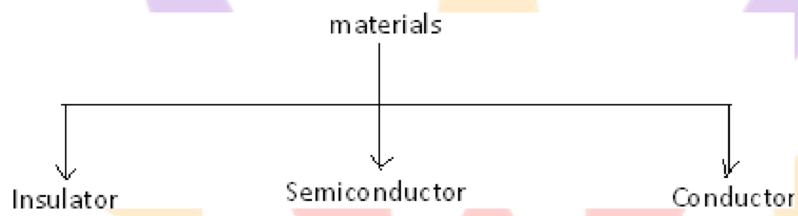
UNIT-I

PN JUNCTION DIODE

1.0 INTRODUCTON

1.0.1. Based on the electrical conductivity all the materials in nature are classified as insulators, semiconductors, and conductors.



Insulator: An insulator is a material that offers a very low level (or negligible) of conductivity when voltage is applied. Eg: Paper, Mica, glass, quartz. Typical resistivity level of an insulator is of the order of 10^{10} to 10^{12} Ω-cm. The energy band structure of an insulator is shown in the fig.1.1. Band structure of a material defines the band of energy levels that an electron can occupy. Valance band is the range of electron energy where the electron remain bended too the atom and do not contribute to the electric current. Conduction bend is the range of electron energies higher than valance band where electrons are free to accelerate under the influence of external voltage source resulting in the flow of charge.

The energy band between the valance band and conduction band is called as forbidden band gap. It is the energy required by an electron to move from balance band to conduction band i.e. the energy required for a valance electron to become a free electron.

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

For an insulator, as shown in the fig.1.1 there is a large forbidden band gap of greater than 5Ev. Because of this large gap there a very few electrons in the CB and hence the conductivity of insulator is poor. Even an increase in temperature or applied electric field is insufficient to transfer electrons from VB to CB.

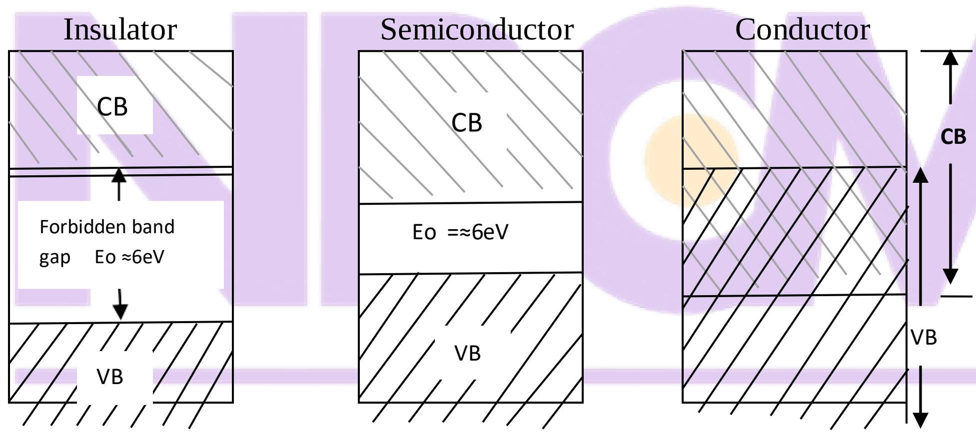


FiG:1.1 Energy band diagrams insulator, semiconductor and conductor

Conductors: A conductor is a material which supports a generous flow of charge when a voltage is applied across its terminals. i.e. it has very high conductivity. Eg: Copper, Aluminum, Silver, Gold. The resistivity of a conductor is in the order of 10^{-4} and 10^{-6} Ω-cm. The Valance and conduction bands overlap (fig1.1) and there is no energy gap for the electrons to move from valance band to conduction band. This implies that there are free electrons in CB even at absolute zero temperature (0K). Therefore at room temperature when electric field is applied large current flows through the conductor.

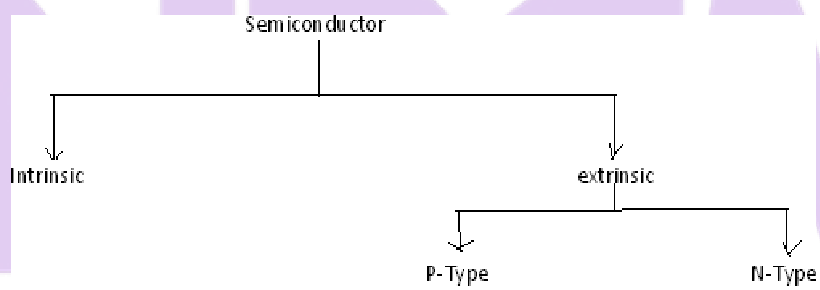
Semiconductor: A semiconductor is a material that has its conductivity somewhere between theinsulator and conductor. The resistivity level is in the range of 10 and 10^{4} Ω-cm. Two of the most commonly used are Silicon (Si=14 atomic no.) and germanium (Ge=32 atomic no.). Both have 4 valance electrons. The forbidden band gap is in the order of 1eV. For eg., the band gap energy for Si, Ge and GaAs is 1.21, 0.785 and 1.42 eV, respectively at absolute zero temperature (0K). At 0K and at low temperatures, the valance band electrons do not have sufficient energy to move from V to CB. Thus semiconductors act a insulators at 0K. as the temperature increases, a large number of valance electrons acquire sufficient energy to leave the VB, cross the forbidden bandgap and reach CB. These are now free electrons as they can move freely under the influence of electric field. At room temperature there are sufficient electrons in the CB and hence the semiconductor is capable ofconducting some current at room temperature.

Inversely related to the conductivity of a material is its resistance to the flow of charge or current. Typical resistivity values for various materials' are given as follows.

Insulator	Semiconductor	Conductor
10^{-6} Ω-cm (Cu)	50Ω-cm (Ge)	10^{12} Ω-cm (mica)
	50×10^{3} Ω-cm (Si)	

Typical resistivity values

1.0.1 Semiconductor Types



A pure form of semiconductors is called as intrinsic semiconductor. Conduction in intrinsic sc is either due to thermal excitation or crystal defects. Si and Ge are the two most important semiconductors used. Other examples include Gallium arsenide GaAs, Indium Antimonide (InSb) etc.

Let us consider the structure of Si. A Si atomic no. is 14 and it has 4 valance electrons. These 4 electrons are shared by four neighboring atoms in the crystal structure by means of covalent bond. Fig. 1.2a shows the crystal structure of Si at absolute zero temperature (0K). Hence a pure SC acts has poor conductivity (due to lack of free electrons) at low or absolute zero temperature.

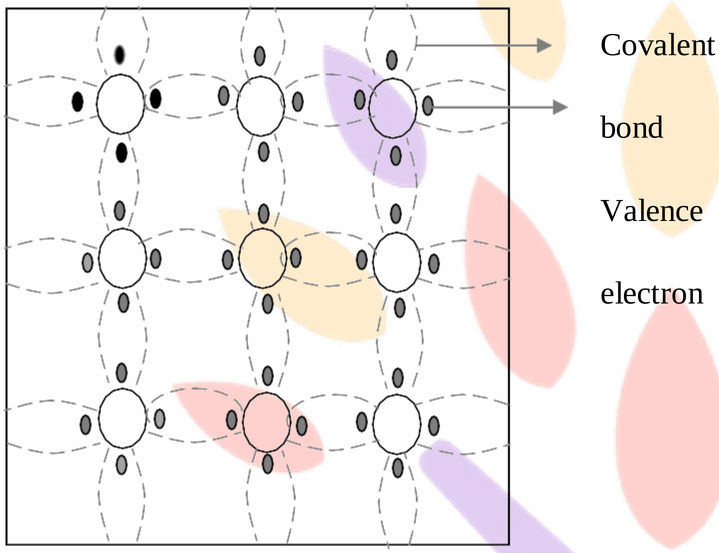


Fig. 1.2a crystal structure of Si at 0K

At room temperature some of the covalent bonds break up to thermal energy as shown in fig 1.2b. The valance electrons that jump into conduction band are called as free electrons that are available for conduction.

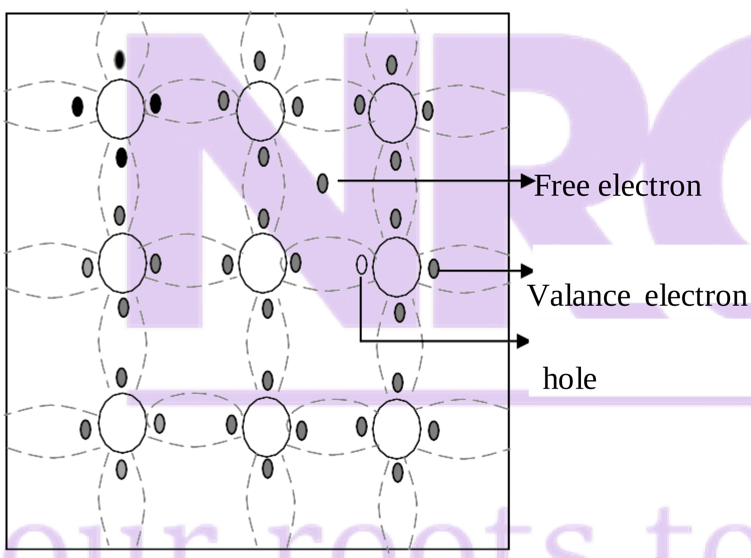
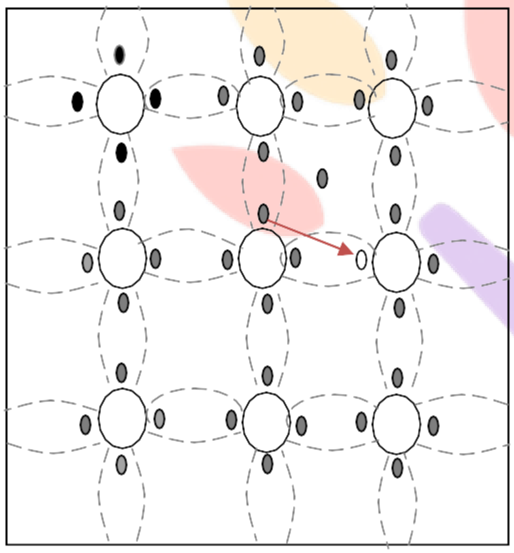


Fig. 1.2b crystal structure of Si at roomtemperature0K

The absence of electrons in covalent bond is represented by a small circle usually referred to ashole which is of positive charge. Even a hole serves as carrier of electricity in a manner similar to thatof free electron.

