ and $I_C = 40$ mA.

We know that (β), $$100 = \frac{I_C}{I_B} = \frac{40}{I_B}$$

$$\therefore \quad I_B = 40/100 = 0.4 \text{ mA}$$

and the emitter current,

$$I_E = I_B + I_C = 0.4 + 40 = 40.4 \text{ mA } \textbf{Ans.}$$

3.6.5 Input and Output Characteristics of a Transistor in a Common Emitter Configuration

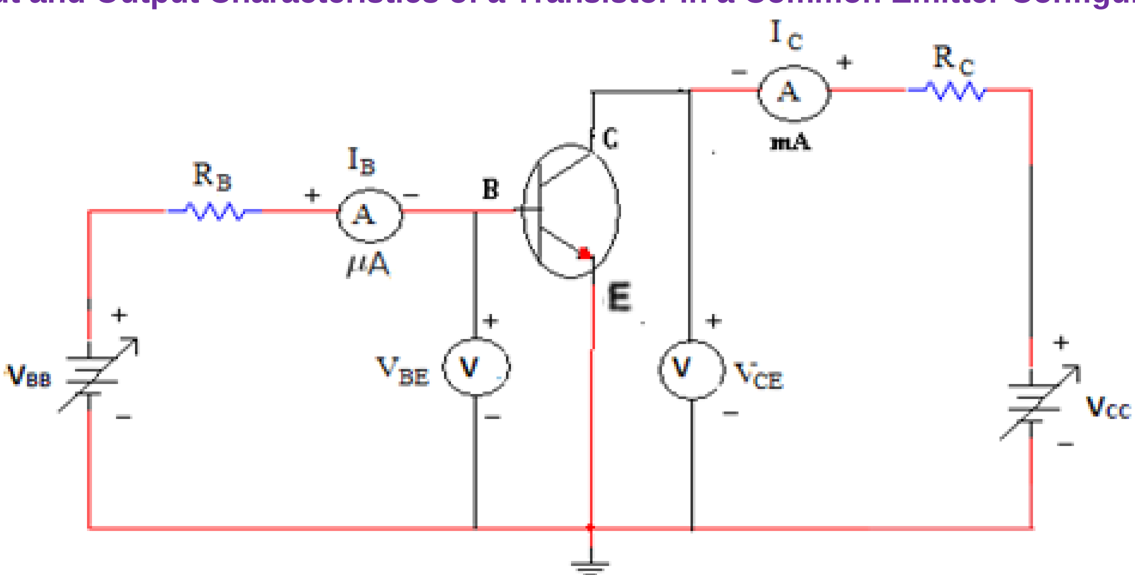


Fig. 3.11 Circuit arrangement for determining common base transistor characteristics

- Following are two important characteristics of a transistor in a common Emitter (CE) configuration.
  - ➢ **Input characteristics**
    - These curves give the relationship between the base current (I_B) and the base to emitter voltage (V_{BE}) for a constant collector to emitter voltage (V_{CE}).

➢ **Output characteristics**

- These curves give the relationship between the collector current (I_C) and the collector to emitter voltage (V_{CE}) for a constant base current (I_B).

- In this circuit, the NPN transistor is connected in a common emitter configuration.
- The d.c milli ammeters and d.c voltmeters are connected in the base and collector circuits of a transistor to measure the voltages and currents.

3.6.5.1 Input Characteristics of a Transistor in Common Emitter Configuration

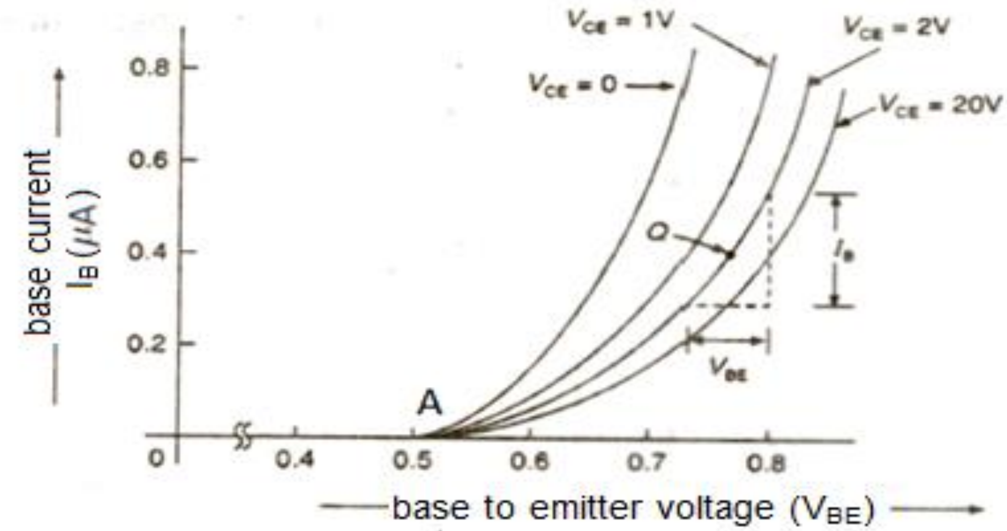


Fig. 3.12 Input characteristics of a common emitter transistor

- These curves may be obtained by using the circuit arrangement as shown in Fig. 3.11.
- First of all, vary the collector to emitter voltage (V_{CE}) to one volt.
- Then increase the base to emitter voltage (V_{BE}) in small suitable steps (i e., of the order of 0.1 V) and record the corresponding values of base current (I_B) at each step.
- Now, if we plot a graph with base to emitter voltage (V_{BE}) along the horizontal axis and the base current (I_B) along the vertical axis, we shall obtain a curve marked V_{CE} = 1 V as shown in Fig. 3.12.
- A similar procedure may be used to obtain curves at different collector to emitter voltage 2 V and 20V as shown in the figure 3.12.
- From the input characteristics the following important points are derived.
  - ➢ Up to region OA, the base current is negligibly small.
  - ➢ Beyond the point A, for a fixed collector to emitter voltage the base current (I_B) increases rapidly with a small increase in base to emitter voltage (V_{BE}).
  - ➢ The input characteristic may be used to determine the value of a.c input resistance.
  - ➢ Its value at any point on the curve is given by the ratio of a change in base to emitter voltage (ΔV_{BE}) to the resulting change in base current (ΔI_B) for a constant collector to emitter voltage (V_{CE}).
  - ➢ Mathematically the a.c input resistance,

$$\boxed{R_i = \frac{\Delta V_{BE}}{\Delta I_B}}$$

3.6.5.2 Output Characteristics of a Transistor in Common Emitter Configuration

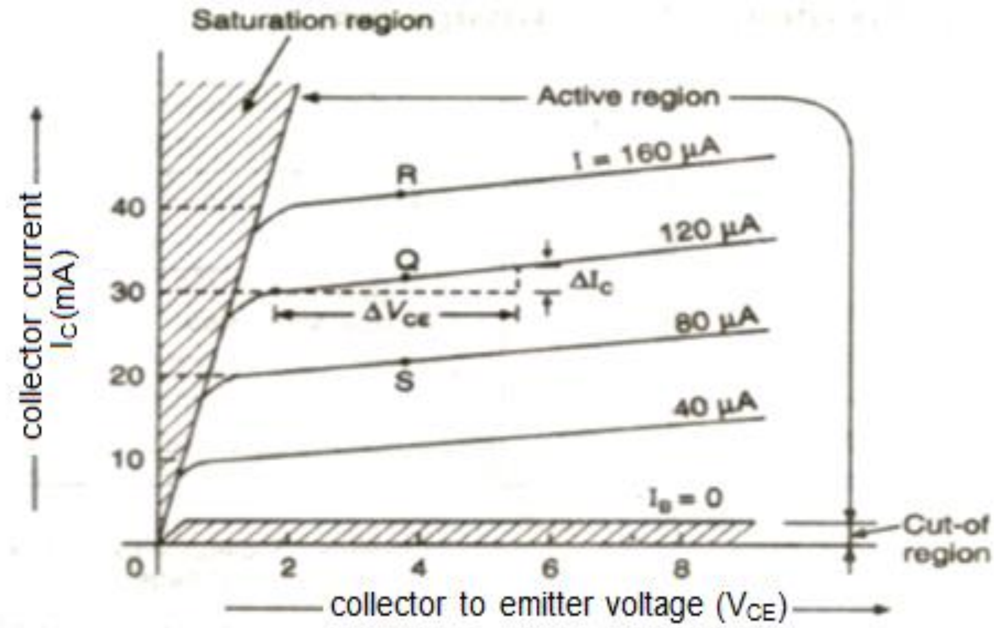


Fig. 3.13 Output characteristics of a common emitter transistor

- These characteristics may be obtained by using the circuit shown in Fig. 3.11.
- First of all, vary the base to emitter voltage (V_{BE}) to get a suitable value of base current (I_E) say 40 μA.
- Keeping the base current constant, we increase the collector to emitter voltage (V_{CE}) from zero in a number of suitable steps and record the corresponding values of the collector current (I_C) at each Step.
- If we plot a graph with collector to emitter voltage (V_{CE}) along the horizontal axis and the collector current (I_C) along the vertical axis, we shall obtain a curve marked I_B = 40 μA as shown in Fig. 3.13.
- A similar procedure may be used to obtain the characteristics at different values of emitter current *i.e.,* I_B = 80, 120 and 160 μA.
- From the output characteristics the following important points are derived.
    - ➢ The output characteristics may be divided into three important regions namely saturation region, active region and cut-off region.
    - ➢ The saturation and cut-off regions are shown by the shaded areas, while the active region is the region between the saturation and cut off region.
    - ➢ As the collector to emitter voltage (V_{CE}) is increased above zero, the collector current (I_C) increases rapidly to a saturation value, depending upon the value of base current.
    - ➢ When collector to emitter voltage (V_{CE}) is increased further, the collector current I_C slightly increases.

- The collector current (I_C) is zero, when the base current (I_B) is zero. Under this condition the transistor is said to be cut off.
- The characteristic may be used to determine the common emitter transistor a.c output resistance.
- Its value at any given operating point *Q* is given by the ratio of a change in collector to emitter voltage (ΔV_{CE}) to the resulting change in collector current (ΔI_C) for a constant base current.
- Mathematically, the a.c output resistance,

$$\boxed{R_o = \frac{\Delta V_{CE}}{\Delta I_C}}$$

3.7 Common Collector Configuration

- The Fig. 3.14 shows the common collector configuration.

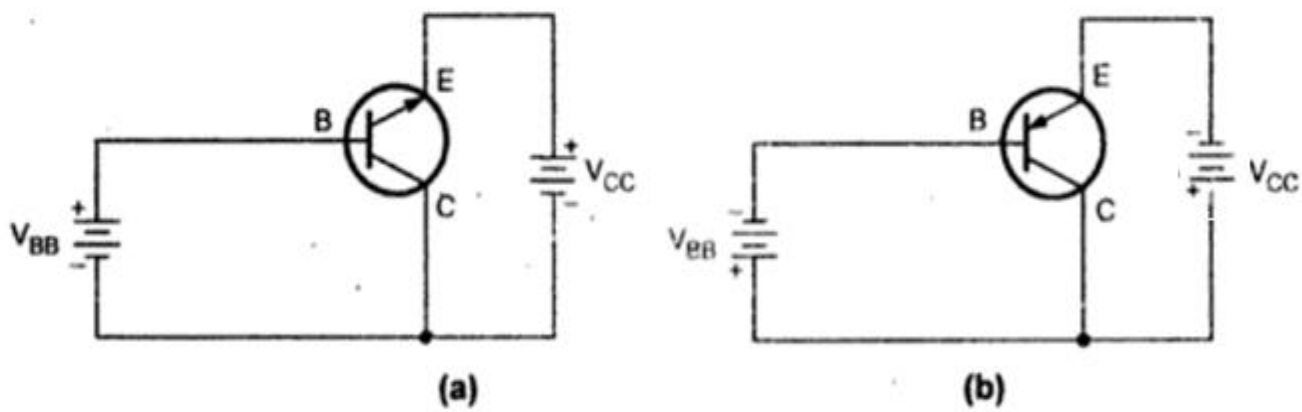


Fig. 3.14 Common collector configurations

- In this configuration input is applied between base and collector, and output is taken from emitter and collector.
- Here, collector of the transistor is common to both input and output circuits, and hence the name common collector configuration.
- Common collector connections for both n-p-n and p-n-p transistors are shown in Fig. 3.14 (a) and (b) respectively.

3.7.1 Common collector d.c current gain (ϒ)

- It is defined as the ratio of emitter current (I_E) to base current (I_B) and is usually designated by ϒ, $ϒ_{DC}$ or h_{FC}
- Mathematically, the common current d.c current gain,

$$\boxed{\gamma = \frac{I_E}{I_B}}$$

- Emitter current of a transistor is much larger than the base current.
- Therefore, current gain ϒ is always greater than unity.

3.7.2 Common collector a.c current gain (Υ_0)

- It is defined as the ratio of small change in emitter current (ΔI_E) to a small change in base current (ΔI_B) for a constant collector to emitter voltage (V_{CE}).
- It is designated by Υ, Υ_{ac} or h_{fc}.
- Mathematically, the common collector a.c current gain

$$\boxed{\gamma_0 = \frac{\Delta I_E}{\Delta I_B}}$$

3.7.3 Current Relations in CC Configuration

- In CC configuration, I_B is the input current and the I_E is the output current.
- Relate the output current I_E with the input current I_B is

$$I_E = (1+\beta_{dc})\, I_B + (1+\beta_{dc})\, I_{CBO}$$

Example : *If $\beta = 100$, $I_{CBO} = 10\ \mu A$ and $I_B = 80\ \mu A$. Find I_E.*

Solution : We know that,

$$\begin{aligned} I_E &= (1+\beta)\, I_B + (1+\beta)\, I_{CBO} \\ &= (1+100)\times 80\times 10^{-6} + (1+100)\times 10\times 10^{-6} \\ &= \mathbf{9.09\ mA} \end{aligned}$$

Example : *If $\alpha = 0.98$, $I_{CBO} = 10\ \mu A$ and $I_B = 100\ \mu A$. Find I_E.*

Solution : We know that, $\beta = \dfrac{\alpha}{1-\alpha}$

$\therefore$ $$\beta = \frac{0.98}{1-0.98} = 49$$

Current I_E can be given as,

$$\begin{aligned} I_E &= (1+\beta)\, I_B + (1+\beta)\, I_{CBO} \\ &= (1+49)\times 100\times 10^{-6} + (1+49)\times 10\times 10^{-6} = \mathbf{5.5\ mA} \end{aligned}$$

3.7.4 Input and Output Characteristics of a Transistor in a Common Collector Configuration

- Following are two important characteristics of a transistor in a common Collector (CC) configuration.
  - **Input characteristics**
    - These curves give the relationship between the base current (I_B) and the base to collector voltage (V_{BC}) for a constant emitter to collector voltage (V_{EC}).

- **Output characteristics**
    - These curves give the relationship between the emitter current (I_E) and the emitter to collector voltage (V_{EC}) for a constant base current (I_B).

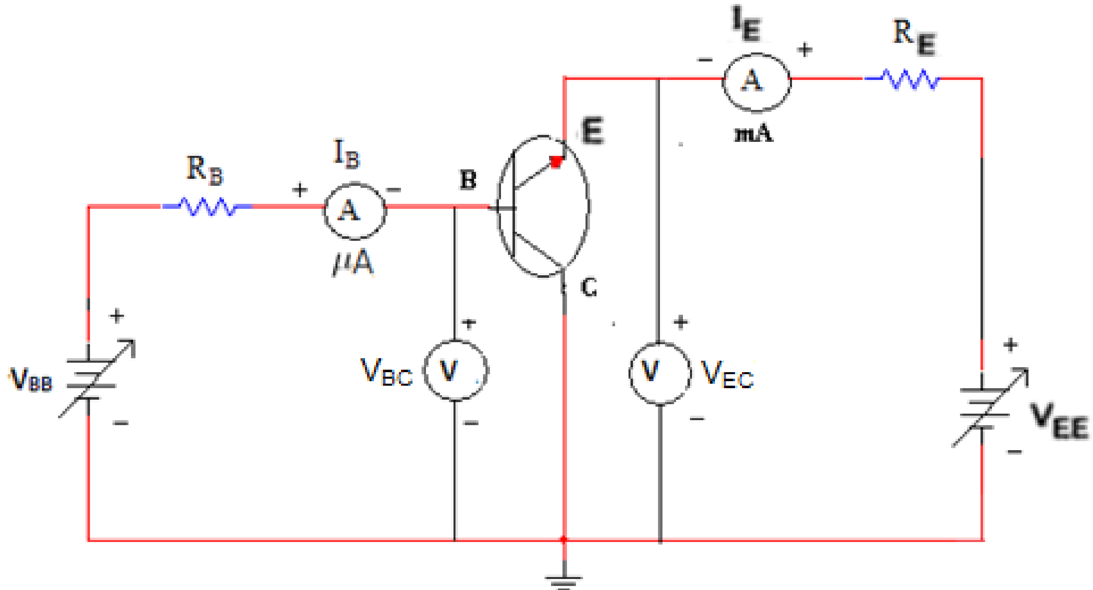


Fig. 3.15 Circuit arrangement for determining common collector transistor characteristics

2.7.4.1 Input Characteristics of a Common Collector Configuration

- It is the graph of input current I_B versus input voltage V_{BC} at constant V_{EC}.
- The base current is taken along Y-axis and collector base voltage V_{BC} is taken along X-axis.
- Fig. 3.16 shows the input characteristics of a typical transistor in common collector configuration.
- The common collector input characteristics are quite different from either common base or common emitter input characteristics.
- This difference is due to the fact that the input voltage V_{BC} is largely determined by the level of emitter to collector voltage V_{EC}.