The mechanism by which a hole contributes to conductivity is explained as follows:
When a bond is in complete so that a hole exists, it is relatively easy for a valance electron in the neighboring atom to leave its covalent bond to fill this hole. An electron moving from a bond to filla hole moves in a direction opposite to that of the electron. This hole, in its new position may now be filled by an electron from another covalent bond and the hole will correspondingly move one more step in the direction opposite to the motion of electron. Here we have a mechanism for conduction of electricity which does not involve free electrons. This phenomenon is illustrated in fig1.3



Electron

movementHole

movement

Fig. 1.3a

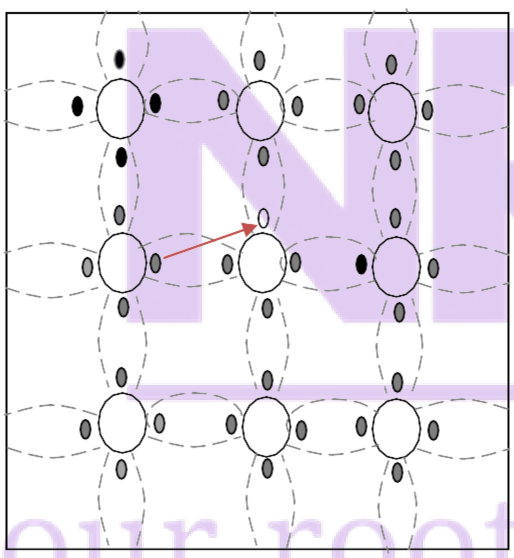


Fig. 1.3b

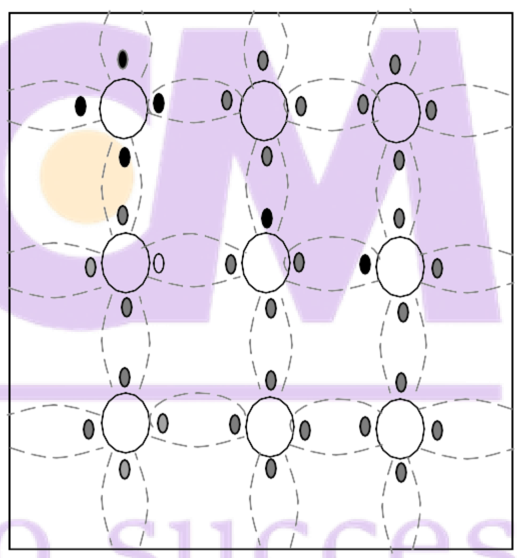


Fig. 1.3c

Fig 1.3a show that there is a hole at ion 6.Imagine that an electron from ion 5 moves into the hole at ion 6 so that the configuration of 1.3b results. If we compare both fig1.3a &fig 1.3b, it appears as if the hole has moved towards the left from ion6 to ion 5. Further if we compare fig 1.3b and fig1.3c, the hole moves from ion5 to ion 4. This discussion indicates the motion of hole is in a direction opposite to that of motion of electron. Hence we consider holes as physical entities whose movement constitutes flow of current.

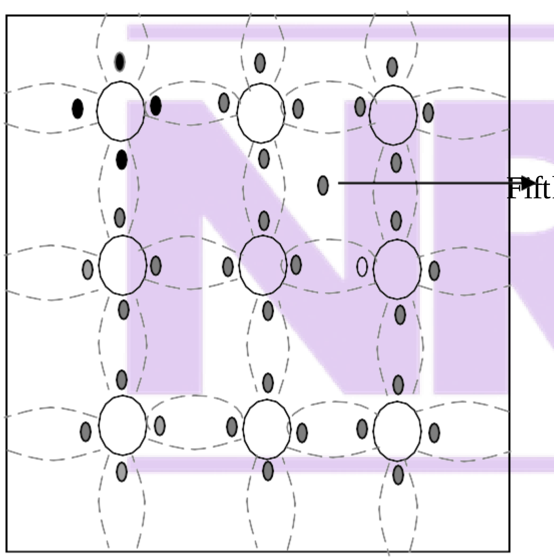
In a pure semiconductor, the number of holes is equal to the number of free electrons.

1.0.2 EXTRINSIC SEMICONDUCTOR

Intrinsic semiconductor has very limited applications as they conduct very small amounts of current at room temperature. The current conduction capability of intrinsic semiconductor can be increased significantly by adding a small amounts impurity to the intrinsic semiconductor. By adding impurities it becomes impure or extrinsic semiconductor. This process of adding impurities is called as doping. The amount of impurity added is 1 part in 10^6 atoms.

N type semiconductor: If the added impurity is a pentavalent atom, then the resultant semiconductoris called N-type semiconductor. Examples of pentavalent impurities are Phosphorus, Arsenic, Bismuth, Antimony etc.

A pentavalent impurity has five valance electrons. Fig 1.4a shows the crystal structure of N-type semiconductor material where four out of five valance electrons of the impurity atom(antimony) forms covalent bond with the four intrinsic semiconductor atoms. The fifth electron is loosely bound to the impurity atom. This loosely bound electron can be easily.



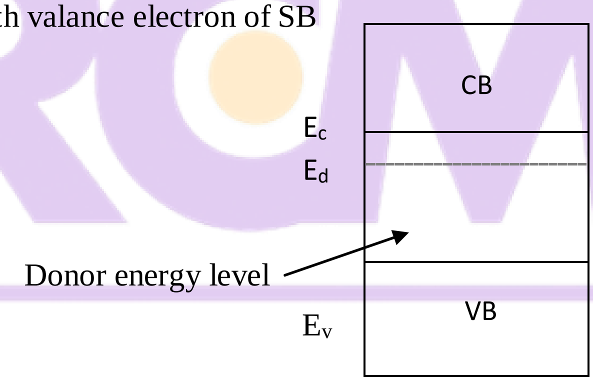


Fig. 1.4a crystal structure of N type SC

Fig. 1.4bEnergy band diagram of N type

Excited from the valance band to the conduction band by the application of electric field or increasing the thermal energy. The energy required to detach the fifth electron form the impurity atom is very small of the order of 0.01ev for Ge and 0.05 eV for Si.

The effect of doping creates a discrete energy level called donor energy level in the forbidden band gap with energy level E_d slightly less than the conduction band (fig 1.4b). The difference between the energy levels of the conducting band and the donor energy level is the energy required to free the fifthvalance electron (0.01 eV for Ge and 0.05 eV for Si). At room temperature almost all the fifth electrons from the donor impurity atom are raised to conduction band and hence the number of electrons in theconduction band increases significantly. Thus every antimony atom contributes to one conduction electron without creating a hole.

In the N-type sc the no. of electrons increases and the no. of holes decreases compared to those available in an intrinsic sc. The reason for decrease in the no. of holes is that the larger no. of electrons present increases the recombination of electrons with holes. Thus current in N type sc is dominated by electrons which are referred to as majority carriers. Holes are the minority carriers in N type sc

P type semiconductor: If the added impurity is a trivalent atom then the resultant semiconductor is called P-type semiconductor. Examples of trivalent impurities are Boron, Gallium , indium etc.

The crystal structure of p type sc is shown in the fig1.5a. The three valance electrons of the impurity (boon) forms three covalent bonds with the neighboring atoms and a vacancy exists in the fourth bond giving rise to the holes. The hole is ready to accept an electron from the neighboring atoms. Each trivalent atom contributes to one hole generation and thus introduces a large no. of holes in the valance band. At the same time the no. electrons are decreased compared to those available in intrinsic sc because of increased recombination due to creation of additional holes.

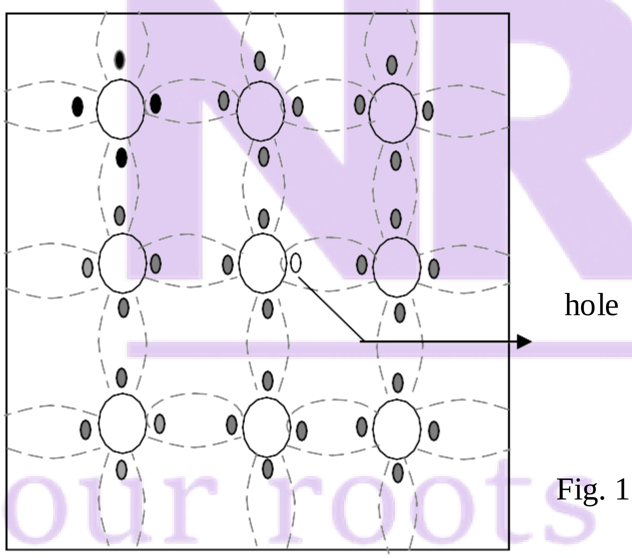


Fig. 1.5a crystal structure of P type sc

Thus in P type sc , holes are majority carriers and electrons are minority carriers. Since each trivalent impurity atoms are capable accepting an electron, these are called as acceptor atoms. The following fig 1.5b shows the pictorial representation of P type sc

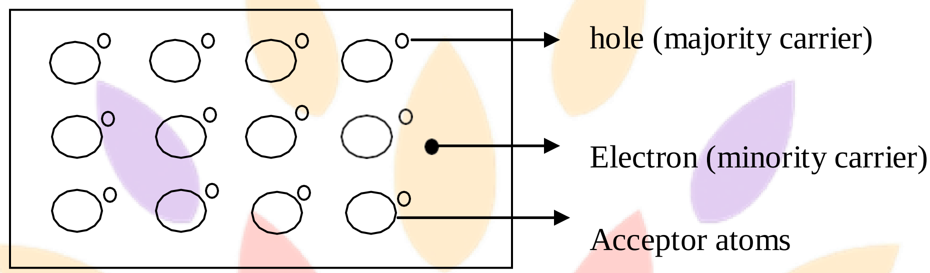


Fig. 1.5b crystal structure of P type sc

- The conductivity of N type sc is greater than that of P type sc as the mobility of electron is greater than that of hole.
- For the same level of doping in N type sc and P type sc, the conductivity of an Ntype sc is around twice that of a P type sc

1.0.3 CONDUCTIVITY OF SEMICONDUCTOR

In a pure sc, the no. of holes is equal to the no. of electrons. Thermal agitation continue to produce new electron- hole pairs and the electron hole pairs disappear because of recombination. with each electron hole pair created , two charge carrying particles are formed . One is negative which is a free electron with mobility μ_n . The other is a positive i.e., hole with mobility μ_p . The electrons and hole move in opppsitte direction in a an electric field E, but since they are of opposite sign, the current due to each is in the same direction. Hence the total current density J within the intrinsic sc is given by

$J = J_n + J_p$

$= q\, n\, \mu_n E + q\, p\, \mu_p E$

$= (n\, \mu_n + p\, \mu_p) qE$

$= \varsigma E$

Where n=no. of electrons / unit volume i.e., concentration of free electronsP=

no. of holes / unit volume i.e., concentration of holes

E=applied electric field strength, V/m

q= charge of electron or hole I n Coulombs

Hence, ς is the conductivity of sc which is equal to $(n\,\mu_n + p\,\mu_p)q$. he resistivity of sc is reciprocal of conductivity.

$P = 1/\varsigma$

It is evident from the above equation that current density with in a sc is directly proportional to applied electric field E.

For pure sc, $n=p=n_i$ where n_i = intrinsic concentration. The value of n_i is given

by $n_i^2 = AT^3 \exp(-E_{GO}/KT)$

therefore, $J = n_i(\mu_n + \mu_p)\,q\,E$

Hence conductivity in intrinsic sc is $\varsigma i = n_i(\mu_n + \mu_p)\,q$

Intrinsic conductivity increases at the rate of 5% per ^{o} C for Ge and 7% per ^{o} C for Si.

Conductivity in extrinsic sc (N Type and P Type):

The conductivity of intrinsic sc is given by $\varsigma i = n_i(\mu_n + \mu_p)\,q = (n\,\mu_n + p$

$\mu_p)q$For N type , $n>>p$

Therefore $\varsigma = q\,n\,\mu_n$

For P type ,$p>>n$

Therefore $\varsigma = q\,p\,\mu_p$

1.0.4 CHARGE DENSITIES IN P TYPE AND N TYPE SEMICONDUCTOR:

Mass Action Law:

Under thermal equilibrium for any semiconductor, the product of the no. of holes and the concentration of electrons is constant and is independent of amount of donor and acceptor impurity doping.

$n.p = n_i^2$

where n= eleetron concentration

p = hole concentration

n_i^2= intrinsic concentration

Hence in N type sc , as the no. of electrons increase the no. of holes decreases. Similarly in P type as the no. of holes increases the no. of electrons decreases. Thus the product is constant and is equal to n_i^2 in case of intrinsic as well as extrinsic sc.

The law of mass action has given the relationship between free electrons concentration and hole concentration. These concentrations are further related by the law of electrical neutrality as explained below.

Law of electrical neutrality:

Sc materials are electrically neutral. According to the law of electrical neutrality, in an electrically neutral material, the magnitude of positive charge concentration is equal to tat of negative charge concentration. Let us consider a sc that has N_D donor atoms per cubic centimeter and N_A acceptor atoms per cubic centimeter i.e., the concentration of donor and acceptor atoms are N_D and N_A respectively. Therefore N_D positively charged ions per cubic centimeter are contributed by donor atoms and N_A negatively charged ions per cubic centimeter are contributed by the acceptor atoms. Let n, p is concentration of free electrons and holes respectively. Then according to the law of neutrality

$N_D + p = N_A + n$..eq 1.1

For N type sc, $N_A = 0$ and $n >> p$. Therefore $N_D \approx n$ .... eq 1.2

Hence for N type sc the free electron concentration is approximately equal to the concentration of donor atoms. In later applications since some confusion may arise as to which type of sc is under consideration a the given moment, the subscript n or p is added for Ntype or P type respectively. Hence eq1.2 becomes $N_D \approx n_n$

Therefore current density in N type sc is $J = N_D \mu_n q$

EAnd conductivity $\varsigma = N_D \mu_n q$

For P type sc, $N_D = 0$ and $p >> n$. Therefore $N_A \approx p$

Or $N_A \approx p_p$

Hence for P type sc the hole concentration is approximately equal to the concentration ofacceptor atoms.

Therefore current density in N type sc is $J = N_A \mu_p q$

EAnd conductivity $\varsigma = N_A \mu_p q$

Mass action law for N type, $n_n p_n = n_i^2$

$$p_n = n_i^2 / N_D \quad \text{since } (n_n \approx N_D)$$

Mass action law for P type, $n_p\, p_p = n_i^2$

$$n_p = n_i^2 / N_A \quad \text{since } (p_p \approx N_A)$$

1.1 QUANTITATIVE THEORY OF PN JUNCTION DIODE

1.1.1 PN JUNCTION WITH NO APPLIED VOLTAGE OR OPEN CIRCUIT CONDITION:

In a piece of sc, if one half is doped by p type impurity and the other half is doped by n type impurity, a PN junction is formed. The plane dividing the two halves or zones is called PN junction. As shown in the fig the n type material has high concentration of free electrons, while p type material has high concentration of holes. Therefore at the junction there is a tendency of free electrons to diffuse over to the P side and the holes to the N side. This process is called diffusion. As the free electrons move across the junction from N type to P type, the donor atoms become positively charged. Hence a positive charge is built on the N-side of the junction. The free electrons that cross the junction uncover the negative acceptor ions by filing the holes. Therefore a negative charge is developed on the p –side of the junction..This net negative charge on the p side prevents further diffusion of electrons into the p side. Similarly the net positive charge on the N side repels the hole crossing from p side to N side. Thus a barrier sis set up near the junction which prevents the further movement of charge carriers i.e. electrons and holes. As a consequence of induced electric field across the depletion layer, an electrostatic potential difference is established between P and N regions, which are called the potentialbarrier, junction barrier, diffusion potential or contact potential, Vo. The magnitude of the contact potential Vo varies with doping levels and temperature. Vo is 0.3V for Ge and 0.72 V for Si.

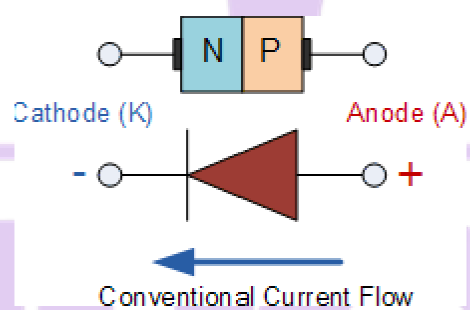


Fig 1.6: Symbol of PN Junction Diode

The electrostatic field across the junction caused by the positively charged N-Type region tends to drive the holes away from the junction and negatively charged p type regions tend to drive the electrons away from the junction. The majority holes diffusing out of the P region leave behindnegatively charged acceptor atoms bound to the lattice, thus exposing a negatives pace charge in a previously neutral region. Similarly electrons diffusing from the N region expose positively ionized donor atoms and a double space charge builds up at the junction as shown in the fig. 1.7a

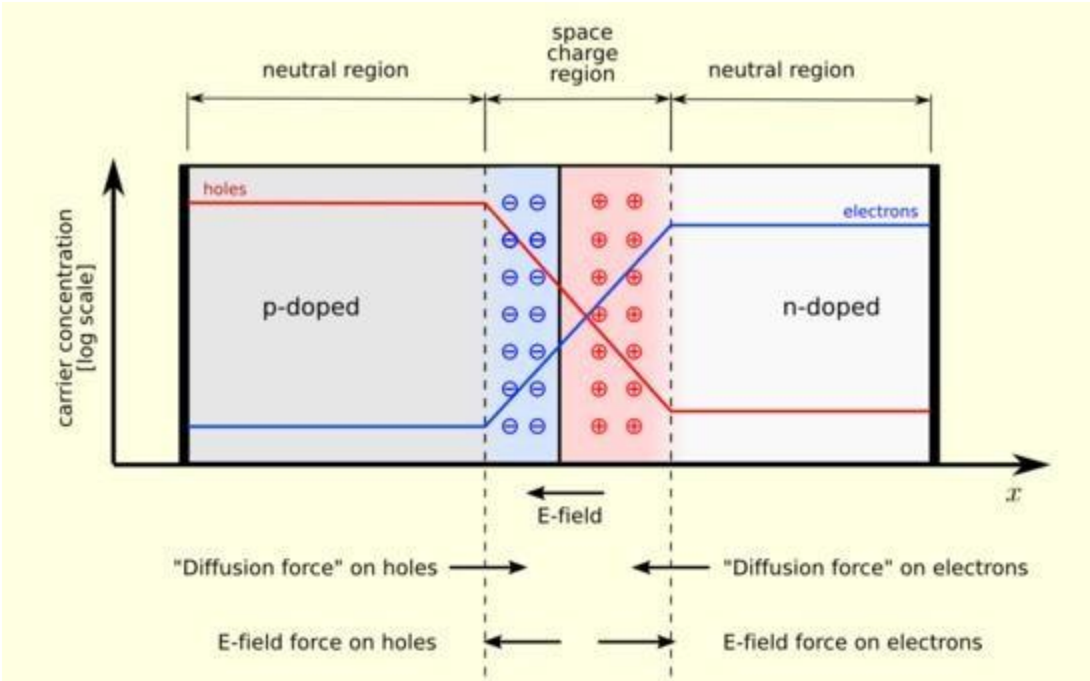


Fig 1.7a

It is noticed that the space charge layers are of opposite sign to the majority carriers diffusing into them, which tends to reduce the diffusion rate. Thus the double space of the layer causes an electric field to be set up across the junction directed from N to P regions, which is in such a directionto inhibit the diffusion of majority electrons and holes as illustrated in fig 1.7b. The shape of the chargedensity, ρ, depends upon how diode id doped. Thus the junction region is depleted of mobile charge carriers. Hence it is called depletion layer, space region, and transition region. The depletion region isof the order of 0.5µm thick. There are no mobile carriers in this narrow depletion region. Hence no current flows across the junction and the system is in equilibrium. To the left of this depletion layer,the carrier concentration is $p= N_A$ and to its right it is $n= N_D$.