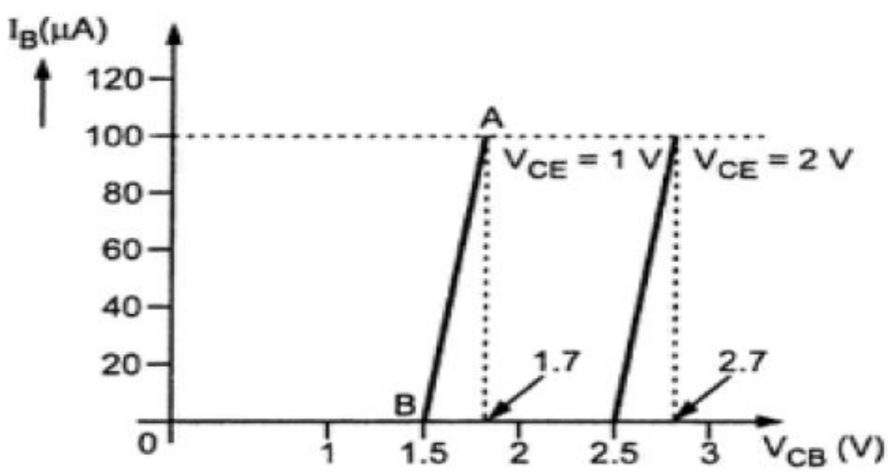


Fig. 3.16 Input characteristics of transistor in CC configuration

3.7.4.2 Output Characteristics of a Common Collector Configuration

- It is the curve between emitter current I_E and collector to emitter voltage V_{CE} at constant base current I_B.
- The emitter current is taken along Y-axis and collector to emitter voltage along X-axis.
- Fig. 3.17 shows the output characteristics of a typical transistor in common collector configuration.

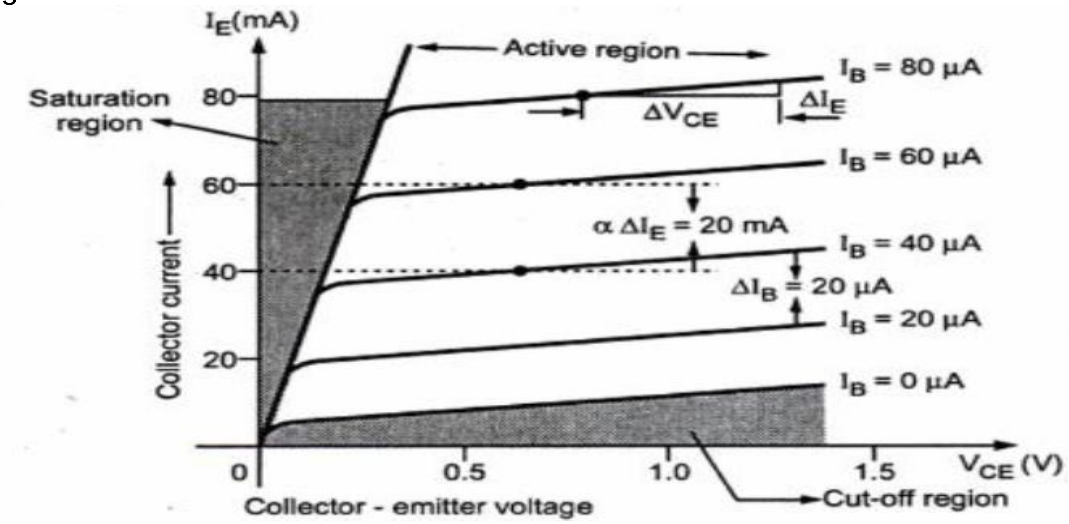


Fig. 3.17 Output characteristics of the transistor In CC configuration

- Since, I_C is approximately equal to I_E, the common collector output characteristics are practically similar to those of the common emitter output characteristics.

3.8 Comparison of Transistor Configurations

Sr. No.	Characteristic	Common Base	Common Emitter	Common Collector
1.	Input resistance (R_i)	Very low (20 Ω)	Low (1 kΩ)	High (500 kΩ)
2.	Output resistance (R_o)	Very high (1 MΩ)	High (40 kΩ)	Low (50 Ω)
3.	Input current	I_E	I_B	I_B
4.	Output current	I_C	I_C	I_E
5.	Input voltage applied between	Emitter and Base	Base and Emitter	Base and Collector
6.	Output voltage taken between	Collector and Base	Collector and Emitter	Emitter and Collector
7.	Current amplification factor	$\alpha_{dc} = \frac{I_C}{I_E}$	$\beta_{dc} = \frac{I_C}{I_B}$	$\frac{I_E}{I_B}$
8.	Current gain (A_i)	Less than unity	High (20 to few hundreds)	High (20 to few hundreds)
9.	Voltage gain (A_v)	Medium	Medium	Less than unity
10.	Applications	As a input stage of multistage amplifier	For audio signal amplification	For impedance matching

3.9 Why CE Configuration is widely used in Amplifier Circuits?

- The CE configuration is the only configuration which provides both voltage gain as well as current gain greater than unity.

3.10 Transistor as a switch

- Transistors are widely used in switching applications.
- In these applications, the voltage levels periodically alternate between a “Low” and a “High” voltage, such as 0 V and + 5 V.
- In switching applications, the transistor operates either in cut-off region or saturation region.
- The circuit diagram for transistor act as a switch is as shown in the Fig. 3.18.

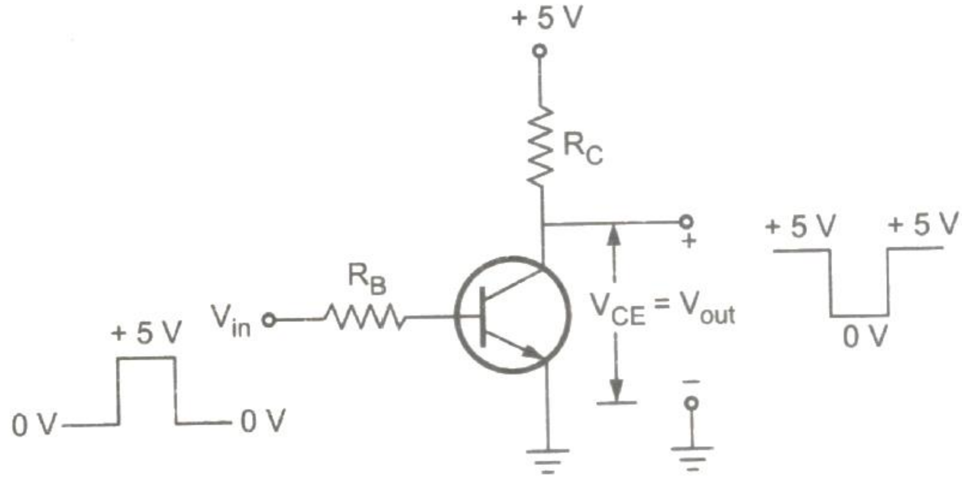


Fig. 3.18 Transistor act as switch

- When input is HIGH, base current and collector current flows and hence transistor is operated in saturation.
- In saturation condition, voltage between collector and emitter, $V_{CE(sat)}$ is typically 0.2 V to 0.3 V and hence transistor acts as closed switch. This is illustrated in Fig. 3.19.

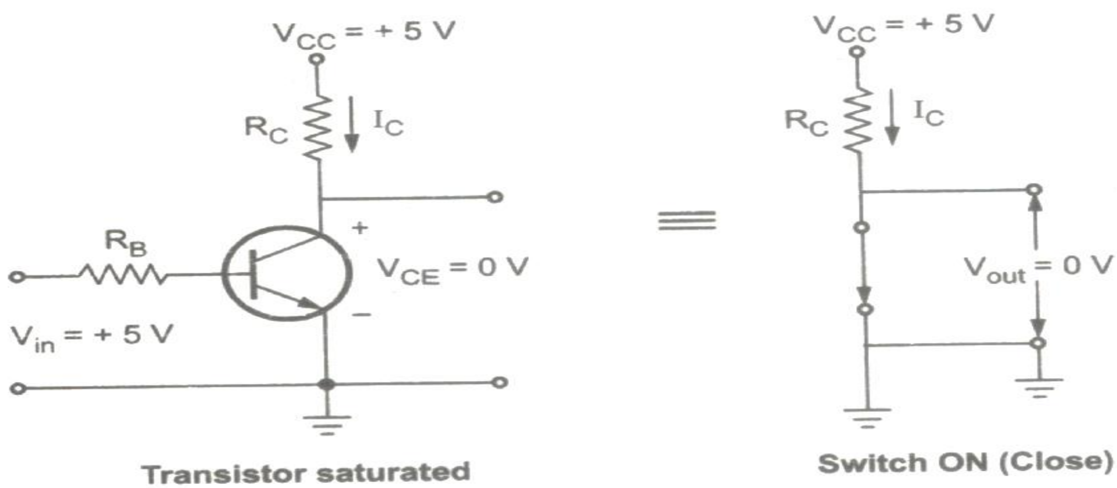


Fig. 3.19 When Input is High

- When input is LOW, base current and collector current is zero and hence transistor is operated in cut-off.
- In cut-off $V_{CE} = V_{CC}$ and transistor acts as open switch. This is illustrated in Fig. 3.20.

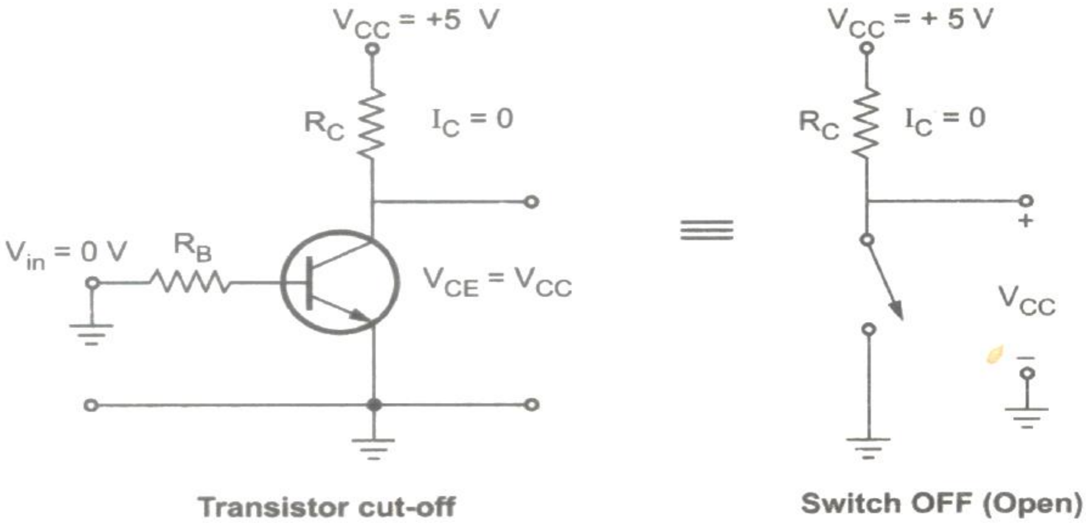


Fig. 3.20 When Input is Low

3.11 Switching times of a transistor

- The switching speed of the transistor is an important quantity when transistor is used as a switch.
- Switching times of a transistor is shown in the figure 3.21.

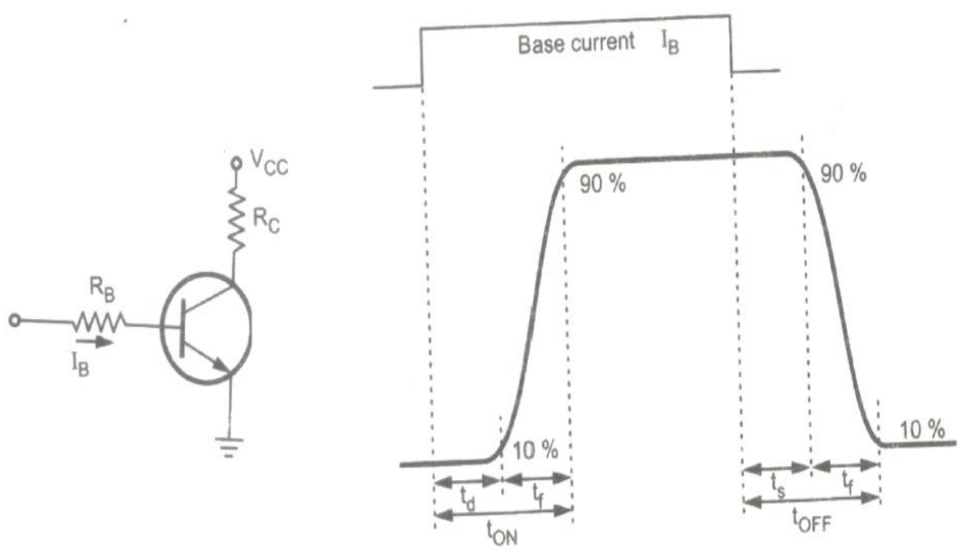


Fig. 3.21 Transistor Turn-ON and Turn-OFF times

- When the base input current I_B is applied, the transistor does not switch on immediately. This is because of the junction capacitance and the transition time of electrons across the junctions.

- The time between the application of the input pulse and the commencement of collector current flow is termed as delay time t_d.
- The time required for I_C to reach 90 % of its maximum level from 10 % level is called the rise time t_r.
- Thus, the turn-on time t_{ON} is the addition of t_r and t_d as shown in the Fig. 3.22.
- When input current I_B is switched OFF, I_C does not go to zero level immediately, but remains almost at its maximum value for a length of time before falling to zero. This period is called the storage time t_S.
- The time required for I_C to go from 90 % to 10 % of its maximum level is called as fall time t_f
- Thus, the turn-off time t_{OFF} is the sum of storage time t_S and fall time t_f as shown in the Fig. 3.22.

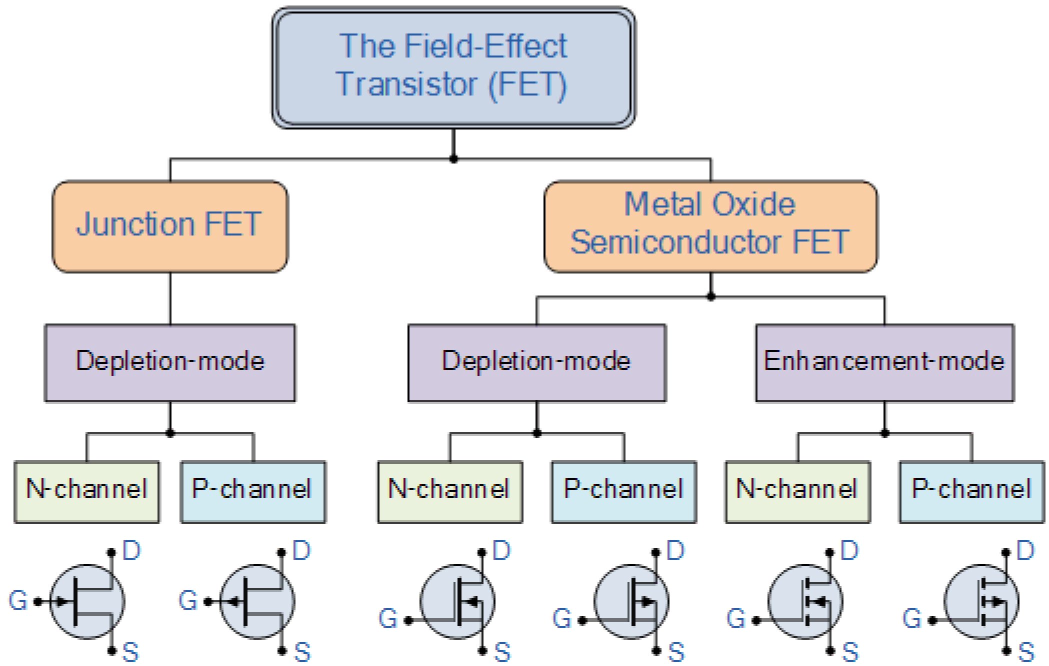
UNIT IV

UNIT IV Field Effect Transistor (FET)

JFET- Construction, Principle of Operation, Pinch-Off Voltage, Volt- Ampere Characteristic, Comparison of BJT and FET, FET as Voltage Variable Resistor, MOSFET, MOSFET as a capacitor.

4.1 Introduction to Field Effect Transistor

- A field effect transistor is a voltage controlled device i.e. the output characteristics of the device are controlled by input voltage. There are two basic types of field effect transistors:
  - Junction field effect transistor (JFET)
  - Metal oxide semiconductor field effect transistor (MOSFET)



4.2 Junction Field Effect Transistor (JFET)

- A JFET is a three terminal semiconductor device in which current conduction is by one type of carrier i.e. electrons or holes.
- It has three terminals namely Source (S), Drain (D) and Gate (G).
- The current conduction is controlled by means of an electric field between the gate and the conducting channel of the device.
- The JFET has high input impedance and low noise level.
- There are two types of JFET's namely N-channel JFET's and P-channel JFET's.
- Generally N-channel JFETs are more preferred than P-channel.