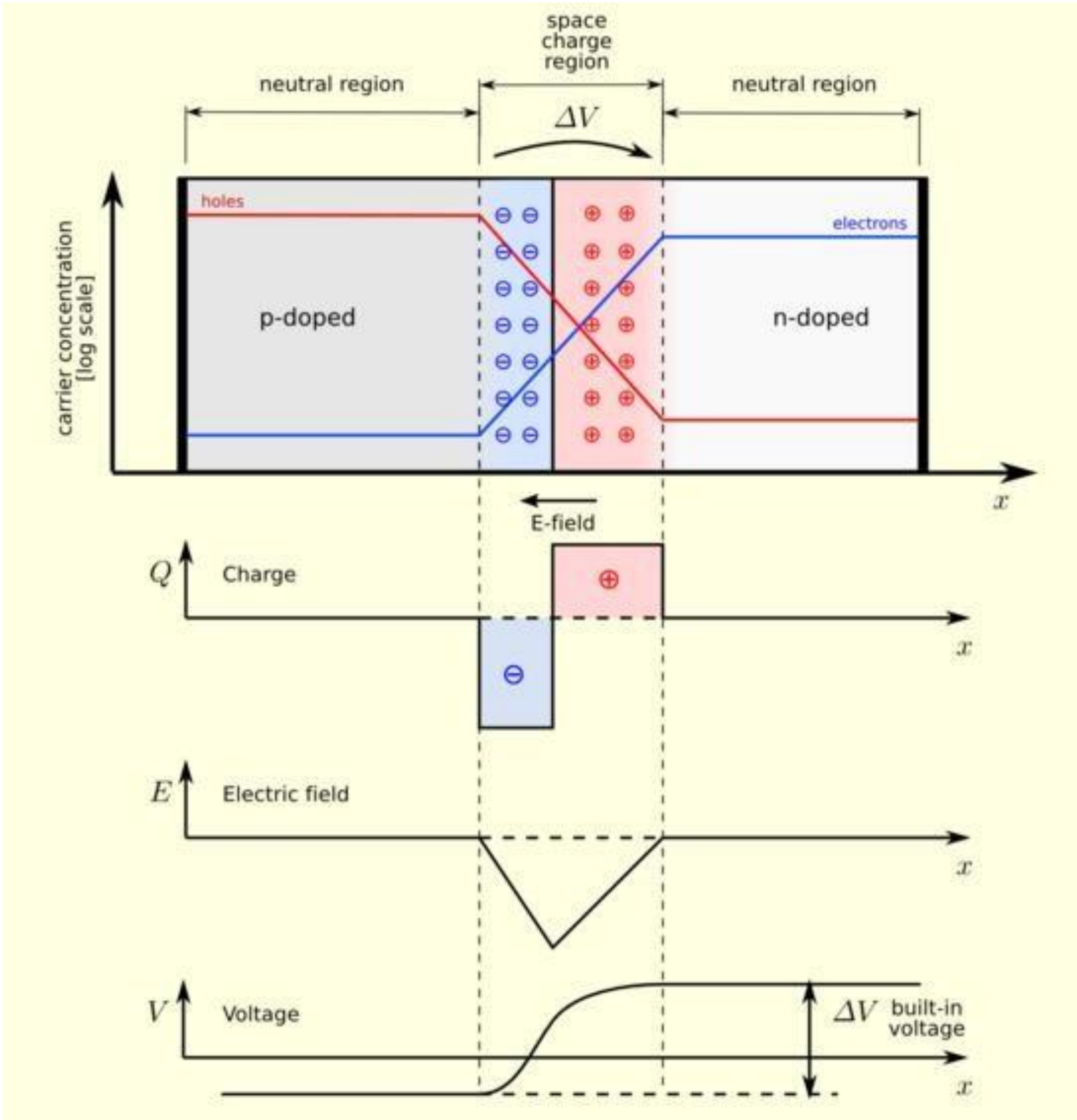


Fig 1.7b

1.1.2 FORWARD BIASED JUNCTION DIODE

When a diode is connected in a **Forward Bias** condition, a negative voltage is applied to the N-type material and a positive voltage is applied to the P-type material. If this external voltage becomes greater than the value of the potential barrier, approx. 0.7 volts for silicon and 0.3 volts for germanium, the potential barriers opposition will be overcome and current will start to flow. This is because the negative voltage pushes or repels electrons towards the junction giving them the energy to cross over and combine with the holes being pushed in the opposite direction towards the junction by the positive voltage. This results in a characteristics curve of zero current flowing up to this voltage point, called the "knee" on the static curves and then a high current flow through the diode with little increase in the external voltage as shown below.

Forward Characteristics Curve for a Junction Diode

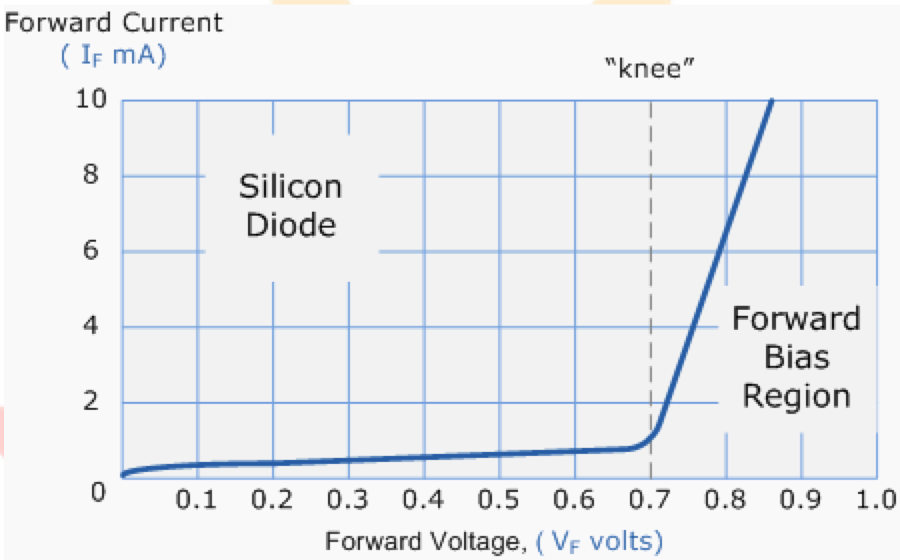


Fig 1.8a: Diode Forward Characteristics

The application of a forward biasing voltage on the junction diode results in the depletion layer becoming very thin and narrow which represents a low impedance path through the junction thereby allowing high currents to flow. The point at which this sudden increase in current takes place is represented on the static I-V characteristics curve above as the "knee" point.

Forward Biased Junction Diode showing a Reduction in the Depletion Layer

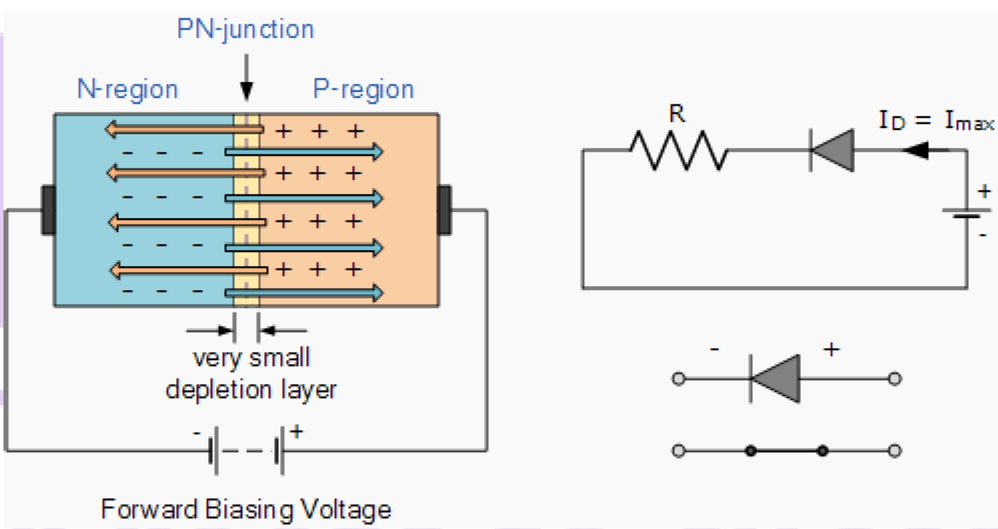


Fig 1.8b: Diode Forward Bias

this condition represents the low resistance path through the PN junction allowing very large currents to flow through the diode with only a small increase in bias voltage. The actual potential difference across the junction or diode is kept constant by the action of the depletion layer at approximately 0.3v for germanium and approximately 0.7v for silicon junction diodes. Since the diode can conduct "infinite" current above this knee point as it effectively becomes a short circuit, therefore resistors are used in series with the diode to limit its current flow. Exceeding its maximum forward current specification causes the device to dissipate more power in the form of heat than it was designed for resulting in a very quick failure of the device.

1.1.2 PN JUNCTION UNDER REVERSE BIAS CONDITION: Reverse Biased Junction Diode

When a diode is connected in a Reverse Bias condition, a positive voltage is applied to the N-type material and a negative voltage is applied to the P-type material. The positive voltage applied to the N-type material attracts electrons towards the positive electrode and away from the junction, while the holes in the P-type end are also attracted away from the junction towards the negative electrode. The net result is that the depletion layer grows wider due to a lack of electrons and holes and presents a high impedance path, almost an insulator. The result is that a high potential barrier is created thus preventing current from flowing through the semiconductor material.