4.2.1 Symbols of JFET

- The symbol of N-channel and P-channel JFETs are shown in the figure 4.1.

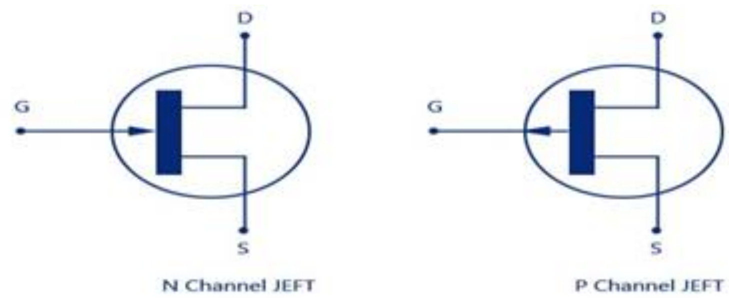


Fig. 4.1 Symbols of N - channel and P- channel JFET

- The vertical line in the symbol may be thought as channel and source S and drain D connected to the line.
- Note that the direction of the arrow at the gate indicates the direction in which the gate current flows.

4.2.2 Construction of JFET

- In an N-channel JFET an N-type silicon bar, referred to as the channel, has two smaller pieces of P-type silicon material diffused on the opposite sides of its middle part, forming P-N junctions, as illustrated in figure 4.2.

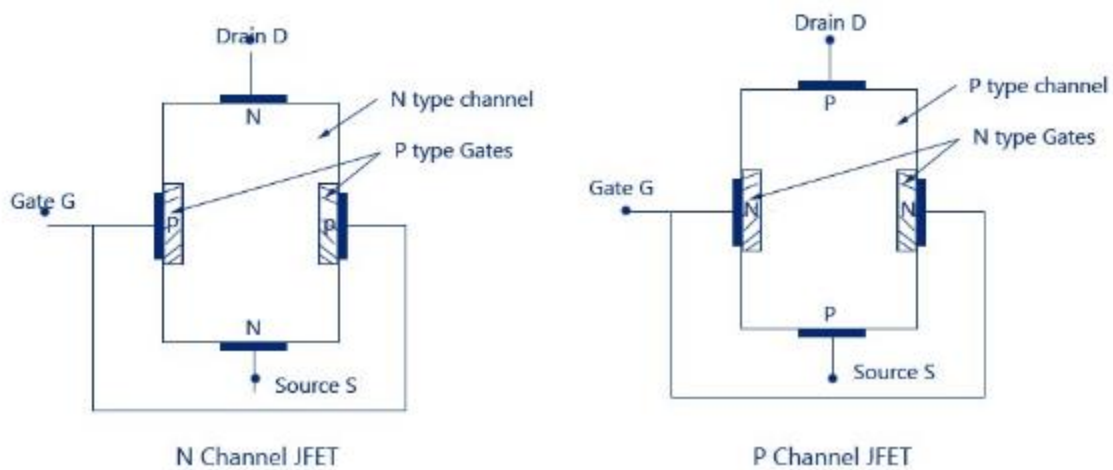


Fig. 4.2 Construction of JFET

- The two P-N junctions forming diodes or gates are connected internally and a common terminal, called the gate terminal, is brought out.
- Ohmic contacts (direct electrical connections) are made at the two ends of the channel—one lead is called the Source terminal S and the other Drain terminal D.
- **Source** – The terminal through which the majority carriers enter the channel, is called the source terminal S
- **Drain** – The terminal, through which the majority carriers leave the channel, is called the drain terminal D

- **Channel** – The region between the source and drain, sandwiched between the two gates is called the channel and the majority carriers move from source to drain through this channel.
- The silicon bar behaves like a resistor between its two terminals D and S.
- The gate terminal is used to control the flow of current from source to drain.
- In the figure above, the gate is P-region, while the source and the drain are N-regions.
- Because of this, a JFET is similar to two diodes.
- The gate and the source form one of the diodes, and the drain form the other diode.
- These two diodes are usually referred as the gate-source diode and the gate-drain diode.
- Since JFET is a silicon device, it takes only 0.7 volts for forward bias to get significant current in either diode.

4.2.3 Polarities of JFET

- Fig.4.3 shows the n-channel JFET polarities and the p-channel JFET polarities.
- In each case, the voltage between the gate and source is such that the gate is reverse biased.
- The source and the drain terminals are interchangeable.

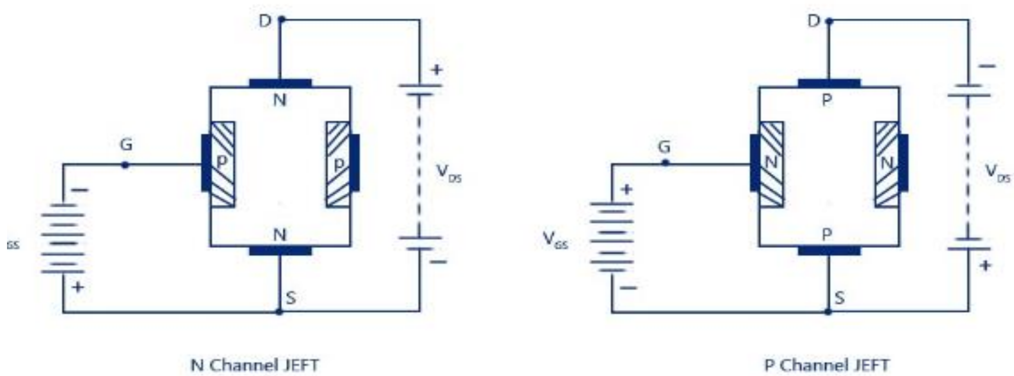


Fig. 4.3 Polarities of JFET

4.2.4 Principle of operation n channel JFET

- The working of JFET can be explained as follows.

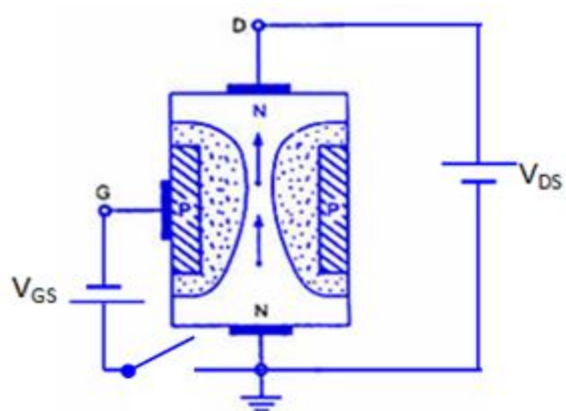


Fig. 4.4 Operation of JFET when V_{GS}=0

Case-i:

- When a voltage V_{DS} is applied between drain and source terminals and voltage on the gate is zero as shown in fig.4.4, then two pn junctions at the sides of the bar establish depletion layers.
- The electrons will flow from source to drain through a channel between the depletion layers.
- The size of the depletion layers determines the width of the channel and hence current conduction through the bar.

Case-ii:

- When a reverse voltage V_{GS} is applied between gate and source terminals, then width of depletion layer is increased which is shown in fig. 4.4.
- This reduces the width of conducting channel, thereby increasing the resistance of n-type bar.
- Consequently, the current from source to drain is decreased.
- On the other hand, when the reverse bias on the gate is decreased, the width of the depletion layer also decreases.
- This increases the width of the conducting channel and hence source to drain current

4.2.5 Principle of operation p channel JFET

- A p channel JFET operates in the same manner as an n-channel JFET except that channel current carries will be the holes instead of electrons and polarities of V_{GS} and V_{DS} are reversed.

4.3 Volt-Ampere characteristics of JFET

- There are two types of static characteristics viz.
    - Output or drain characteristics
    - Transfer characteristics

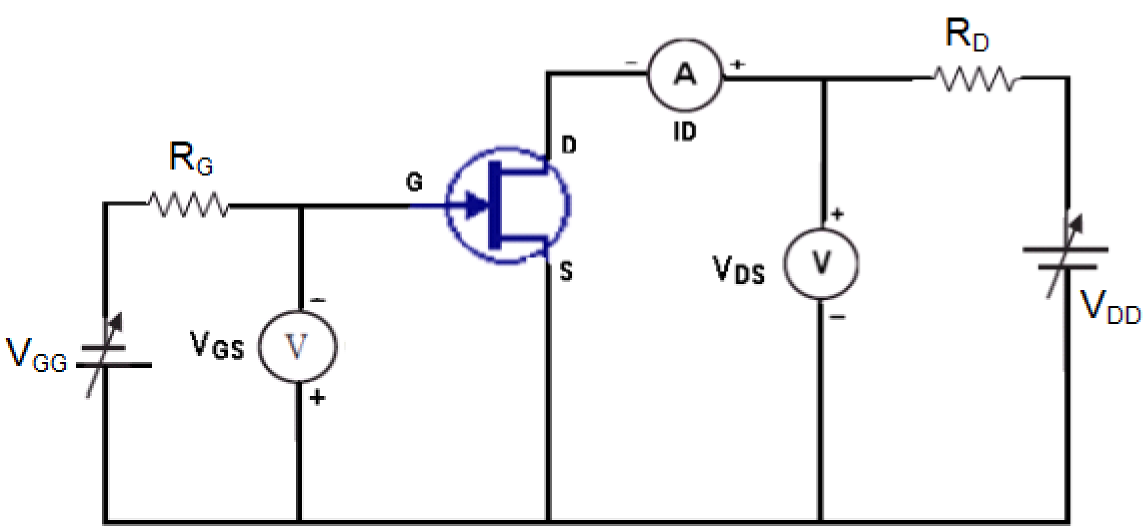


Fig. 4.5 Characteristics of JFET

4.3.1 Output or Drain Characteristics

- The curve drawn between drain current I_D and drain-source voltage V_{DS} by keeping gate-to source voltage V_{GS} as constant as shown in figure 4.6.

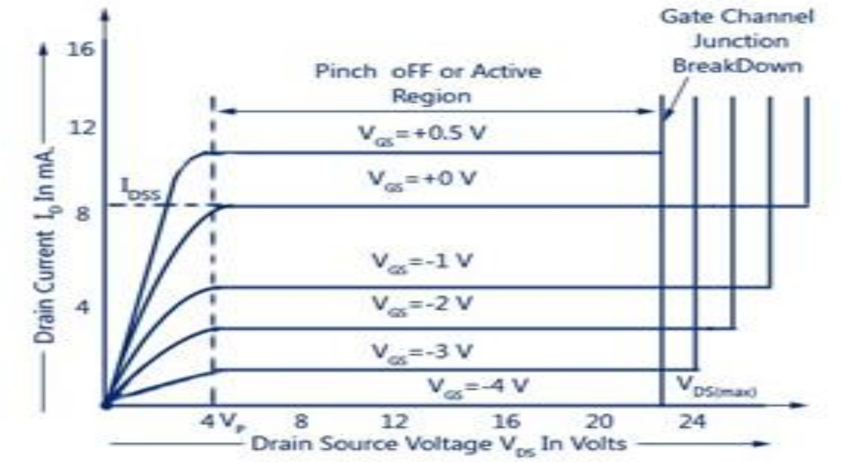


Fig. 4.6 Waveforms of Drain characteristics of JFET

Pinch-off voltage

The value of voltage V_{DS} at which the channel is pinched off (i.e. all the free charges from the channel get removed) and the drain current I_D attains a constant value is called as pinch-off voltage V_p.

- For small applied voltage V_{DS}, the n-type bar acts as a simple semiconductor resistor and the drain current increases linearly with the increase in V_{DS}, upto the knee point.
- So with the increase in V_{DS}, the conducting portion of the channel begins to constrict more at the drain end. Eventually a voltage V_{DS} is reached at which the channel is pinched off.
- The drain current I_D no longer increases with the increase in V_{DS}. It approaches a constant saturation value.
- The drain current in the pinch-off region with V_{GS} = 0 is referred to the drain-source saturation current (I_{DSS}).
- Drain current in the pinch-of region is given by Shockley's equation

$$I_D = I_{DSS}\left[1 - \frac{V_{GS}}{V_{GS(off)}}\right]^2$$

$$I_D = I_{DSS}\left[1 - \frac{V_{GS}}{\mathrm{Vp}}\right]^2$$

Where

I_D = Drain current at given VGS
I_{DSS} = Drain-source saturation current
V_{GS} = Gate-source Voltage
$V_{GS(off)}$ = Gate-source cut off voltage
V_P = Pinch off voltage

4.3.2 Transfer characteristics

- The transfer characteristics for a JFET can be determined experimentally, keeping drain-source voltage V_{DS} as constant and determining drain current I_D for various values of gate-source voltage, V_{GS}.
- The circuit diagram is shown in fig. 4.5.

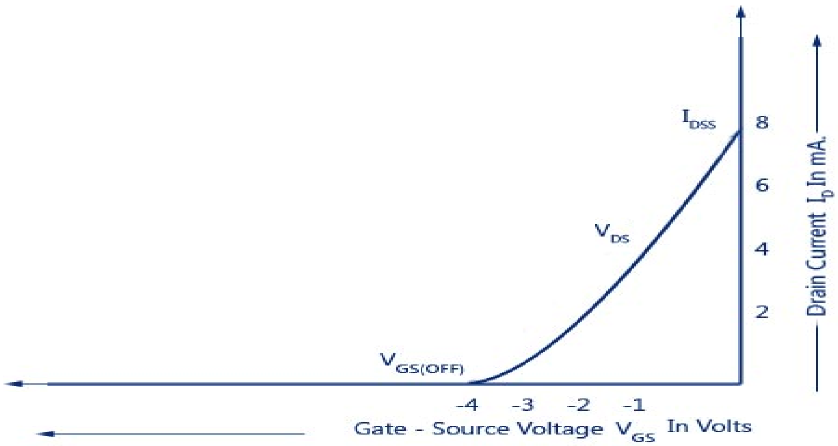


Fig. 4.7 Transfer characteristics

- The curve is plotted between gate-source voltage, V_{GS} and drain current, I_D, as illustrated in fig. 4.7.
- It is observed that
    - Drain current decreases with the increase in negative gate-source bias
    - Drain current, $I_D = I_{DSS}$ when $V_{GS} = 0$
    - Drain current, $I_D = 0$ when $V_{GS} = V_p$

4.5 JFET parameters

- The JFET parameters are the major components of low frequency small signal model for JFET.
- The change in the drain current due to change in gate to source voltage can be determined using the transconductance factor g_m. It is given as

$$\boxed{g_m = \frac{\Delta I_d}{\Delta V_{GS}}}$$

- Another important parameter of JFET is drain resistance r_d. It is given by

$$\boxed{r_d = \left.\frac{\Delta V_{DS}}{\Delta I_D}\right|_{V_{GS}=\text{ constant}}}$$

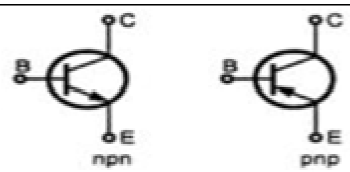
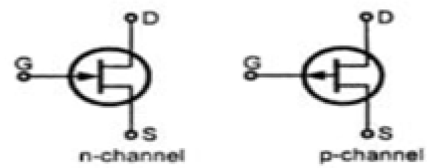
- The amplification factor μ of an FET is defined as

$$\boxed{\mu = \left.\frac{\Delta V_{DS}}{\Delta V_{gS}}\right|_{I_D=\text{const}}}$$

- The parameters g_m, r_d and μ are related by,

$$\boxed{\mu = r_d \, g_m}$$

4.6 Comparison BJT and FET

S. No.	Parameter	BJT	FET
1	Control Element	Current controlled device.	Voltage controlled device
2	Device type	Bipolar device	Unipolar device
3	Types	npn & pnp	n-channel & p-channel
4	Symbols		
5	Configurations	CE, CB, CC	CS, CG, CD
6	Input Resistance	Low	High
7	Size	Bigger	Smaller
8	Sensitivity	High	Low
9	Thermal Stability	Less	More
10	Thermal runaway	Exists	Does not exists
11	Thermal noise	More	Less

4.8 FET as Voltage Variable Resistor

- Let us consider the drain characteristics of FET as shown in the Fig. 4.14.

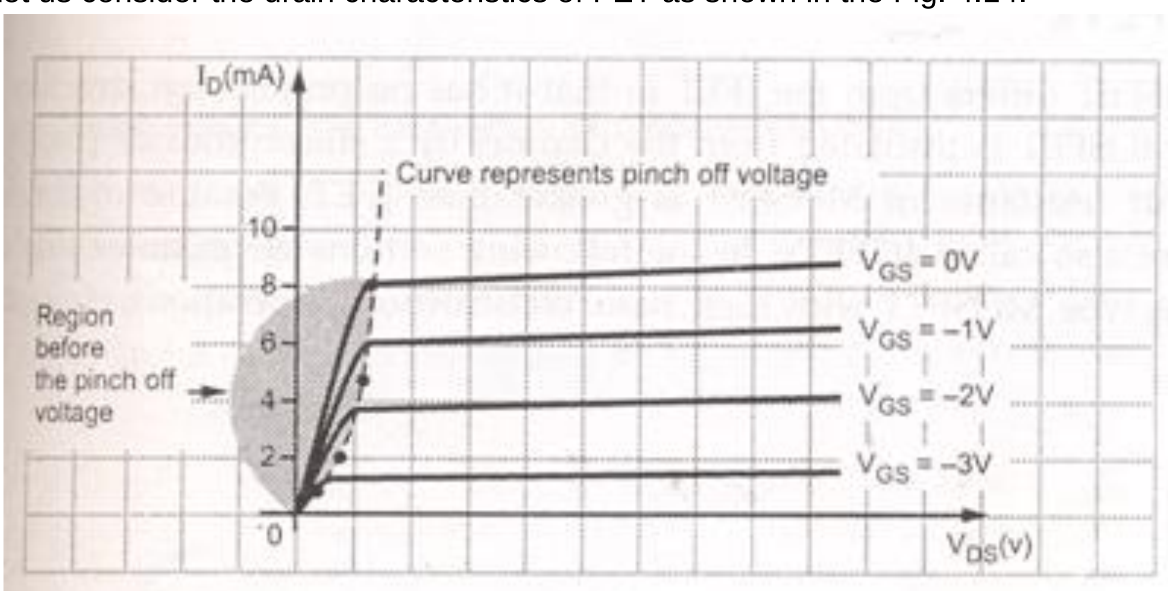


Fig. 4.14 Drain characteristics of FET

- In this characteristic we can see that in the region before pinch off voltage, drain characteristics is Linear, i.e., FET operation is linear.
- In this region the FET is useful as a voltage-controlled resistor, i.e., the drain to source resistance is controlled by the bias voltage V_{GS}.
- The operation of FET in this region is useful in most Linear applications of FET.
- In such an application the FET is also referred to as a Voltage Variable Resistor (VVR) or Voltage Dependent Resistor (VDR).
- The variation of the r_d with V_{GS} can be closely approximated by the empirical expression,

$$r_d = \frac{r_0}{1 - KV_{GS}}$$

Where r_o = drain resistance at zero gate bias, and K = a constant, dependent upon FET type.

- Thus, small signal FET drain resistance r_d varies with applied gate voltage V_{GS} and FET acts like a variable passive resistor.
- For example, the VVR can be used in Automatic Gain Control (AGC) circuit of a multistage amplifier.

4.9 Metal Oxide Semiconductor Field Effect Transistor (MOSFET)

- The field effect transistor that can be operated to enhance the width of the channel. Such a FET is called MOSFET.
- The MOSFET differs from the JFET in that it has no p-n junction structure.
- The gate of the MOSFET is insulated from the channel by a silicon dioxide (SiO_2) layer. So MOSFETs are also called as Insulate Gate FET (IGFET)
- Due to this the input resistance of MOSFET is greater than JFET.

4.9.1 Types of MOSFETs

- **Depletion mode MOSFET or D-MOSFET:**
- **Enhancement mode MOSFET or E-MOSFET:**

4.10 D-MOSFET

- There are two types of D-MOSFETs such as:
    - n-channel D-MOSFET
    - p-channel D-MOSFET

4.10.1 Construction of n-channel D-MOSFET

- A thin layer of metal oxide, usually silicon dioxide (SiO2) is deposited over a small portion of the channel. A metallic gate is deposited over the oxide layer.
- As SiO2 is an insulator, therefore, gate is insulated from the channel.
- The substrate is connected to the source internally so that a MOSFET has three terminals such as Source (S), Gate (G) and Drain (D).

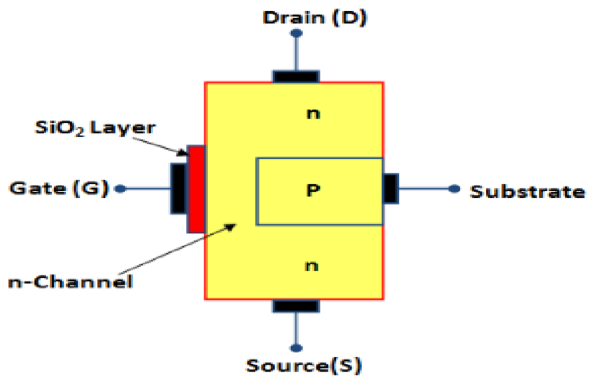


Fig. 4.15 construction of n-channel D-MOSFET

- Since the gate is insulated from the channel, we can apply either negative or positive voltage to the gate.
- Therefore, D-MOSFET can be operated in both depletion-mode and enhancement-mode.
- The p-type substrate constricts the channel between the source and drain so that only a small passage remains at the left side.
- Electrons flowing from source (when drain is positive w.r.t. source) must pass through this narrow channel.

4.10.2 Symbol for n-channel D-MOSFET

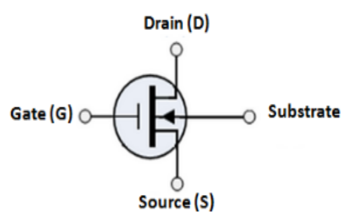


Fig. 4.16 Symbol for n-channel D-MOSFET

- The symbol for n channel D MOSFET is shown in Fig. 4.16 which is having four terminals.
- The substrate is connected to the source as shown in Fig. 4.17. This gives rise to a three terminal device.

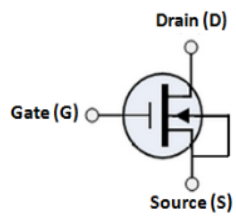


Fig. 4.17 Symbol for n-channel D-MOSFET

4.10.3 Operation of n-channel D- MOSFET

- Fig.4.18 (a) shows the circuit for operation of n-channel D-MOSFET.

- The gate forms a small capacitor. One plate of this capacitor is the gate and the other plate is the channel with metal oxide layer as the dielectric.
- When gate voltage is changed, the electric field of the capacitor changes which in turn changes the resistance of the n-channel.
- Gate voltage is negative, hence there are electrons on the gate as shown in fig. 4.18 (b).
- Since the gate voltage is negative, it induces positive charges (free holes) in the channel by the capacitor action as shown in fig. 4.18 (b).
- These free holes are added to free electrons in the channel, thus the total number of free electrons in the n–channel is decreased.
- Hence a negative gate voltage decreases the conductivity of the channel.

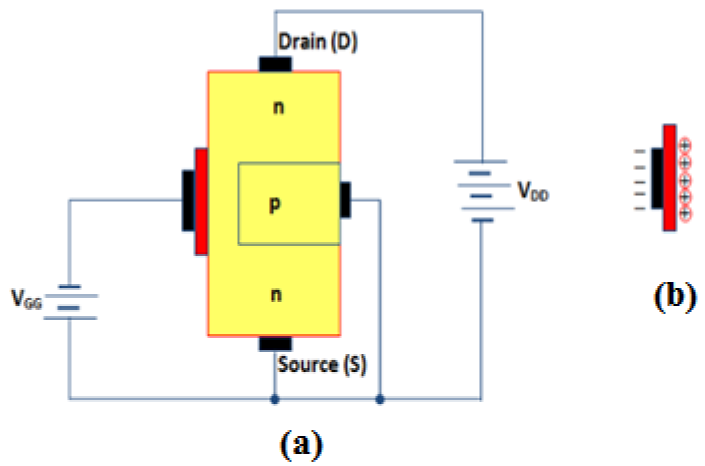


Fig. 4.18 (a) Operation of n channel D- MOSFET (b) Capacitor

- The greater the negative voltage on the gate, the lesser is the current from source to drain.
- Thus by changing the negative voltage on the gate, we can vary the resistance of the n-channel and hence the current from source to drain.
- In a D-MOSFET, the source to drain current is controlled by the electric field of capacitor formed at the gate.
- D-MOSFET has very low input capacitance, which makes the D-MOSFET useful in high frequency applications.

4.10.4 Volt-Ampere characteristics of D-MOSFET

- There are two types of static characteristics viz.
  - Output or drain characteristics
  - Transfer characteristics
- In general, any MOSFET is seen to exhibit three operating regions viz.,
- **Cut-Off Region:**
  - Cut-off region is a region in which the MOSFET will be OFF as there will be no current flow through it.
  - In this region, MOSFET behaves like an open switch and is thus used when they are required to function as electronic switches.

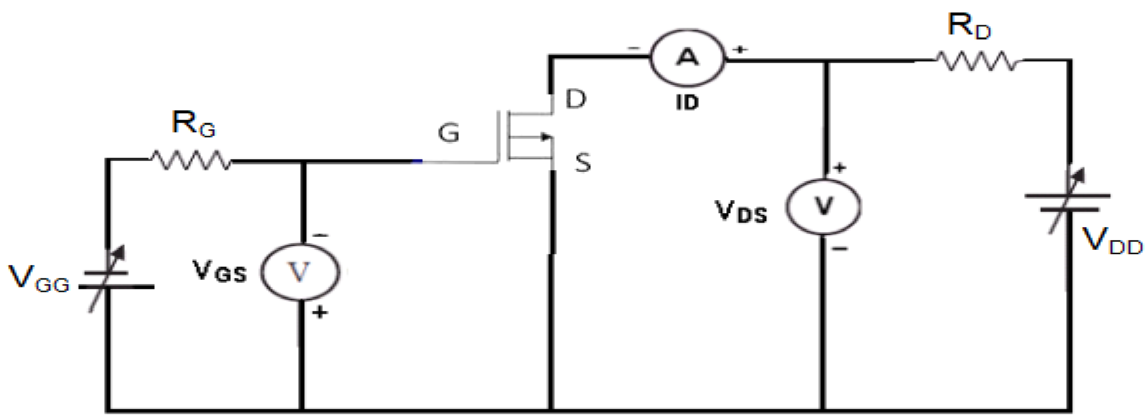


Fig. 4.19 Characteristics of D-MOSFET

- **Ohmic or Linear Region:**
  - Ohmic or linear region is a region where in the current I_{DS} increases with an increase in the value of V_{DS}.
  - When MOSFETs are made to operate in this region, they can be used as amplifiers.
- **Saturation Region:**
  - In saturation region, the MOSFETs have their I_{DS} constant inspite of an increase in V_{DS} and occur once when V_{DS} exceeds the value of pinch-off voltage V_P.
  - Under this condition, the device will act like a closed switch through which a saturated value of I_{DS} flows.
  - As a result, this operating region is chosen whenever MOSFETs are required to perform switching operations.

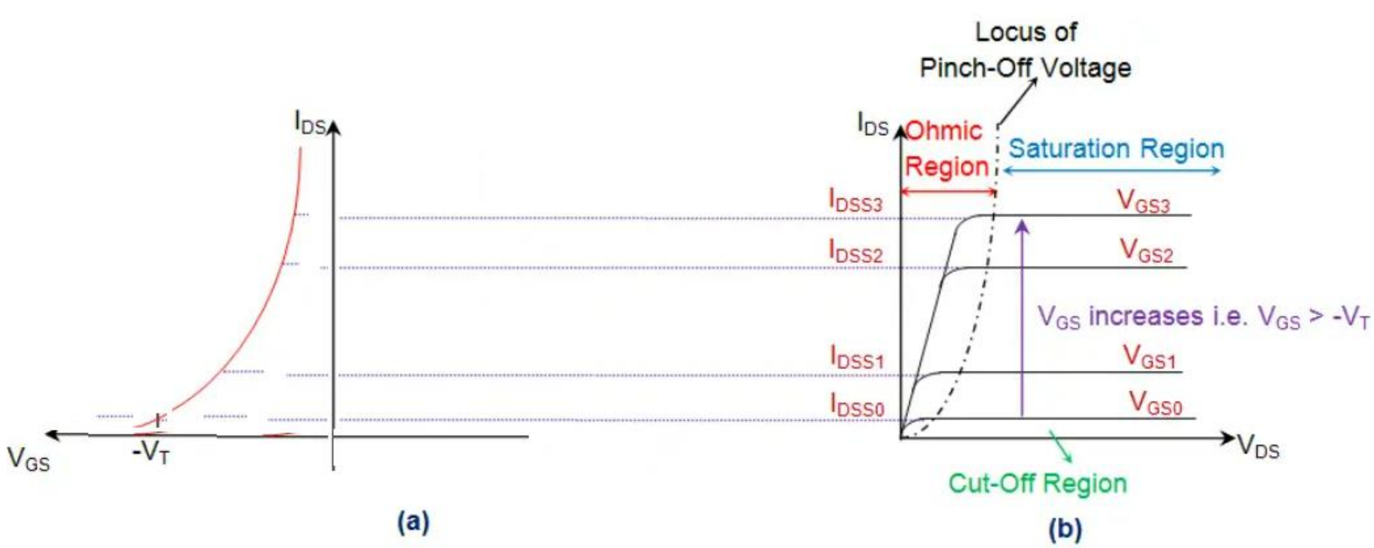


Fig. 4.20 n-channel Depletion-type MOSFET a) transfer characteristics b) output characteristics

- The transfer characteristics of n-channel depletion MOSFET shown by Figure 4.20 (a) indicate that the device has a current flowing through it even when V_{GS} is 0V.

- This indicates that these devices conduct even when the gate terminal is left unbiased, which is further emphasized by the V_{GS0} curve of Figure 4.20 (b).
- Under this condition, the current through the MOSFET is seen to increase with an increase in the value of V_{DS} (Ohmic region) until V_{DS} becomes equal to pinch-off voltage V_P.
- After this, I_{DS} will get saturated to a particular level I_{DSS} (saturation region of operation) which increases with an increase in V_{GS} i.e. $I_{DSS3} > I_{DSS2} > I_{DSS1}$, as $V_{GS3} > V_{GS2} > V_{GS1}$.
- Further, the locus of the pinch-off voltage also shows that V_P increases with an increase in V_{GS}.
- However it is to be noted that, if one needs to operate these devices in cut-off state, then it is required to make V_{GS} negative and once it becomes equal to $-V_T$, the conduction through the device stops ($I_{DS} = 0$) as it gets derived of its n-type channel (Figure 4.20 a).

4.11 E-MOSFET

- There are two types of E-MOSFETs such as:
    - n-channel E-MOSFET
    - p-channel E-MOSFET

4.11.1 Construction of n-channel E-MOSFET

- Fig.4.21 shows the constructional details of n-channel E-MOSFET.
- Its gate construction is similar to that of D-MOSFET.
- The E-MOSFET has no channel between source and drain. The substrate extends completely to the SiO_2 layer so that no channel exists.

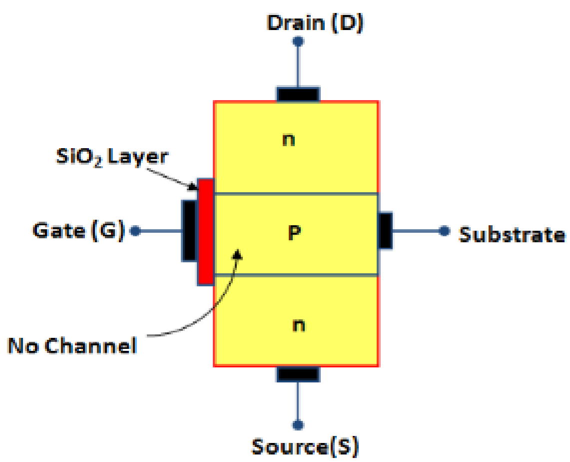


Fig. 4.21 Construction of n-channel E-MOSFET

- The E-MOSFET requires a proper gate voltage to form a channel, called induced channel between the source and the drain.
- It operates only in the enhancement mode and has no depletion mode.
- Only by applying VGS of proper magnitude and polarity, the device starts conducting.
- The minimum value of V_{GS} of proper polarity that turns on the E-MOSFET is called threshold voltage [$V_{GS(th)}$].

- The n-channel device requires positive V_{GS} ($\geq V_{GS(th)}$) and the p-channel device requires negative V_{GS} ($\geq V_{GS(th)}$).

4.11.2 Symbol of n-channel E-MOSFET

- Fig. 4.22 shows the schematic symbols for n-channel E-MOSFET.

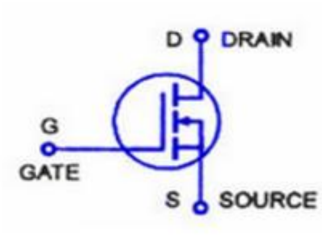


Fig. 4.22 Symbol of n-channel E-MOSFET

4.11.3 Operation of n-channel E-MOSFET

- Fig. 4.23 (a) shows the circuit of operation of n-channel E-MOSFET.
- Again the gate acts like a capacitor. Since the gate is positive, it induces negative charges in the n-channel as shown in fig. 4.23 (b).
- These negative charges are the free electrons drawn into the channel.
- Because these free electrons are added to those already in the channel, the total number of free electrons in the channel is increased.

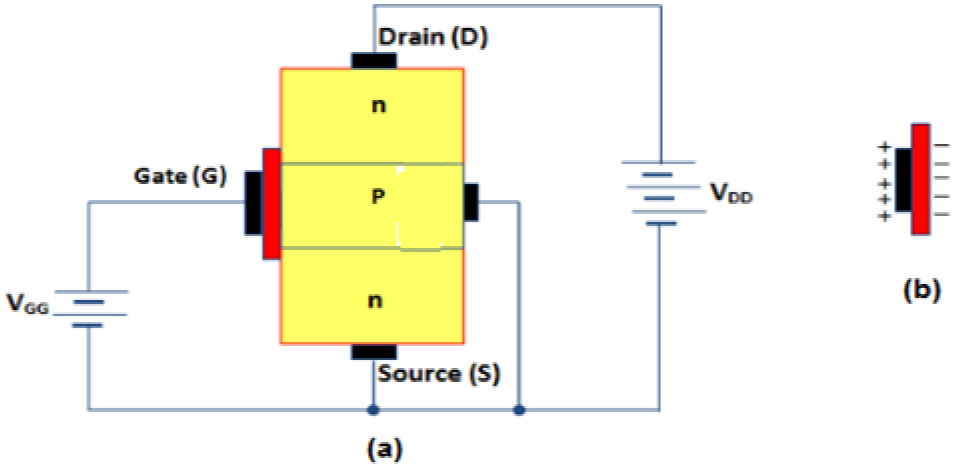


Fig. 4.23 (a) Operation of n-channel E-MOSFET (b) Capacitor

- Thus a positive gate voltage enhances or increases the conductivity of the channel.
- The greater the positive voltage on the gate, greater the conduction from source to drain.
- Thus by changing the positive voltage on the gate, we can change the conductivity of the channel.
- Because the action with a positive gate depends upon enhancing the conductivity of the channel, the positive gate operation is called enhancement mode.
- When V_{GS}= 0V, as shown in fig. 4.23 (a), there is no channel connecting source and drain.