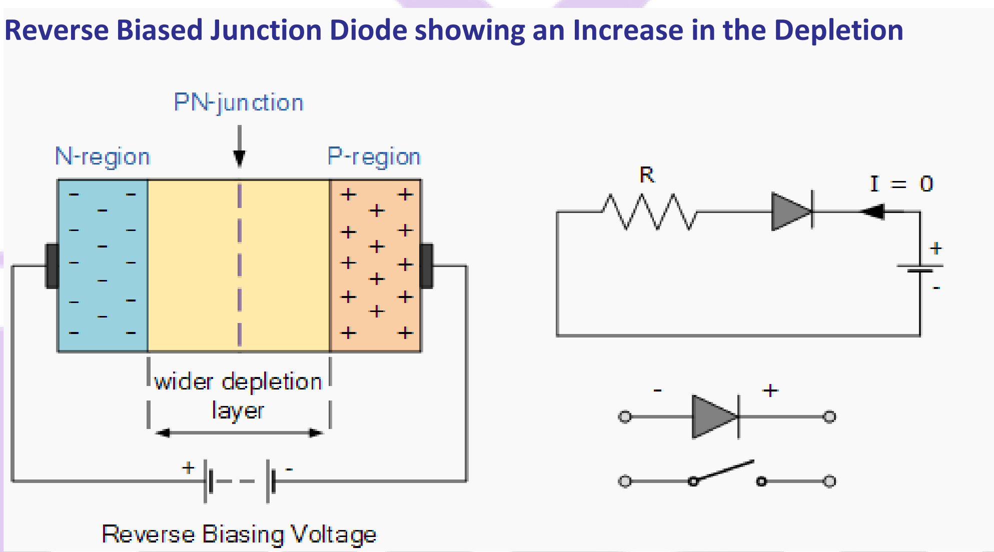


Fig 1.9a: Diode Reverse Bias

This condition represents a high resistance value to the PN junction and practically zero current flows through the junction diode with an increase in bias voltage. However, a very small **leakage current** does flow through the junction which can be measured in microamperes, (μA). One final point, if the reverse bias voltage Vr applied to the diode is increased to a sufficiently high enough value, it will cause the PN junction to overheat and fail due to the avalanche effect around the junction. This may cause the diode to become shorted and will result in the flow of maximum circuit current, and this shown as a step downward slope in the reverse static characteristics curve below.

Reverse Characteristics Curve for a Junction Diode

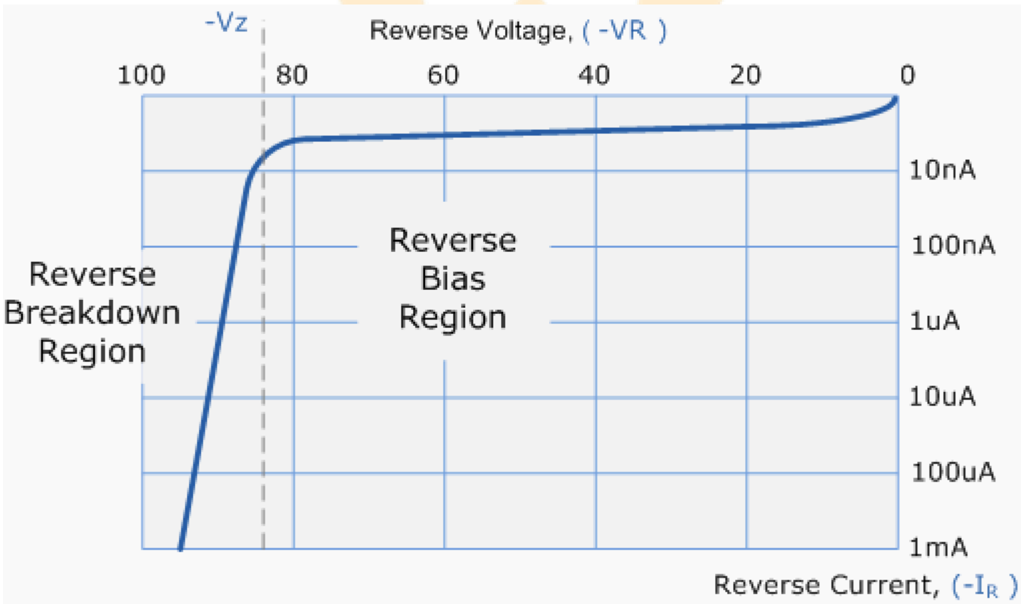


Fig 1.9b: Diode Reverse Characteristics

Sometimes this avalanche effect has practical applications in voltage stabilizing circuits where a series limiting resistor is used with the diode to limit this reverse breakdown current to a preset maximum value thereby producing a fixed voltage output across the diode. These types of diodes are commonly known as **Zener Diodes**

1.2 VI CHARACTERISTICS AND THEIR TEMPERATURE DEPENDENCE

Diode terminal characteristics equation for diode junction current:

$$I_D = I_o \left(e^{v/\eta v_T} - 1\right)$$

Where $V_T = KT/q$;

V_D_ diode terminal voltage, Volts

I_o _ temperature-dependent saturation current, µAT

_ absolute temperature of p-n junction, K

K _ Boltzmann's constant 1.38x 10 -23J/K)

q _ electron charge 1.6x10-19 C, η = empirical constant, 1 for Ge and 2 for Si

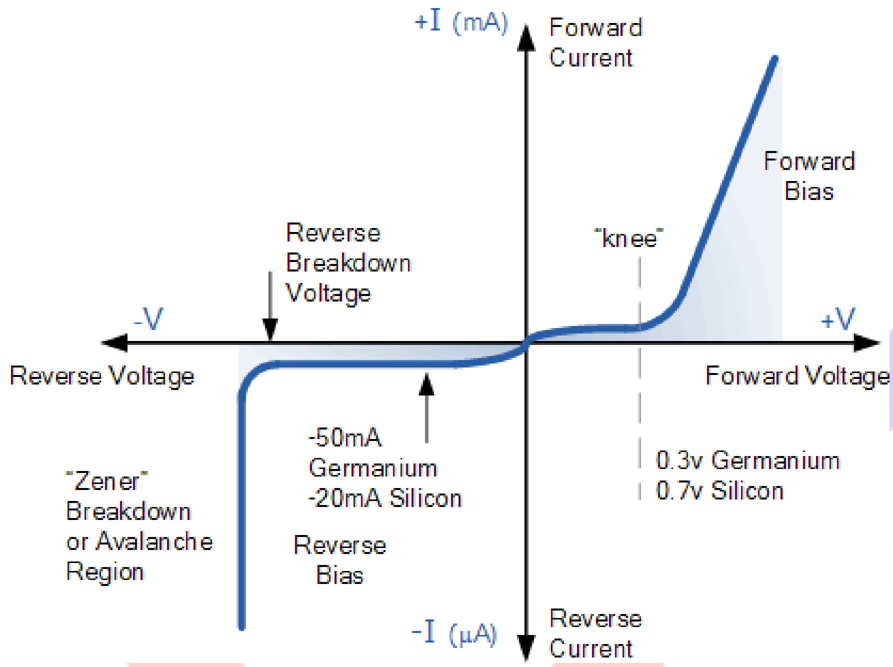


Fig 1.10: Diode Characteristics

Temperature Effects on Diode

Temperature can have a marked effect on the characteristics of a silicon semiconductor diodeas shown in Fig. 11 It has been found experimentally that the reverse saturation current Io will just about double in magnitude for every 10°C increase in temperature.

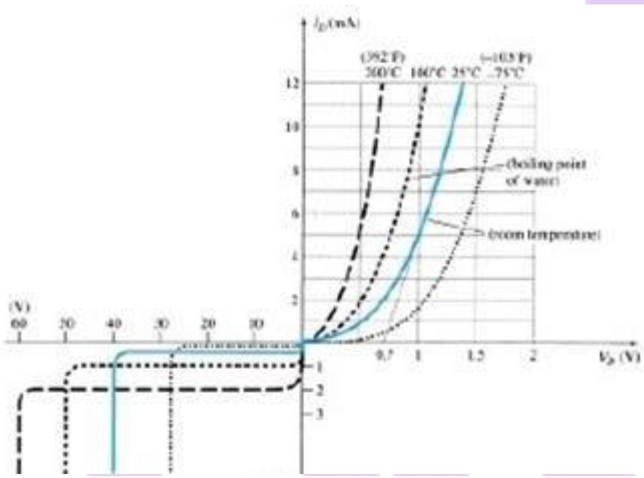


Fig 1.11 Variation in Diode Characteristics with temperature change

It is not uncommon for a germanium diode with an I_o in the order of 1 or 2 A at 25°C to have a leakage current of 100 A - 0.1 mA at a temperature of 100°C. Typical values of I_o for silicon are much lower thanthat of germanium for similar power and current levels. The result is that even at high temperatures the levels of I_o for silicon diodes do not reach the same high levels obtained. For germanium—a very important reason that silicon devices enjoy a significantly higher level of development and utilization indesign. Fundamentally, the open-circuit equivalent in the reverse bias region is better realized at any temperature with silicon than with germanium. The increasing levels of I_o with temperature account for the lower levels of threshold voltage, as shown in Fig. 1.11. Simply increase the level of I_o in and notrise in diode current. Of course, the level of TK also will be increase, but the increasing level of I_o will overpower the smaller percent change in TK. As the temperature increases the forward characteristics are actually becoming more "ideal,"

1.3 IDEAL VERSUS PRACTICAL RESISTANCE LEVELS

DC or Static Resistance

The application of a dc voltage to a circuit containing a semiconductor diode will result in an operating point on the characteristic curve that will not change with time. The resistance of the diode at the operating point can be found simply by finding the corresponding levels of VD and ID as shown in Fig. 1.12 and applying the following Equation:

$$R_D = \frac{V_D}{I_D}$$

The dc resistance levels at the knee and below will be greater than the resistance levels obtained for the vertical rise section of the characteristics. The resistance levels in the reverse-bias region will naturally be quite high. Since ohmmeters typically employ a relatively constant-current source, the resistance determined will be at a preset current level (typically, a few mill amperes).

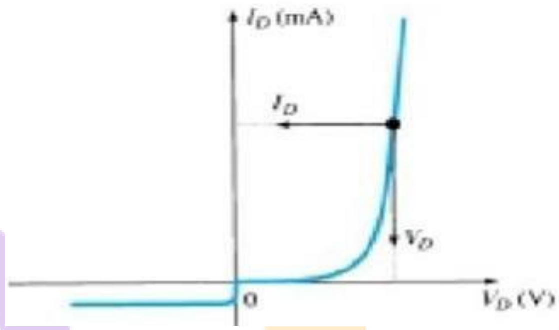


Fig 1.12 Determining the dc resistance of a diode at a particular operating point.