- The p-substrate has only a few thermally produced free electrons (minority carriers) so that drain current is almost zero. For this reason, E-MOSFET is normally OFF when $V_{GS} = 0V$.
- When V_{GS} is positive, i.e gate is made positive as shown in fig. 4.23 (b), it attracts free electrons into the p region. The free electrons combine with the holes next to the SiO_2 layer.
- If V_{GS} is positive enough, all the holes touching the SiO_2 layer are filled and free electrons begin to flow from the source to drain.
- The effect is same as creating a thin layer of n-type material i.e. inducing a thin n-layer adjacent to the SiO_2 layer.
- Thus the E-MOSFET is turned ON and drain current I_D starts flowing from the source to the drain.
- The minimum value of V_{GS} that turns the E-MOSFET ON is called threshold voltage [$V_{GS(th)}$].
- When V_{GS} is less than $V_{GS(th)}$, there is no induced channel and the drain current I_D is zero.
- When V_{GS} is equal to $V_{GS(th)}$, the E-MOSFET is turned ON and the induced channel conducts drain current from the source to the drain.
- Beyond $V_{GS(th)}$, if the value of V_{GS} is increased, the newly formed channel becomes wider, causing to I_D to increase.
- If the value of V_{GS} decreases not less than $V_{GS(th)}$, the channel becomes narrower and I_D will decrease.

4.11.4 Volt-Ampere characteristics of E-MOSFET

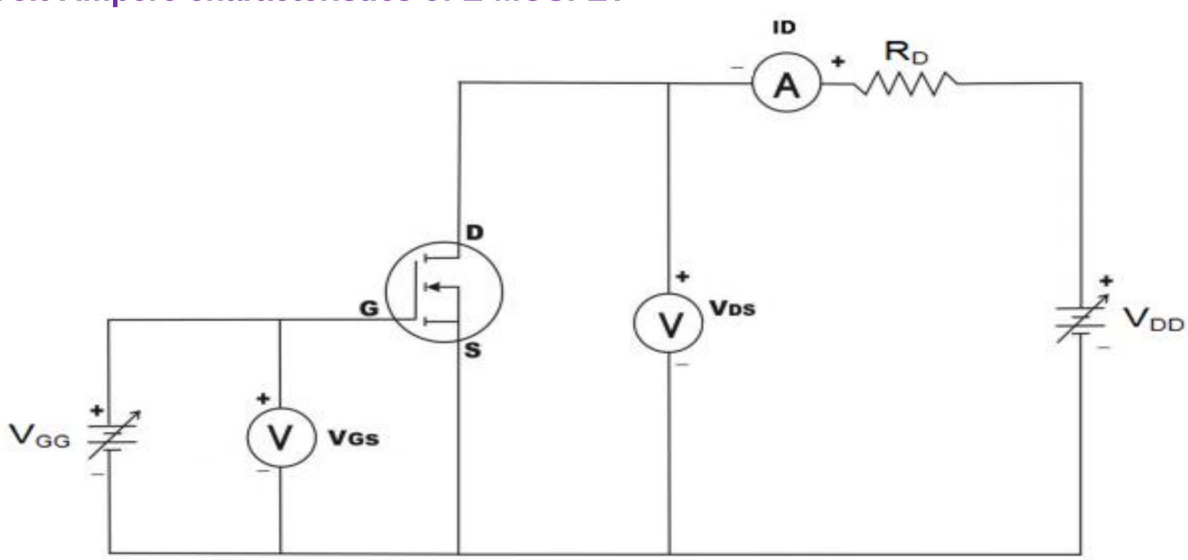


Fig. 4.24 Characteristics of E-MOSFET

- Figure 4.25 (a) shows the transfer characteristics (drain-to-source current I_{DS} versus gate-to-source voltage V_{GS}) of n-channel Enhancement-type MOSFETs.
- From this, it is evident that the current through the device will be zero until the V_{GS} exceeds the value of threshold voltage V_T.
- This is because under this state, the device will be void of channel which will be connecting the drain and the source terminals.

- Under this condition, even an increase in V_{DS} will result in no current flow as indicated by the corresponding output characteristics (I_{DS} versus V_{DS}) shown by Figure 4.25 (b).
- As a result this state represents nothing but the cut-off region of MOSFET's operation.
- Next, once V_{GS} crosses V_T, the current through the device increases with an increase in I_{DS} initially (Ohmic region) and then saturates to a value as determined by the VGS (saturation region of operation) i.e. as VGS increases, even the saturation current flowing through the device also increases.
- This is evident by Figure 4.25 (b) where I_{DSS2} is greater than I_{DSS1} as $V_{GS2} > V_{GS1}$, I_{DSS3} is greater than I_{DSS2} as $V_{GS3} > V_{GS2}$, so on and so forth.
- Further, Figure 4.25 (b) also shows the locus of pinch-off voltage (black discontinuous curve), from which V_P is seen to increase with an increase in V_{GS}.

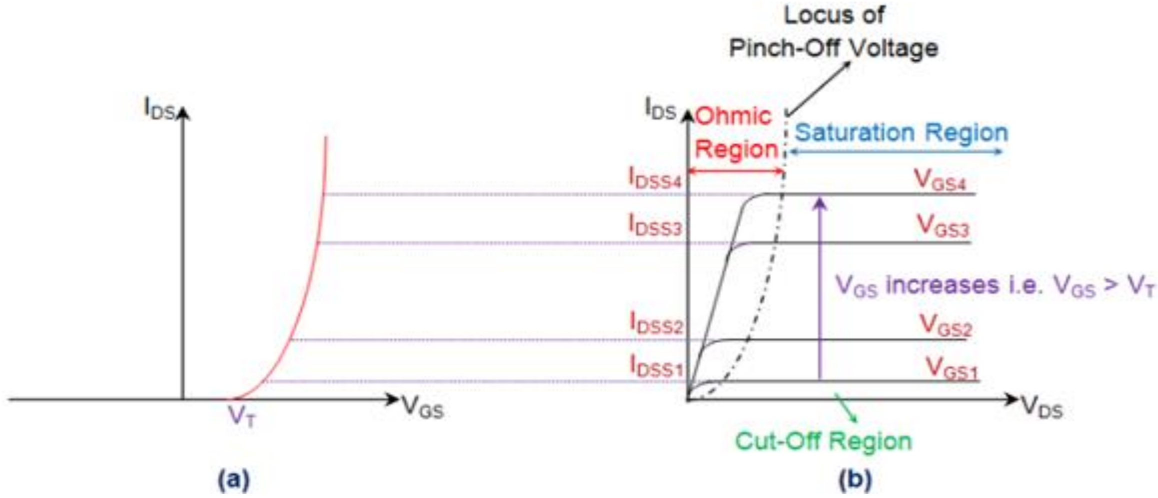


Fig. 4.25 n-channel Enhancement type MOSFET a) transfer characteristics b) output characteristics

4.12 MOSFET as a capacitor

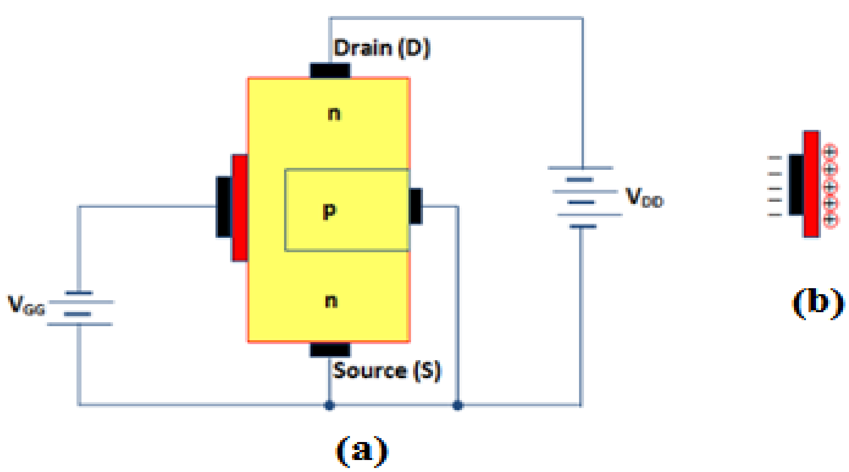


Fig. 4.26 MOSFET act as a Capacitor

- The gate of MOSFET forms a small capacitor which is shown in Fig. 4.26 (a).
- One plate of this capacitor is the gate terminal and the other plate is the channel (Area between Source and Drain) with metal oxide layer as the dielectric.
- Gate voltage is negative, hence there are electrons on the gate as shown in fig. 4.26 (b).
- Since the gate voltage is negative, it induces positive charges (free holes) in the channel by the capacitor action as shown in fig. 4.26 (b).
- When gate voltage is changed, the electric field of the capacitor changes which in turn changes the resistance of the n-channel.

UNIT V - Special Purpose Devices:

Zener Diode - Characteristics, Zener diode as Voltage Regulator, Principle of Operation - SCR, Tunnel diode, UJT, Varactor Diode, Photo diode, Solar cell, LED, Schottky diode.

5.1 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
  - Photo diode
  - Solar Cell
  - LED
  - Schottky diode

5.2 Zener Diode

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

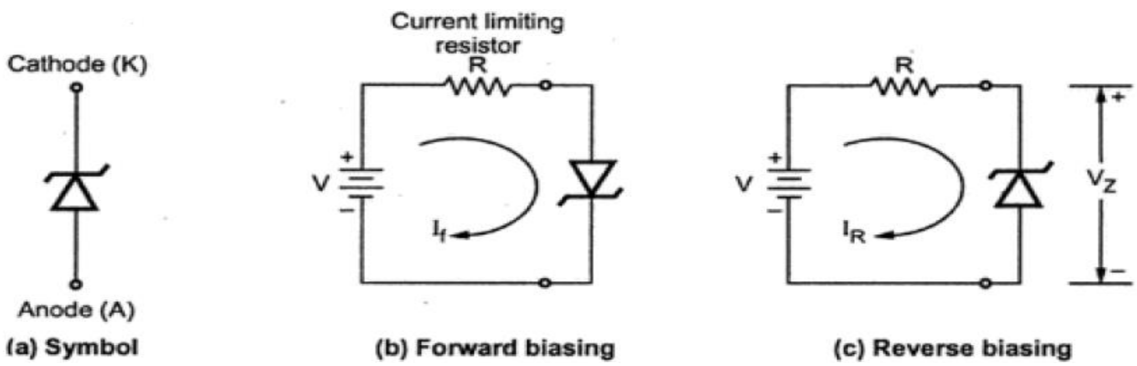


Fig. 5.1 Zener diode

- 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. 5.1 (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. 5.1 (b) and (c).
- Practically zener diodes are operated in **reverse biased mode**.

5.2.1 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 5.2.
- 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.

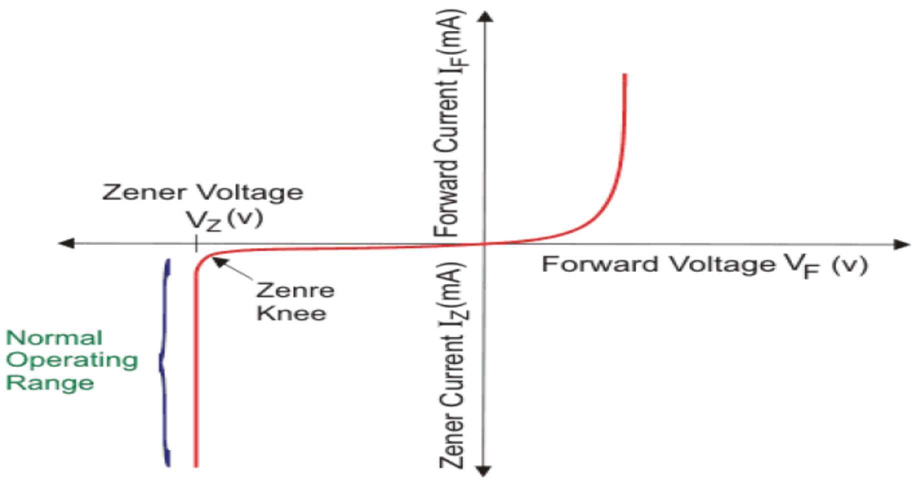


Fig. 5.2 V-I characteristics of Zener diode

- 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.

5.2.2 Applications of Zener Diode

- Voltage Regulator
- Protection circuits
- Voltage Limiters

5.3 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

5.3.1 Regulation with Varying Input Voltage

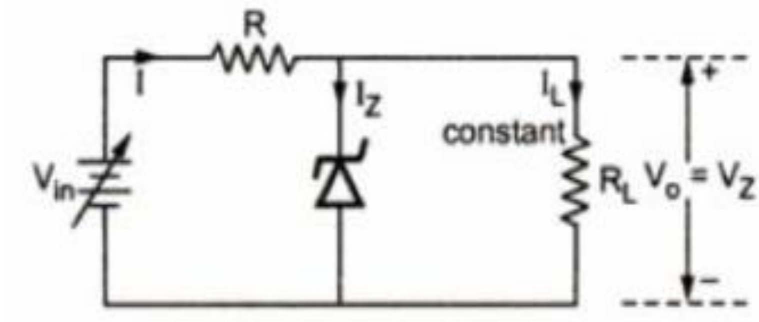


Fig. 5.3 Varying Input condition

- The Fig. 5.3 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

5.3.2 Regulation with Varying Load

- The Fig. 5.4 shows a zener regulator under varying load condition and constant input voltage.
- The input voltage is constant while the load resistance R_L is variable.

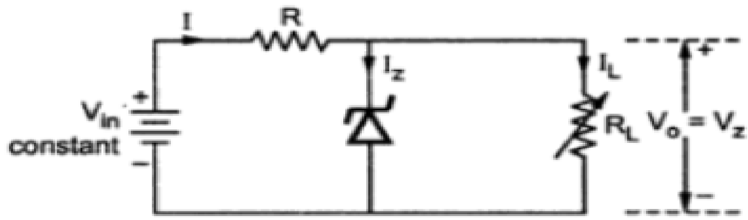


Fig. 5.4 Varying load condition

- 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

5.4 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.

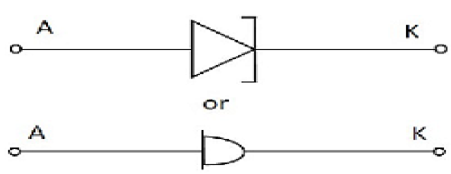


Fig. 5.5 Symbol of tunnel diode

5.4.1 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

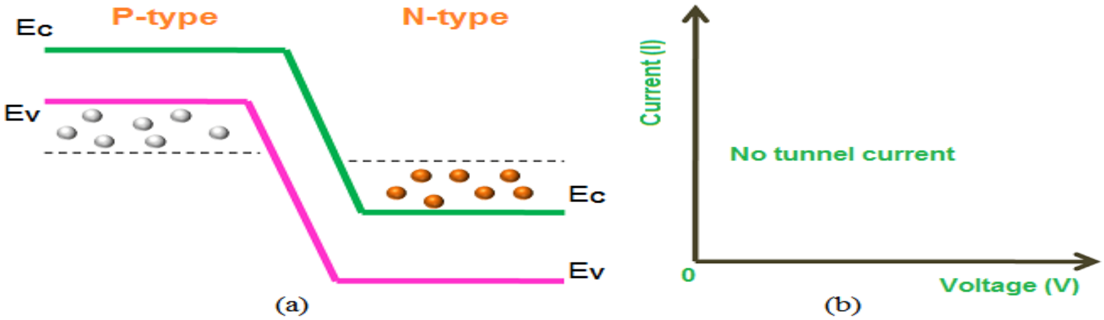


Fig. 5.6 a) Energy Band Diagram b) VI Characteristics

- 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

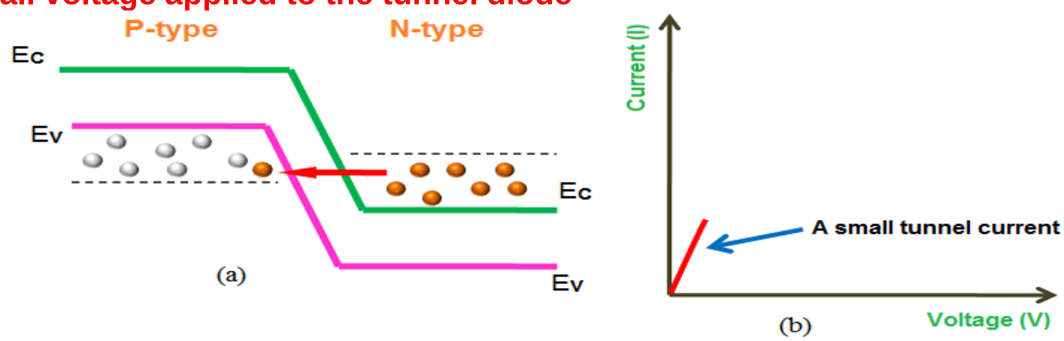


Fig. 5.7 a) Energy Band Diagram b) VI Characteristics

- 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

- 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.

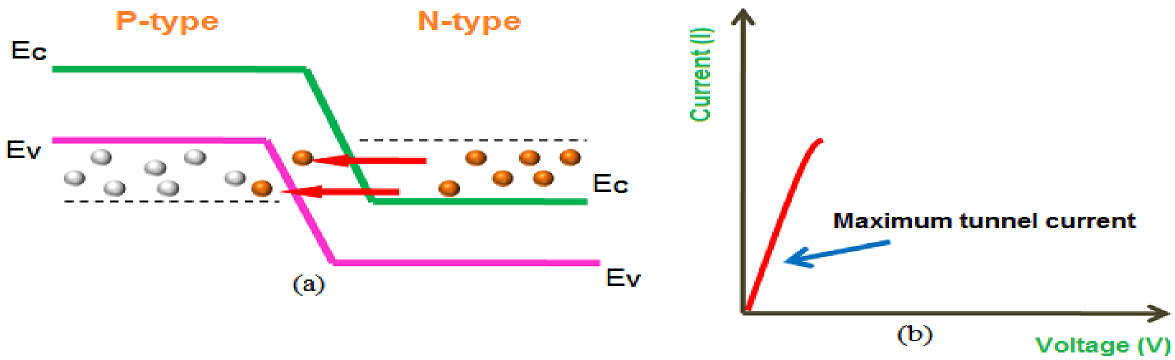


Fig. 5.8 a) Energy Band Diagram b) VI Characteristics

- 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

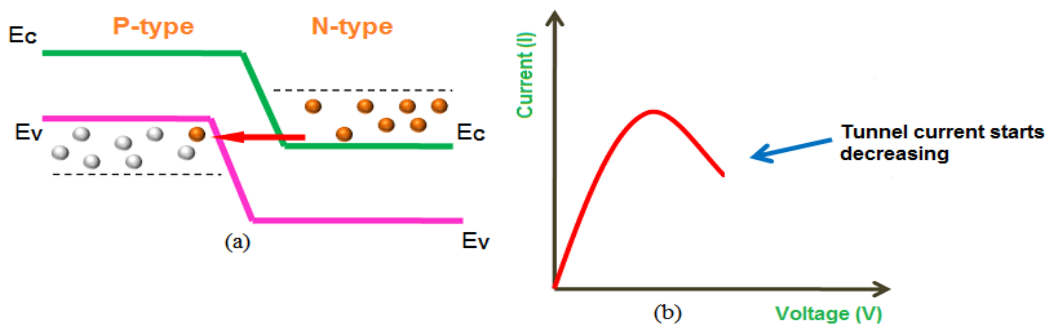


Fig. 5.9 a) Energy Band Diagram b) VI Characteristics

- 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.
- 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.

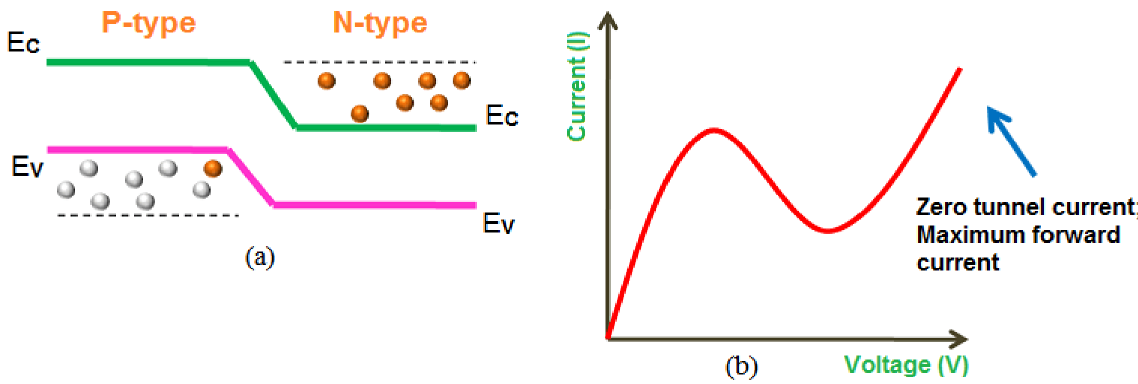


Fig. 5.10 a) Energy Band Diagram   b) VI Characteristics

5.4.2 V-I Characteristics of a Tunnel diode

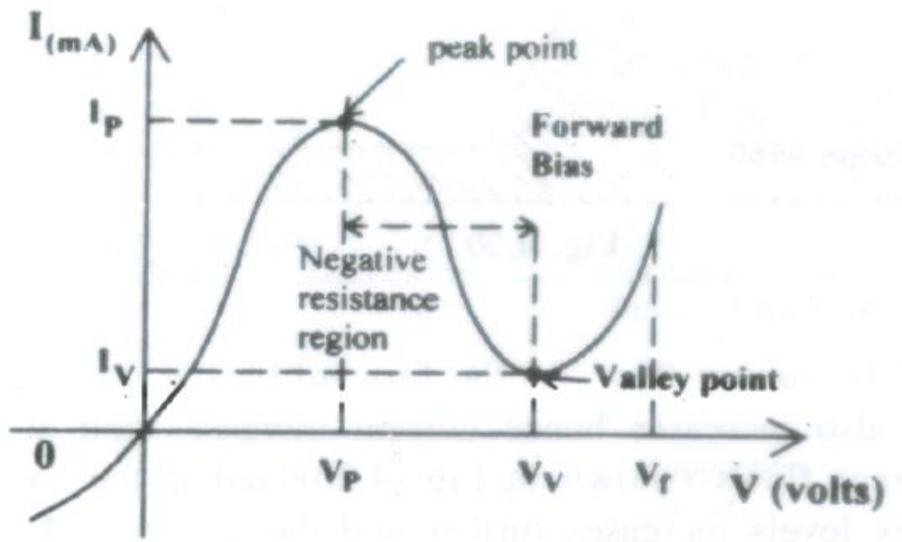


Fig. 5.11 VI characteristics of tunnel diode

- 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.

5.4.3 Advantages of tunnel diode

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

5.4.4 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.

5.4.5 Applications of tunnel diode

- As a high speed switch
- In pulse and digital circuits
- In negative resistance and high frequency oscillator
- In switching networks
- In timing and computer logic circuitry.
- Design of pulse generators and amplifiers.

5.5 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.

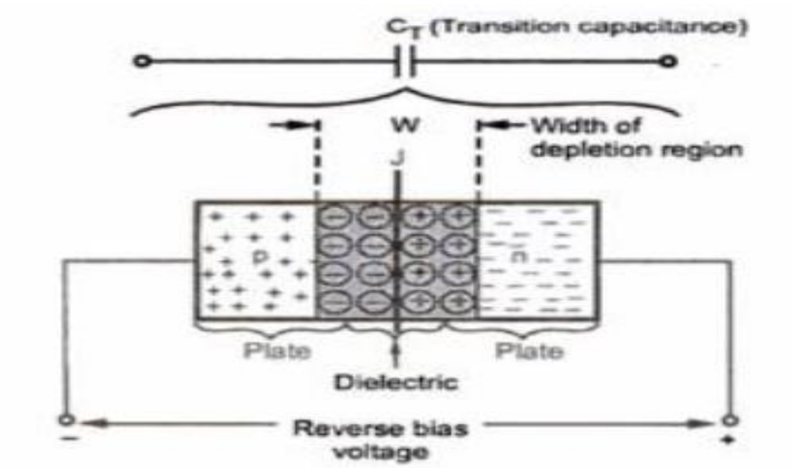


Fig. 5.12 Varactor diode

- 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 5.12.
- 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

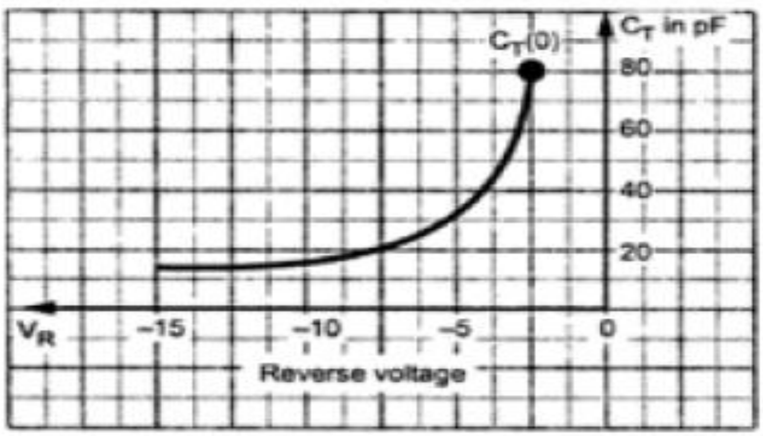


Fig. 5.13 Variation of C_T versus Reverse voltage

- 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. 5.13.
- 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.

5.5.1 Symbol and Equivalent Circuit of Varactor diode

- The Fig. 5.14 (a) shows the symbol of Varactor diode while the Fig. 5.14 (b) shows the first approximation for its equivalent circuit in the reverse bias region.

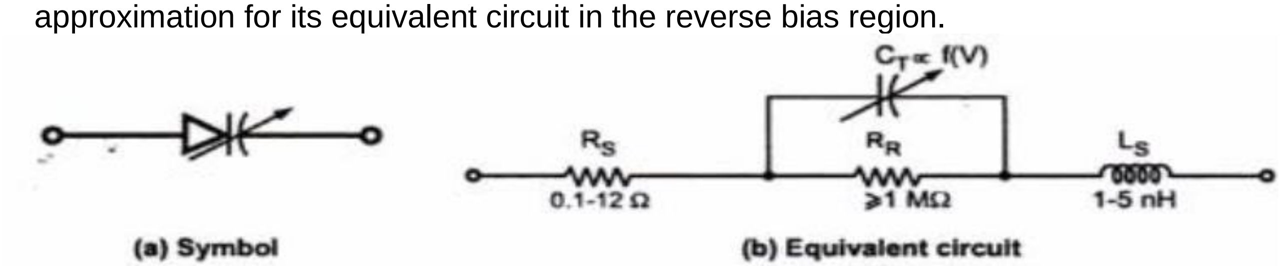


Fig. 5.14 Varactor diode

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

5.5.2 Applications of Varactor diode

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

5.6 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.

5.6.1 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. 5.15.

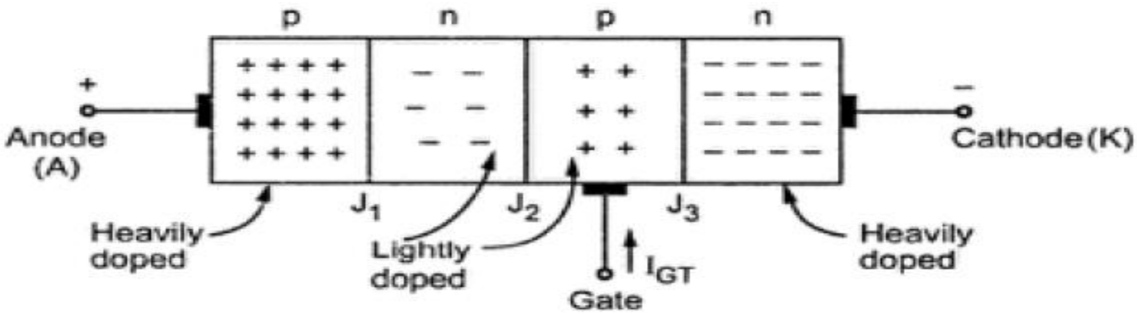


Fig. 5.15 Construction of SCR

- 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. 5.16 shows the symbol of SCR

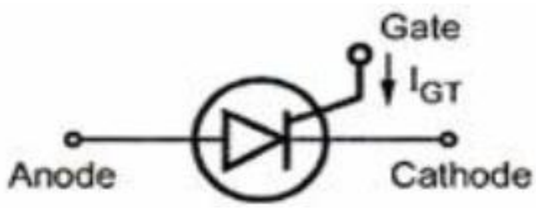


Fig. 5.16 Symbol of SCR

5.6.2 Operation of SCR

The operation of SCR is divided into two categories.

- When gate is open
- When gate is closed

5.6.2.1 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. 5.17 (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.

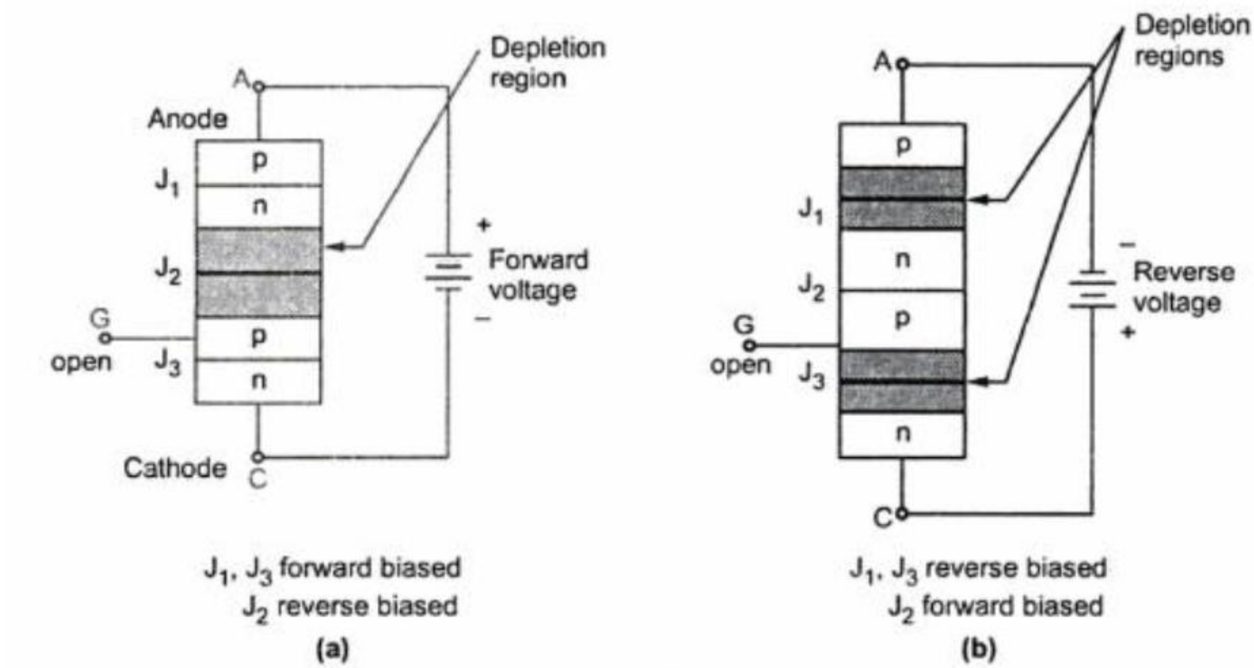


Fig. 5.17 Operation of SCR when Gate is open

- This is shown in the Fig. 5.17 (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.

5.6.2.2 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.

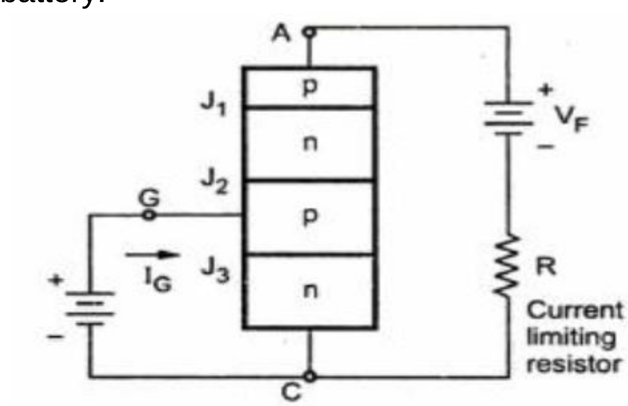


Fig. 5.18 Operation of SCR when Gate is closed

- 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. 5.18.
- The resistance R is required to limit the current.
- Once the SCR conducts, the gate loses its control.