AC or Dynamic Resistance

It is obvious from Eq. 1.3 that the dc resistance of a diode is independent of the shape of the characteristic in the region surrounding the point of interest. If a sinusoidal rather than dc input is applied, the situation will change completely. The varying input will move the instantaneous operating point up and down a region of the characteristics and thus defines a specific change in current and voltage as shown in Fig. 1.13. With no applied varying signal, the point of operation would be the Q- point appearing on Fig. 1.13 determined by the applied dc levels. The designation Q-point is derived from the word quiescent, which means “still or unvarying.” A straight-line drawn tangent to the curve through the Q-point as shown in Fig. 1.13 will define a particular change in voltage and current that canbe used to determine the ac or dynamic resistance for this region of the diode characteristics. In equation form,

$$r_d = \frac{\Delta V_d}{\Delta I_d}$$

Where Δ Signifies a finite change in the quantity

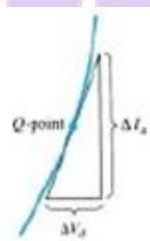


Fig 1.13: Determining the ac resistance of a diode at a particular operating point.

1.4 DIODE EQUIVALENT CIRCUITS

An equivalent circuit is a combination of elements properly chosen to best represent the actual terminal characteristics of a device, system, or such in a particular operating region. In other words, once the equivalent circuit is defined, the device symbol can be removed from a schematic and the equivalent circuit inserted in its place without severely affecting the actual behavior of the system. The result is often a network that can be solved using traditional circuit analysis techniques.

Piecewise-Linear Equivalent Circuit

One technique for obtaining an equivalent circuit for a diode is to approximate the characteristics of the device by straight-line segments, as shown in Fig. 1.31. The resulting equivalent circuit is naturally called the piecewise-linear equivalent circuit. It should be obvious from Fig. 1.31 thatthe straight-line segments do not result in an exact duplication of the actual characteristics, especially in the knee region. However, the resulting segments are sufficiently close to the actual curve to establish an equivalent circuit that will provide an excellent first approximation to the actual behaviourof the device. The ideal diode is included to establish that there is only one direction of conduction through the device, and a reverse-bias condition will result in the open- circuit state for the device. Since a silicon semiconductor, diode does not reach the conduction state until VD reaches 0.7 V with a forward bias (as shown in Fig. 1.14a), a battery V_T opposing the conduction direction must appear inthe equivalent circuit as shown in Fig. 1.14b. The battery simply specifies that the voltage across the device must be greater than the threshold battery voltage before conduction through the device in the direction dictated by the ideal diode can be established. When conduction is established, the resistance of the diode will be the specified value of r_{av}.

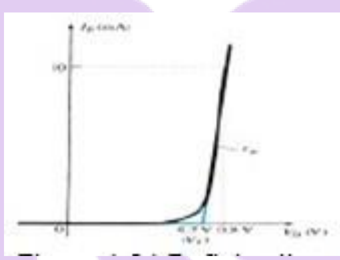


Fig: 1.14aDiode piecewise-linear model characteristics

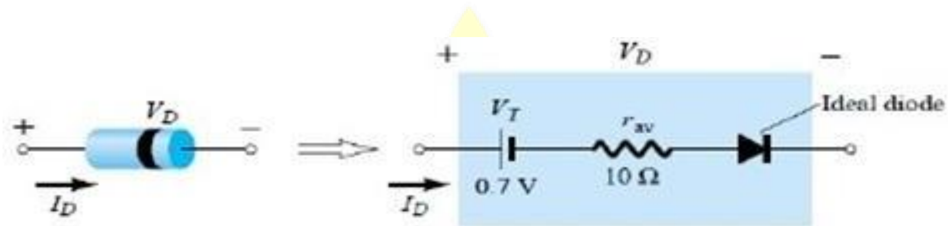


Fig: 1.14b Diode piecewise-linear model equivalent circuit

The approximate level of r_{av} can usually be determined from a specified operating point on the specification sheet. For instance, for a silicon semiconductor diode, if IF _ 10 mA (a forward conduction current for the diode) at VD _ 0.8 V, we know for silicon that a shift of 0.7 V is required before the characteristics rise.

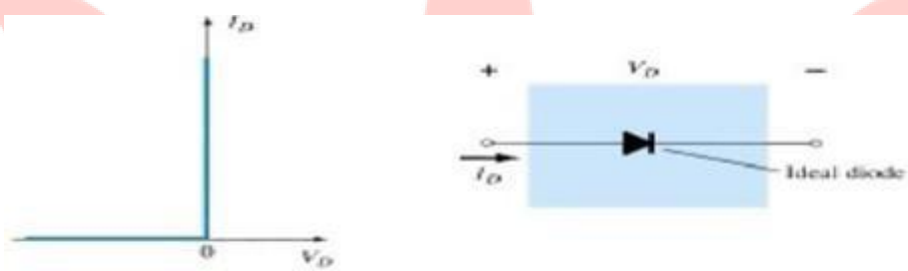


Fig 1.15 Ideal Diode and its characteristics

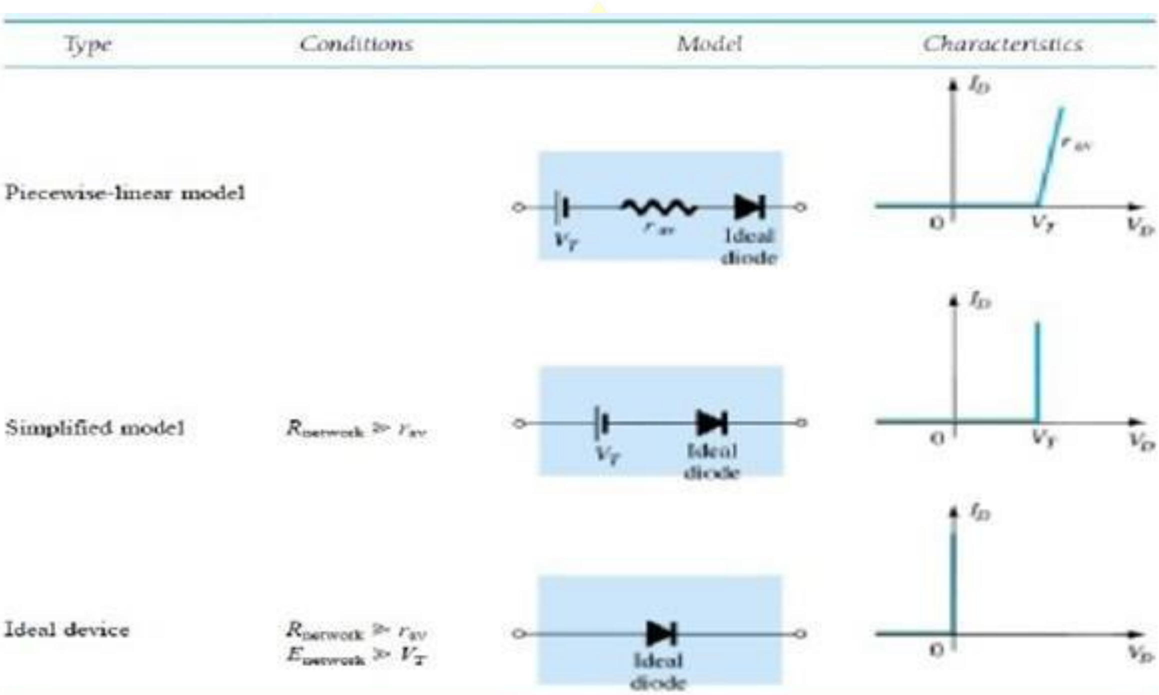


Fig 1.16: Diode equivalent circuits(models)

1.5 TRANSITION AND DIFFUSION CAPACITANCE

Electronic devices are inherently sensitive to very high frequencies. Most shunt capacitive effects that can be ignored at lower frequencies because the reactance $X_C=1/2\pi fC$ is very large (open- circuit equivalent). This, however, cannot be ignored at very high frequencies. XC will become sufficiently small due to the high value of f to introduce a low-reactance “shorting” path. In the p-n semiconductor diode, there are two capacitive effects to be considered. In the reverse-bias region we have the transition- or depletion region capacitance (CT), while in the forward-bias region we have the diffusion (CD) or storage capacitance. Recall that the basic equation for the capacitance of a parallel- plate capacitor is defined by C=€A/d, where € is the permittivity of the dielectric (insulator) between the plates of area A separated by a distance d. In the reverse-, bias region there is a depletion region (free of carriers) that behaves essentially like an insulator between the layers of opposite charge. Since the depletion width (d) will increase with increased reverse-bias potential, the resulting transition capacitance will decrease. The fact that the capacitance is dependent on the applied reverse-bias potential has application in a number of electronic systems. Although the effect described above will also be present in the forward-bias region, it is over shadowed by a capacitance effect directly dependent on the rate at which charge is injected into the regions just outside the depletion region. The capacitive effects described above are represented by a capacitor in parallel with the ideal diode, as shown in Fig. 1.38. For low- or mid-frequency applications (except in the power area), however, the capacitor is normally not included in the diode symbol.

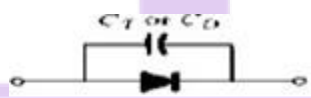


Fig 1.17: Including the effect of the transition or diffusion capacitance on the semiconductor diode

Diode capacitances: The diode exhibits two types of capacitances transition capacitance and diffusion capacitance.

- Transition capacitance: The capacitance which appears between positive ion layer in n-region and negative ion layer in p-region.
- Diffusion capacitance: This capacitance originates due to diffusion of charge carriers in the opposite regions.

The transition capacitance is very small as compared to the diffusion capacitance.

In reverse bias transition, the capacitance is the dominant and is given by:

$$C_T = \epsilon\ A/W$$

where C_T - transition capacitance

A - diode cross sectional area

W - depletion region width

In forward bias, the diffusion capacitance is the dominant and is given by:

$$C_D = dQ/dV = \tau*dI/dV = \tau*g = \tau/r \text{ (general)}$$

where C_D - diffusion capacitance

dQ - change in charge stored in depletion region

V - change in applied voltage

τ - time interval for change in voltage

g - diode conductance

r - diode resistance

The diffusion capacitance at low frequencies is given by the formula:

$$C_D = \tau*g/2 \text{ (low frequency)}$$

The diffusion capacitance at high frequencies is inversely proportional to the frequency and is given by the formula:

$$C_D = g(\tau/2\omega)^{1/2}$$

Note: The variation of diffusion capacitance with applied voltage is used in the design of varactor.