5.6.3 VI Characteristics of SCR

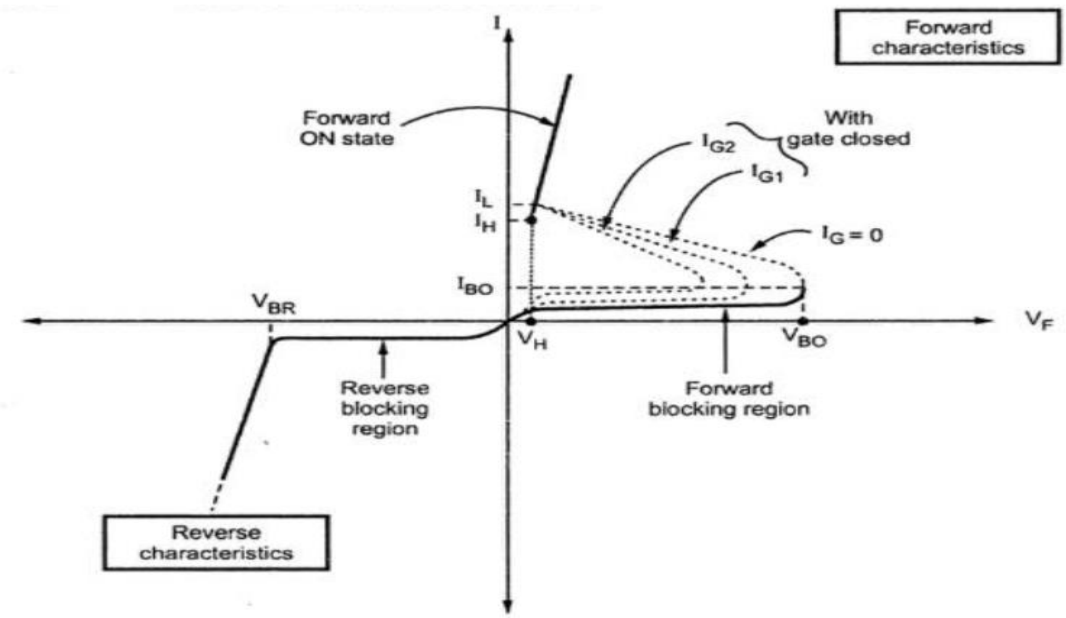


Fig. 5.19 VI Characteristics of SCR

- The Fig. 5.19 shows the characteristics of SCR. The characteristics are divided into two sections.
    - Forward characteristics
    - Reverse characteristics

5.6.3.1 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.

5.6.3.2 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}.

5.6.4 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.

5.6.5 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.

5.6.6 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.

5.6.7 Applications of SCR

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

5.7 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).

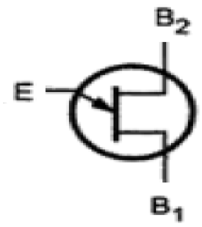


Fig. 5.20 Symbol of UJT

5.7.1 Equivalent Circuit of UJT

- The Fig. 5.21 (a) shows the basic structure of UJT while the Fig. 5.21 (b) shows the equivalent circuit of UJT.

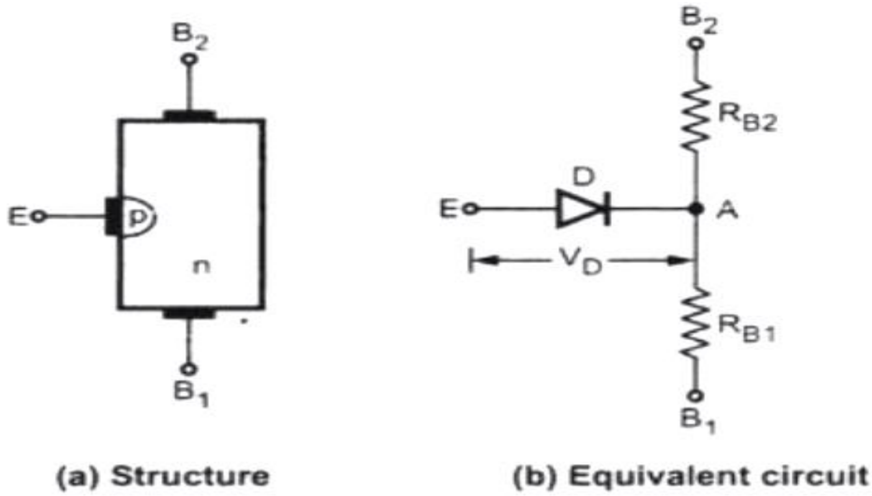


Fig. 5.21 Equivalent Circuit of UJT

- 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.

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

5.7.2 Intrinsic Standoff Ratio (η)

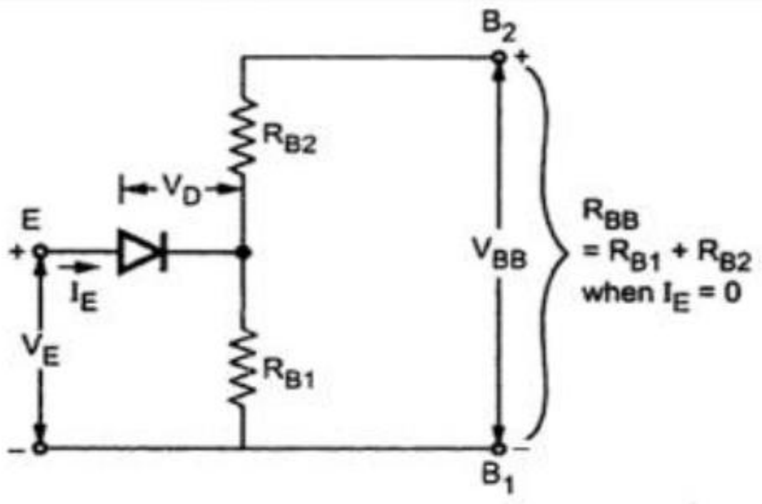


Fig. 5.22 Intrinsic Standoff Ratio

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.

5.7.3 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. 5.23.

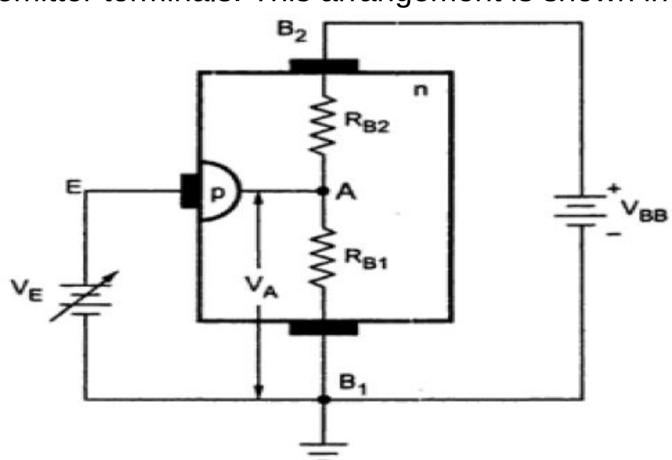


Fig. 5.23 Operation of UJT

- Let us see the effect of change in V_E. The potential of A is decided by η and is equal to ηV_{BB}.

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.

5.7.4 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. 5.24.

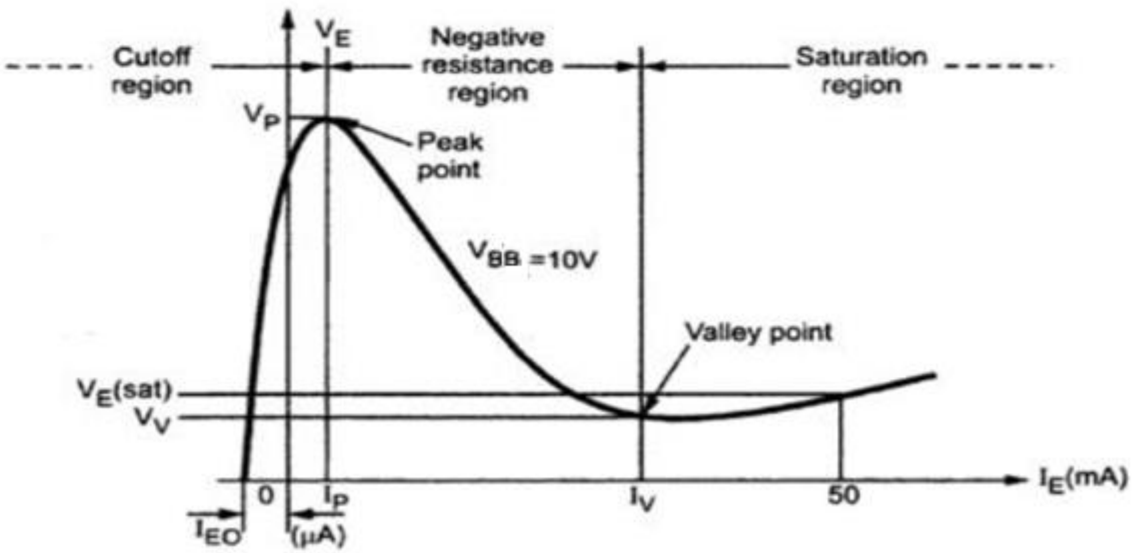


Fig. 5.24 Characteristics of UJT

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.

5.7.5 Applications of UJT

- Triggering of SCR
- Sawtooth Wave Generators
- Relaxation Oscillator

5.8 Photo Diode

- The photodiode is a semiconductor p-n junction device whose region of operation is limited to the reverse biased region.

5.8.1 Construction of Photo Diode

- The Fig. 5.25 (a) shows the symbol of photodiode while the Fig. 5.25 (b) shows the working principle of photodiode.

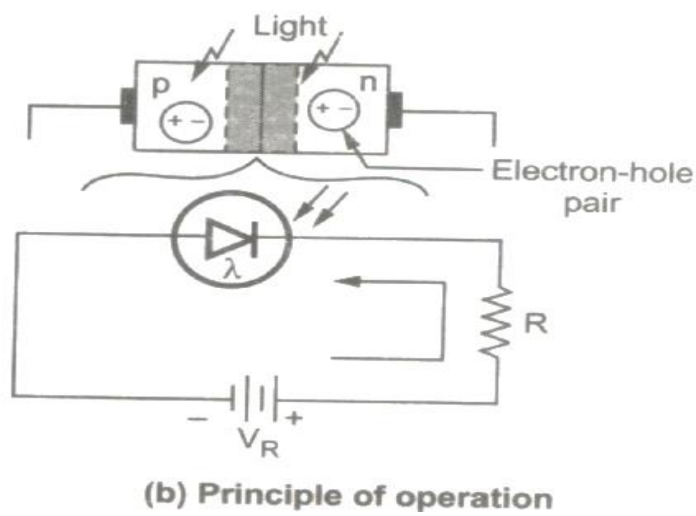


Fig. 5.25 Photodiode

- The Photo diode is connected in reverse biased condition. The depletion region width is large.
- Under normal condition, it carries small reverse current due to minority charge carriers.

- When light is incident through glass window on the p-n junction, photons in the light bombard the p-n junction and some energy is imparted to the valence electrons.
- Due to this, valence electrons are dislodged from the covalent bonds and become free electrons.
- Thus more electron-hole pairs are generated.
- Thus total number of minority charge carriers increases and hence the reverse current increases.

5.8.2 Operation of Photo Diode

- The photodiode is designed such that it is sensitive to the light.
- When there is no light, the reverse biased photodiode carries a current which is very small and called dark current. It is denoted as I_λ.
- It is purely due to thermally generated minority carriers. ;
- When light is allowed to fall on a p-n junction through a small window, photons transfer energy to valence electrons to make them free.
- Hence reverse current increases. It is proportional to the light intensity.

5.8.3 Characteristics of Photo Diode

- The Fig. 5.26 shows the photodiode characteristics.
- The Fig. 5.26 (a) shows the relation between reverse current and light intensity.
- The Fig. 5.26 (b) shows relation between reverse voltage and reverse current at different light intensities.

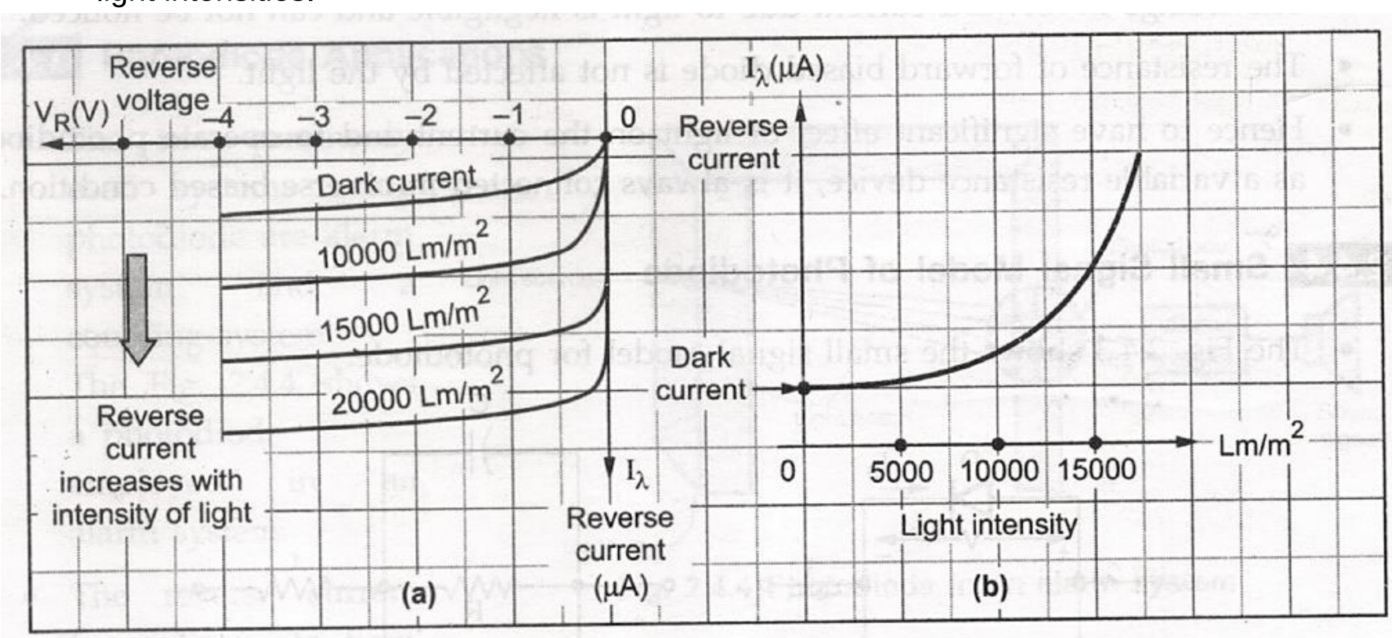


Fig. 5.26 Photodiode characteristics

- It can be seen that reverse current is not dependent on reverse voltage and totally depends on light intensity.

5.8.4 Advantages:

- Low noise
- Highly sensitive to noise
- It operates at high frequencies
- Long lifetime
- High voltage is not required
- It operates very fast

5.8.5 Disadvantages:

- The active area is very small
- Temperature stability is less, when the temperature increases the dark current also increases
- Change in current is very small
- Should not exceed the working temperature limit

5.8.6 Application of Photodiode:

- Used in counters and switching circuits.
- Used widely in optical communication system.
- Used in detection of both visible and invisible light rays.
- Used in safety electronics like fire and smoke detector.
- Used as photo sensors in camera.
- Used in medical applications like pulsed oximeters, in instruments which analyze sample.

5.9 Solar cell

- Solar cell is a device which converts light energy into electrical energy by using photovoltaic effect.
- Solar cell is basically a normal PN Junction diode.
- Solar cell is also called as photovoltaic cell.

5.9.1 Construction of Solar cell

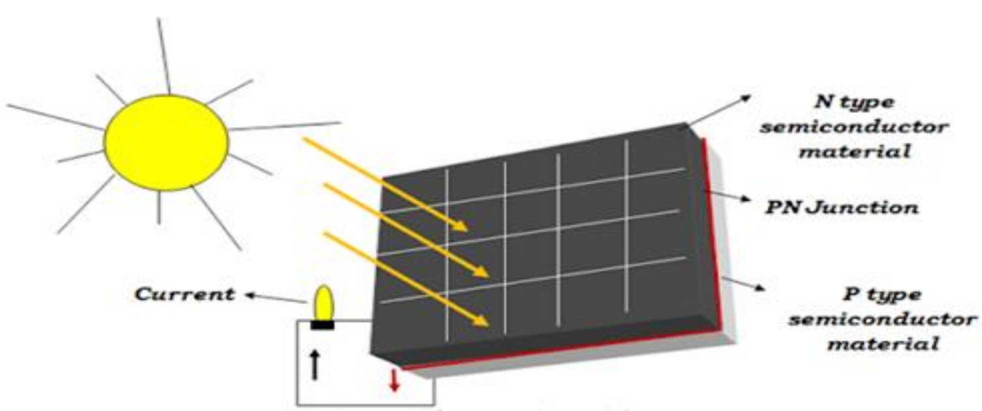


Fig. 5.27 Construction of Solar cell

- It consists of N type and P type semiconductor material.
- N type is highly doped and P type is lightly doped.
- Top and bottom is of conducting electrode to collect the current.
- The bottom is fully covered with the conductive layer and top layer is not fully covered because the sun rays should not be fully blocked.
- Since semiconductors are reflective in nature, antireflective coating is used.
- The whole arrangement is kept inside a thin glass to avoid mechanical shock.