1.6 BREAK DOWN MECHANISMS

When an ordinary **P-N junction diode** is reverse biased, normally only very small reverse saturation current flows. This current is due to movement of minority carriers. It is almost independent of the voltage applied. However, if the reverse bias is increased, a point is reached when the junction breaks down and the reverse current increases abruptly. This current could be large enough to destroy the junction. If the reverse current is limited by means of a suitable series resistor, the power dissipation at the junction will not be excessive, and the device may be operated continuously in its breakdown region to its normal (reverse saturation) level. It is found that for a suitably designed diode, the breakdown voltage is very stable over a wide range of reverse currents. This quality gives the breakdown diode many useful applications as a voltage reference source.

The critical value of the voltage, at which the breakdown of a P-N junction diode occurs, is called the *breakdown voltage*. The breakdown voltage depends on the width of the depletion region, which, in turn, depends on the doping level. The junction offers almost zero resistance at the breakdown point.

There are two mechanisms by which breakdown can occur at a reverse biased P-N junction:

1. ***avalanche breakdown*** **and**
2. ***Zener breakdown.***

Avalanche breakdown

The minority carriers, under reverse biased conditions, flowing through the junction acquire a kinetic energy which increases with the increase in reverse voltage. At a sufficiently high reverse voltage (say 5 V or more), the kinetic energy of minority carriers becomes so large that they knock out electrons from the covalent bonds of the semiconductor material. As a result of collision, the liberated electrons in turn liberate more electrons and the current becomes very large leading to the breakdownof the crystal structure itself. This phenomenon is called the avalanche breakdown. The breakdown region is the knee of the characteristic curve. Now the current is not controlled by the junction voltage but rather by the external circuit.

Zener breakdown

Under a very high reverse voltage, the depletion region expands and the potential barrier increases leading to a very high electric field across the junction. The electric field will break some of the covalent bonds of the semiconductor atoms leading to a large number of free minority carriers, which suddenly increase the reverse current. This is called the Zener effect. The breakdown occurs at a particular and constant value of reverse voltage called the breakdown voltage, it is found that Zener breakdown occurs at electric field intensity of about 3×10^7 V/m.

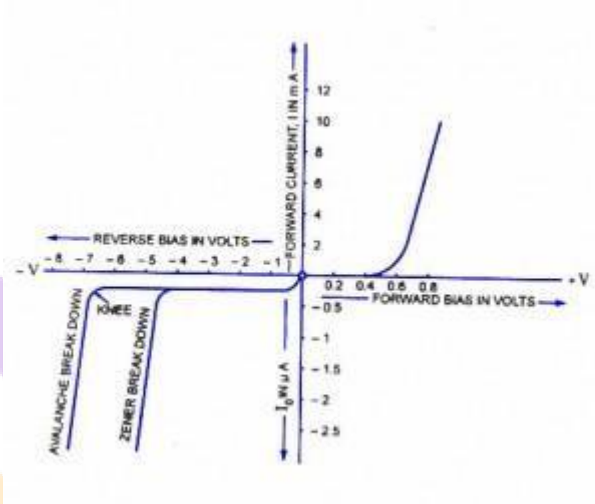


Fig 1.18: Diode characteristics with breakdown

Either of the two (Zener breakdown or avalanche breakdown) may occur independently, or both of these may occur simultaneously. Diode junctions that breakdown below 5 V are caused by Zener effect. Junctions that experience breakdown above 5 V are caused by avalanche effect. Junctions that breakdown around 5 V are usually caused by combination of two effects. The Zener breakdown occurs in heavily doped junctions (P-type semiconductor moderately doped and N-type heavily doped), which produce narrow depletion layers. The avalanche breakdown occurs in lightly doped junctions, which produce wide depletion layers. With the increase in junction temperature Zener breakdown voltage is reduced while the avalanche breakdown voltage increases. The Zener diodes have a negative temperature coefficient while avalanche diodes have a positive temperature coefficient. Diodes that have breakdown voltages around 5 V have zero temperature coefficient. The breakdown phenomenon is reversible and harmless so long as the safe operating temperature is maintained.

1.7 ZENER DIODES

The **Zener diode** is like a general-purpose signal diode consisting of a silicon PN junction. When biased in the forward direction it behaves just like a normal signal diode passing the rated current, but as soon as a reverse voltage applied across the zener diode exceeds the rated voltage of the device, the diodes breakdown voltage V_B is reached at which point a process called *Avalanche Breakdown* occurs in the semiconductor depletion layer and a current starts to flow through the diode to limit this increase in voltage.

The current now flowing through the zener diode increases dramatically to the maximum circuit value (which is usually limited by a series resistor) and once achieved this reverse saturation current remains fairly constant over a wide range of applied voltages. This breakdown voltage point, V_B is called the "zener voltage" for zener diodes and can range from less than one volt to hundreds of volts.

The point at which the zener voltage triggers the current to flow through the diode can be very accurately controlled (to less than 1% tolerance) in the doping stage of the diodes semiconductor construction giving the diode a specific *zener breakdown voltage*, (V_Z) for example, 4.3V or 7.5V. This zener breakdown voltage on the I-V curve is almost a vertical straight line.

Zener Diode I-V Characteristics

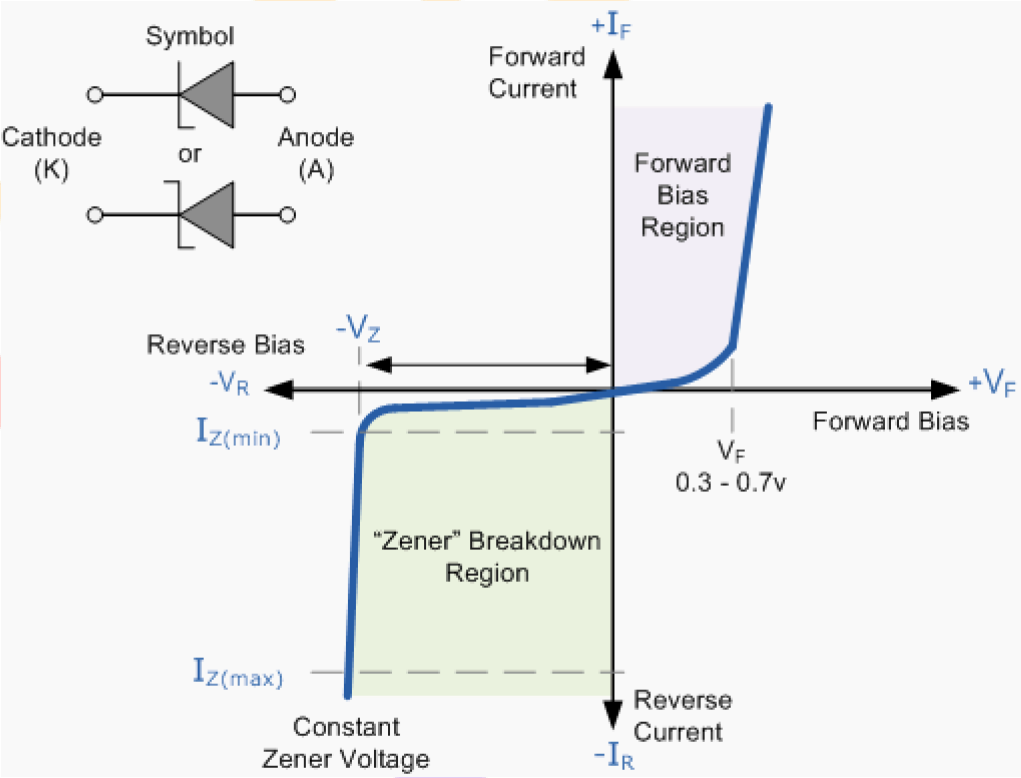


Fig 1.19 : Zener diode characteristics

The **Zener Diode** is used in its "reverse bias" or reverse breakdown mode, i.e. the diodes anode connects to the negative supply. From the I-V characteristics curve above, we can see that the zener diode has a region in its reverse bias characteristics of almost a constant negative voltage regardless of the value of the current flowing through the diode and remains nearly constant even with large changes in current as long as the zener diodes current remains between the breakdown current $I_{Z(min)}$ and the maximum current rating $I_{Z(max)}$.

This ability to control itself can be used to great effect to regulate or stabilize a voltage source against supply or load variations. The fact that the voltage across the diode in the breakdown region is almost constant turns out to be an important application of the zener diode as a voltage regulator. The function of a regulator is to provide a constant output voltage to a load connected in parallel with it in spite of the ripples in the supply voltage or the variation in the load current and the zener diode will continue to regulate the voltage until the diodes current falls below the minimum $I_{Z(min)}$ value in the reverse breakdown region.

UNIT-2 DIODE APPLICATIONS(23EC204)

INTRODUCTION

A typical d.c. power supply consists of various stages. The Fig. 1.1 shows the block diagram of a typical d.c. power supply consisting of various circuits. The nature of voltages at various points is also shown in the Fig. 1.1

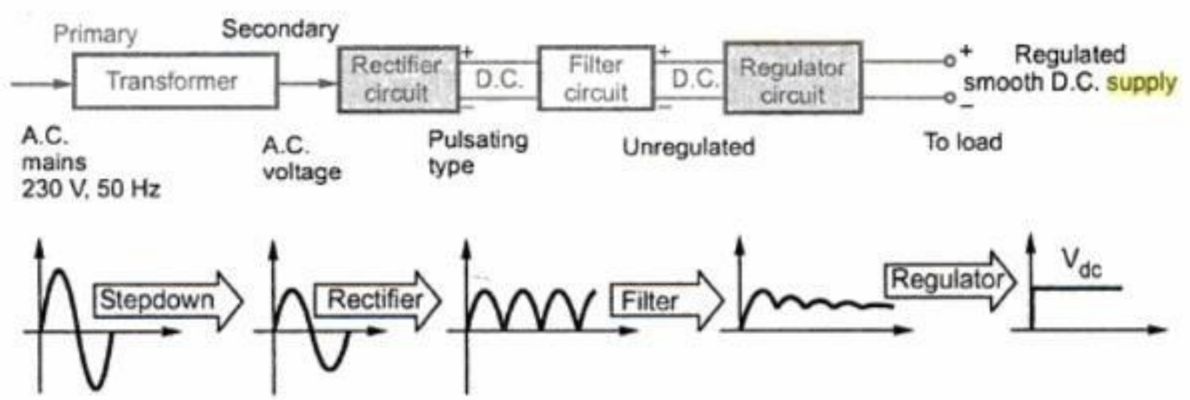


Fig. 1.1 Block diagram of Regulated Power supply with waveforms

The a.c. voltage (230 V, 50 Hz) is connected to the primary of the transformer. The transformer steps down the a.c. voltage, to the level required for the desired d.c. output. Thus, with suitable turns ratio we get desired a.c. secondary voltage. The rectifier circuit converts this a.c. voltage into a **pulsating d.c. voltage**. A pulsating d.c. voltage means a unidirectional voltage containing large varying component called **ripple** in it. The **filter** circuit is used after a rectifier circuit, which reduces the ripple content in the pulsating d.c. and tries to make it smoother. Still then the filter output contains some ripple. This voltage is called **unregulated d.c. voltage**. A circuit used after the filter is a regulator circuit which not only makes the d.c. voltage smooth and almost ripple free but it also keeps the d.c. output voltage constant though input d.c. voltage varies under certain conditions. It keeps the output voltage constant under variable load conditions, as well. The output of a regulator is called **d.c. supply**, to which the load can be connected. Nowadays, complete regulator circuits are available in the integrated circuit (IC) form.