5.9.2 Operation of Solar cell

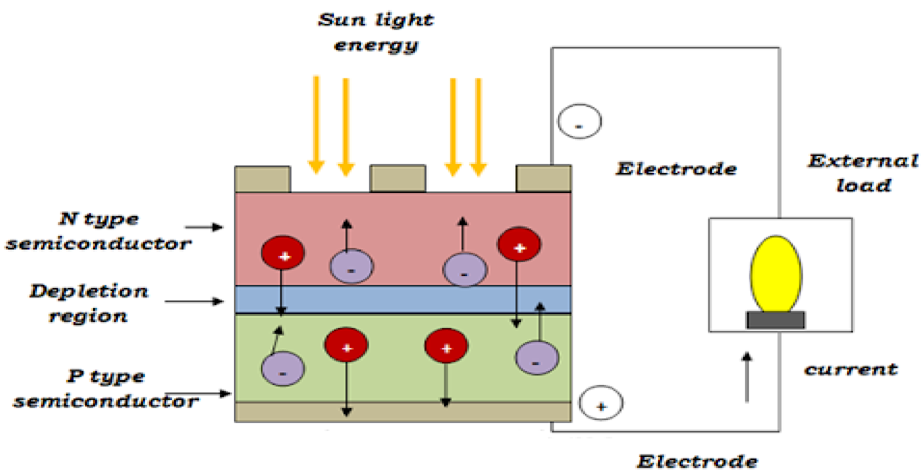


Fig. 5.28 Working of Solar cell

- The working of solar cell is based on photovoltaic effect.
  Photovoltaic effect.
  - It is an effect in which current or voltage is generated when exposed to light.
- Through this effect solar cells convert sunlight into electrical energy.
- A depletion layer is formed at the junction of the N type and P type semiconductor material.
- When light energy of the sun rays falls on the solar panel, the photons which is the small bundle of energy whose energy is higher than the energy gap gives energy to the electrons and holes in the depletion region.
- The electrons and holes move to the higher level which is the conduction band.
- The electrons move towards N type and holes move towards P type and they act as a battery.
- So this movement of electrons and holes forms the electric current.

5.9.3 V-I characteristics of Solar cell

- Fig. 5.29 shows the V-I characteristics of Solar cell.
  - I_{sc} is the short circuit current and it is measured by short circuiting the terminals.
  - V_{oc} is the open circuit voltage and it is measured when no load is connected.
  - P_m is maximum power,

- I_m is maximum current,
- V_m is maximum voltage and it occurs at the bend of the characteristic curve.

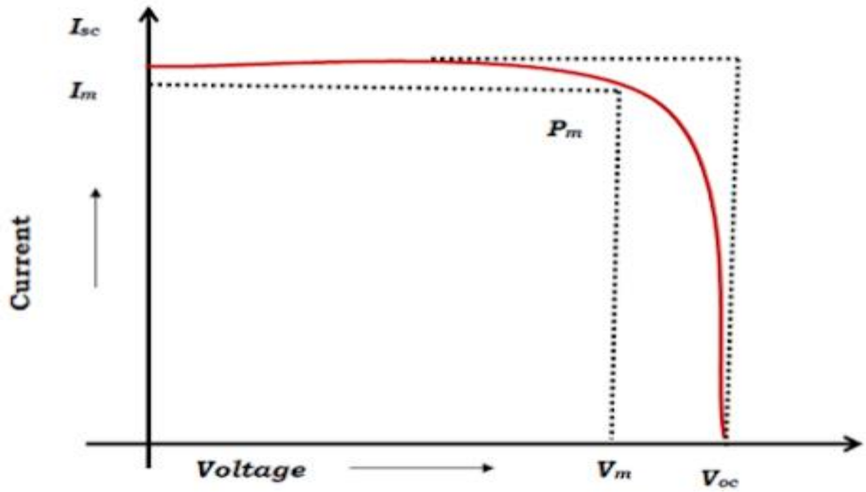


Fig. 5.29 V-I characteristics of Solar cell

5.9.4 Advantages of Solar cell

- It uses renewable energy
- No pollution so it is environment friendly
- It lasts for many years
- No maintenance cost

5.9.5 Disadvantages of Solar cell

- Energy is not produced during rainy, cloudy days and during night times.
- Cost of installation is high.

5.9.6 Applications of Solar cell

- It is used in calculators and in wrist watches
- Used in storage batteries
- Street lights
- Portable power supplies
- Satellites

5.10 Light Emitting Diode

- Light emitting diode (LED) is similar to the semiconductor PN Junction diode.
- When it is forward biased the holes from P type and electrons from N type combine with each other and it emits energy in the form of light.
- When reverse biased, the current does not flow.
- Available LED colors are red, green, blue, yellow, amber and white.
- It has two terminals Anode and Cathode. Symbol of LED is shown in fig. 5.30

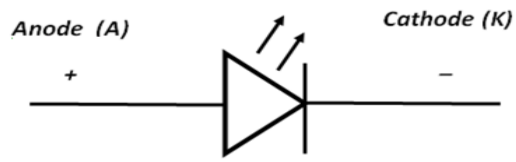


Fig. 5.30 Symbol of LED

5.10.1 Construction of LED

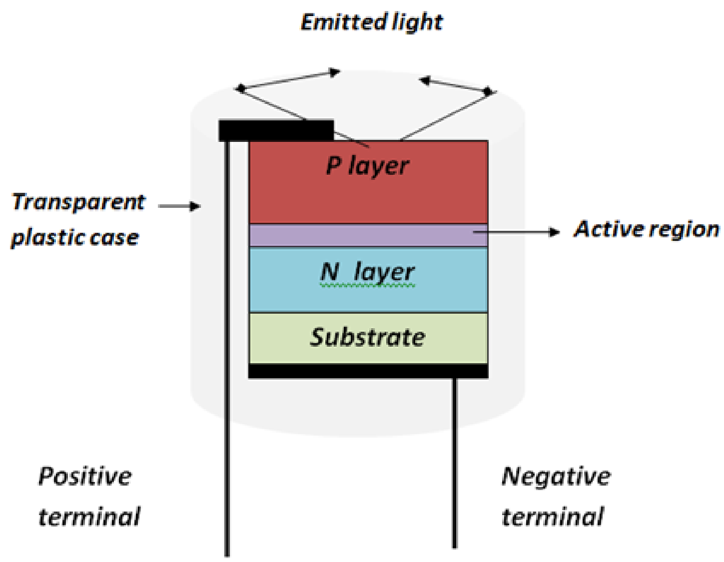


Fig. 5.31 Construction of LED

- The structure and the construction of LED differ from the normal semiconductor diodes.
- PN junction is formed by material which have low energy band gap like gallium antimonide, gallium arsenide, indium antimonide and indium arsenide.
- The PN junction is then covered with hemispherical shaped shell body made up of transparent solid plastic epoxy resin.
- LED is made with rectangular or cylindrical shaped dome also. This protects the LED from atmospheric disturbances, vibration and thermal shock.
- The LED is constructed in such a way that the light emitted by the photons in the junction is focused at the top of the dome.
- The P type material is the surface of LED.
- The anode is deposited at the edge of the P type material.
- Below the P type material N type material is placed and the cathode is made of gold film which is placed below the N type material.
- Gold film is used for better reflection.

5.10.2 Operation of LED

- When it is forward biased (when P type is connected with positive terminal and when N type is connected to negative terminal), the current starts to flow.
- So the majority carriers and minority carriers combine each other and it neutralizes the charge carriers in the depletion region which is the junction of P and N type semiconductors.

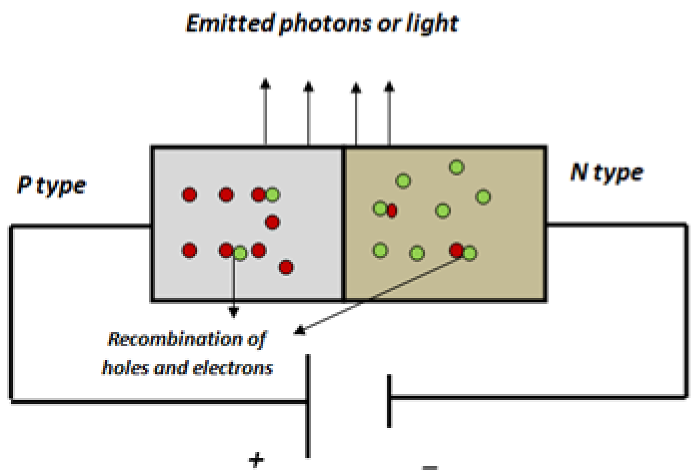


Fig. 5.32 Working of LED

- When the energy of electrons decreases from higher level to lower level it emits energy in the form of photons.
- So the movement of majority and minority charge carriers releases some amount of photons in the form of monochromatic light.
- Its wavelength is in nm which resembles the color of the LED.
- LED needs very low voltage of about 0.3V to turn on the device.
- When it is reverse biased, current does not flow.
- When the applied external voltage is increased, it permanently damages the device.

5.10.3 V-I characteristics of LED

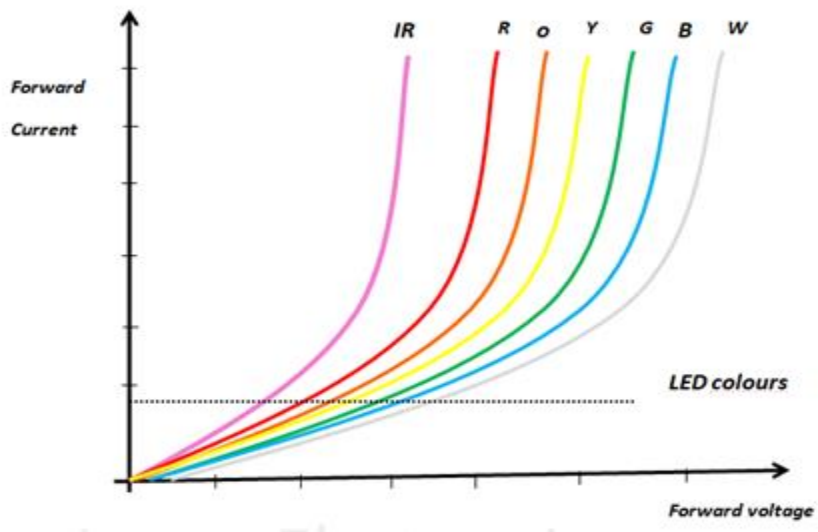


Fig. 5.33 V-I Characteristics of LED

- Different color LED was formed by using different types of semiconductor material. Each color have particular wavelength.

5.10.4 Advantages:

- Long life time
- Energy efficient
- It is made up of solid material, no filament
- It is environment friendly, does not consist of hazardous materials
- The brightness and the color can be controlled
- Low power consumption
- It does not produce heat

5.10.5 Disadvantages:

- LEDs are expensive
- The color of the object look different than in the sunlight
- High temperature and over usage can results in permanent device failure
- Blue light hazard from LED may affect the eyes

5.10.6 Application of LED:

- Used in general lighting as bulbs
- Used in traffic light signal
- Used in vehicles used to dim the light
- Used in remote controls
- Used in camera flashes
- Used in lighted wallpaper
- Used in horticulture grow lamps

5.11 Schottky diode

- A Schottky diode is a metal-semiconductor junction diode that has less forward voltage drop and can be used in high-speed switching applications.
- The symbol of Schottky diode is shown in fig. 5.34. In this metal form the anode terminal and semiconductor region form the cathode terminal.

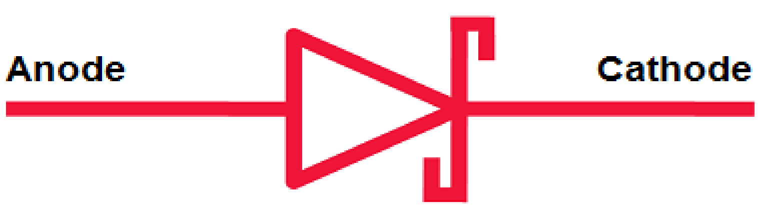


Fig. 5.34 Symbol of Schottky diode

5.11.1 Construction of Schottky Diode

- It is formed of metal and semiconductor.
- The metal such as gold, silver, molybdenum, tungsten or platinum is used.
- The N-type semiconductor is used. Usually, Gallium is used as a semiconductor for the schottky diode.

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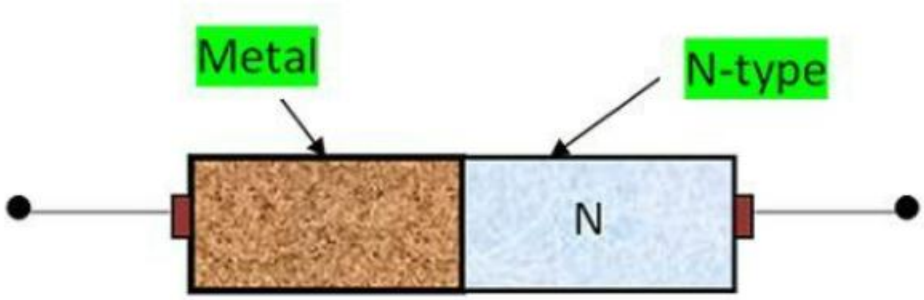

Fig. 5.35 Construction of Schottky Diode

5.11.2 Working of Schottky diode

5.11.2.1 Forward Bias

- When external voltage is applied electrons receives more energy to cross the junction barrier and move from N type semiconductor to the metal and thus the current starts to flow.
- The current is due to the drift of majority charge carriers.
- Since there is no P type semiconductor there is no holes and thus no minority carriers.
- When the current starts to flow there is a voltage drop across the terminals, the voltage drop of normal diode is 0.6V to 1.7V, but for schottky diode the voltage drop is 0.15V to 0.45V.

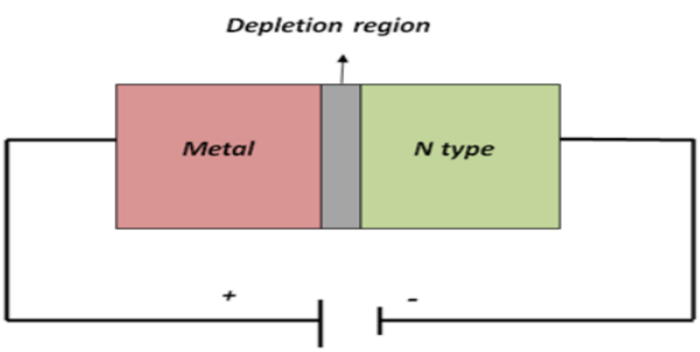

Fig. 5.36 Forward bias of Schottky diode

5.11.2.2 Reverse Bias

- When the diode is reverse biased, the metal is connected to the negative terminal and N type material is connected to the positive terminal.

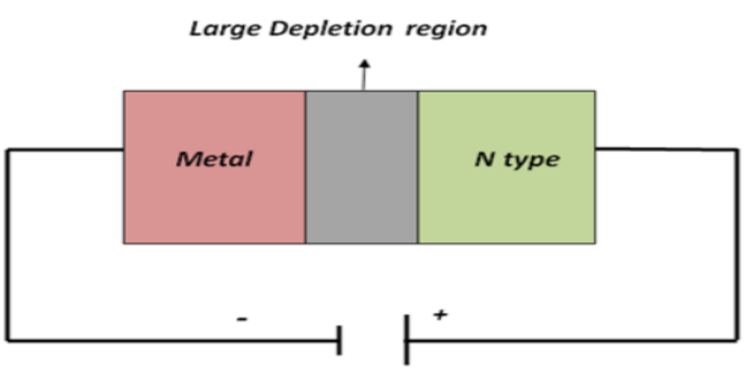

Fig. 5.37 Reverse bias of Schottky diode

- The size of the depletion region increases and the current stops to flow.
- There is small amount of leakage current.
- When the applied voltage is increased further the current increases and when increased further the depletion region breaks down which damages the device permanently.

5.11.3 V-I Characteristics of Schottky diode

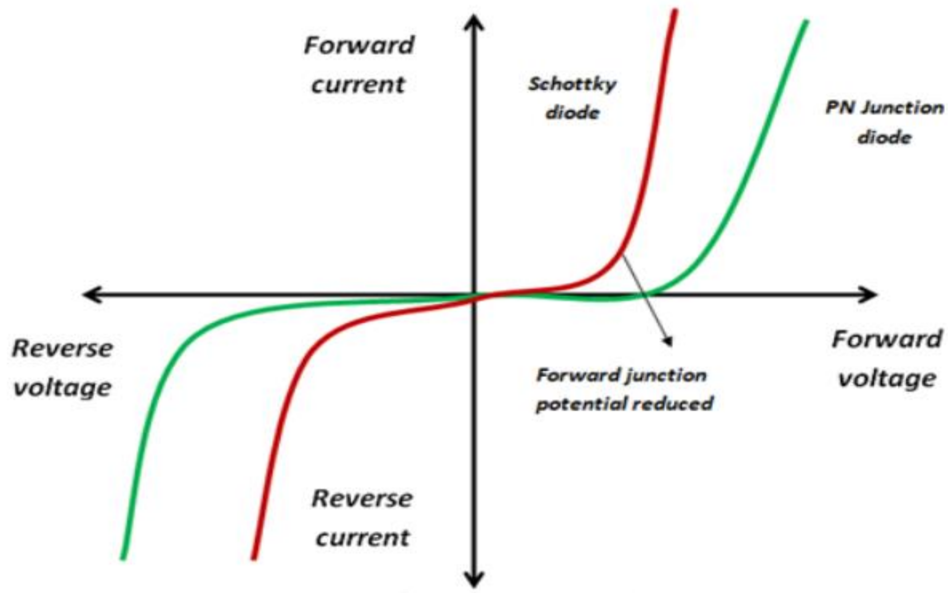

Fig. 5.38 V-I Characteristics of Schottky diode

5.11.4 Advantages

- It switches very fast.
- Low junction capacitance
- Operates at high frequencies
- Low cut-in voltage
- Very low power consumption
- High efficiency

5.11.5 Disadvantages

- It is more expensive
- Operates at low voltages
- It gets heated up very quickly
- It has high reverse current

5.11.6 Application of Schottky diode

- Diode rectifier
- Voltage clamping application
- High speed switching applications