RECTIFIER CIRCUIT

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

The p-n junction diode conducts only in one direction. It conducts when forward biased while practically it does not conduct when rever se biased. Thus if an alternating voltage is applied across a p-n junction diode, during positive half cycle the diode will be forward biased and will conduct successfully. While during the negative half cycle it will be reversed biased and will not conduct at all. Thus the conduction occurs only during positive half cycle. If the resistance is connected in series with the diode, the output voltage across the resistance will be unidirectional i.e. d.c.

Important Characteristics of Rectifier Circuits

a) **Waveform of the load current :** As rectifier converts a.c. to pulsating d.c., it is important to analyze the nature of the current through load which ultimately determines the waveform of the load voltage.

b) **Regulation of the output voltage :** As the load current changes, load voltage changes. Practically load voltage should remain constant. So concept of regulation is to study the effect of change in load current on the load voltage.

c) **Rectifier efficiency :** It signifies, how efficiently the rectifier circuit converts a.c. power into d.c. power.

d) **Peak value of current in the rectifier circuit :** The peak value is the maximum value of an alternating current in the rectifier circuit. This decides the rating of the rectifier circuit element which is diode.

e) **Peak value of voltage across the rectifier element in the reverse direction (PIV) :** When the diode is not conducting, the reverse voltage gets applied across the diode. The peak value of such voltage decides the peak inverse voltage i.e. PIV rating of a diode.

f) **Ripple factor :** The output of the rectifier is of pulsating d.c. type. The amount of a.c. content in the output can be mathematically expressed by a factor called ripple factor.

Using one or more diodes following rectifier circuits can be designed.

1. Half wave rectifier
2. Full wave rectifier
3. Bridge rectifier

HALF WAVE RECTIFIER

In half wave rectifier, rectifying element conducts only during positive half cycle of input a.c. supply. The negative half cycles of a.c. supply are eliminated from the output.

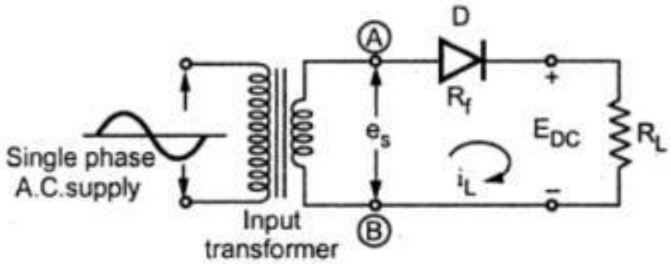


Fig. 1.2 Half wave rectifier

This rectifier circuit consists of resistive load, rectifying element, i.e. p-n junction diode, and the source of a.c. voltage, all connected in series. The circuit diagram is shown in the Fig. 1.2 Usually, the rectifier circuits are operated from a.c. mains supply. To obtain the desired d.c. voltage across the load, the a.c. voltage is applied to rectifier circuit using suitable step-up or step-down transformer, mostly a step-down one, with necessary turns ratio.

The input voltage to the half-wave rectifier circuit shown in the Fig. 1.2 is a sinusoidal a.c. voltage, having a frequency which is the supply frequency, 50 Hz.

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 value of the primary voltage then,

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

where E_{sm} = The peak value of the secondary a.c. voltage.

As the nature of E_{sm} is sinusoidal the instantaneous value will be,

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

$$\omega = 2\pi f$$

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

Operation

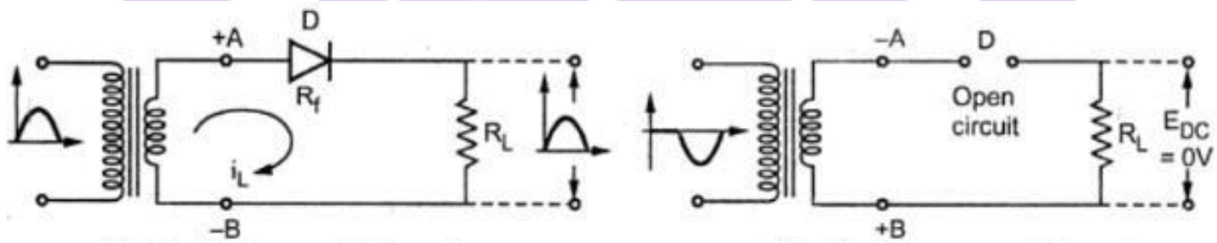


Fig. 1.3 Operation of half wave rectifier

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 in the clockwise direction, as shown in the Fig. 1.3 (a). The current will flow for almost full positive half cycle. This current is also flowing through load resistance R_L hence denoted as i_L, the load current.

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 as shown in the Fig. 1.3 (b). 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. 1.4.

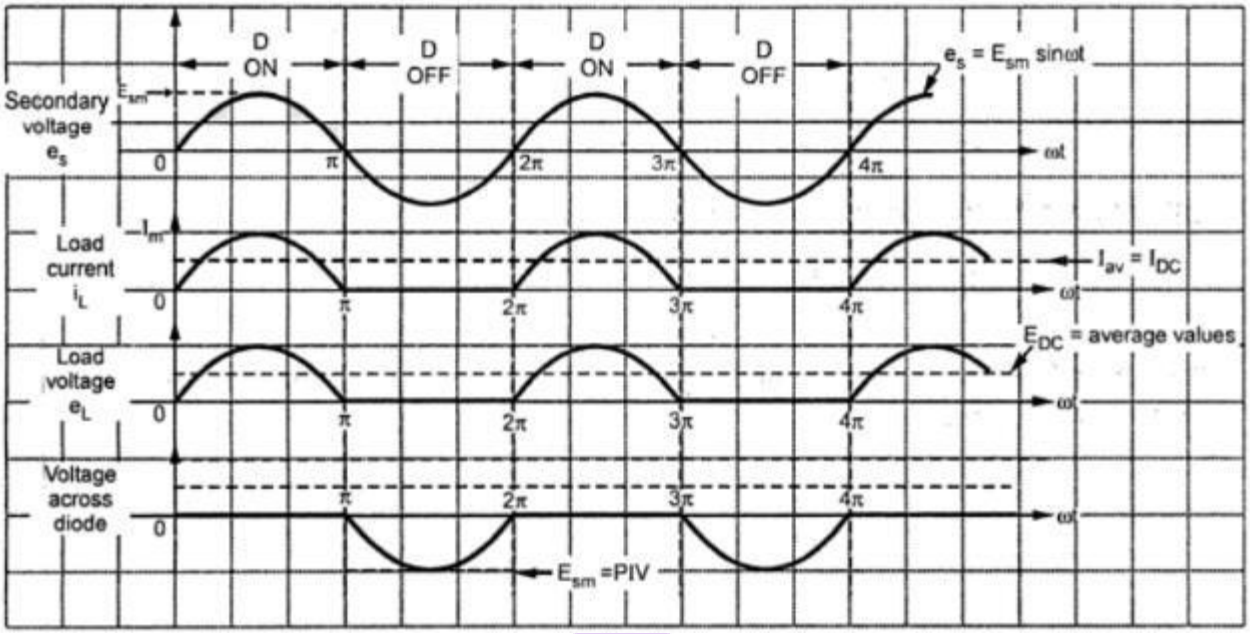


Fig. 1.4 Load current and Load voltage waveforms for half wave rectifier

The d.c. output waveform is expected to be a straight line but the half wave rectifier gives output in the form of positive sinusoidal pulses.

Key Point: *Hence the output is called* ***pulsating d.c.*** *It is discontinuous in nature. Hence it is necessary to calculate the average value of load current and average value of output voltage.*

Average DC Load Current (I_{DC})

The average or 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 i.e. 2π .

Mathematically, current waveform can be described as,

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

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

where I_m = Peak value of load current

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

As no current flows during negative half cycle of a.c. input voltage, i.e. between $\omega t = \pi$ to $\omega t = 2\pi$, we change the limits of integration.

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

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

$$\therefore \quad \boxed{I_{DC} = \frac{I_m}{\pi} = \text{average value}}$$

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. If R_s is not given it should be neglected while calculating I_m.

Average DC 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},

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

The winding resistance R_s and forward diode resistance R_f are practically very small compared to R_L.

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

But as R_f and R_s are small compared to R_L, $(R_f + R_s)/R_L$ is negligibly small compared to 1. So neglecting it we get,

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

Note : When R_f and R_s are finite, calculate I_m, then I_{DC} and from that E_{DC} as $I_{DC}R_L$. Do not calculate E_{DC} as E_{sm}/π directly for finite R_f and R_s.

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,

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

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

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

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

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

DC Power Output (P_{DC})

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

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

$$\text{D.C. Power output} = I_{DC}^2 R_L = \left[\frac{I_m}{\pi}\right]^2 R_L = \frac{I_m^2}{\pi^2} R_L$$

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

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

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

AC Power Input (P_{AC})

The power input taken from the secondary of transformer is the power supplied to three resistances namely load resistance R_L , the diode resistance R_f and winding resistance R_s. The a.c. power is given by,

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

but $$I_{RMS} = \frac{I_m}{2} \qquad \text{for half wave,}$$

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

Rectifier Efficiency (η)

The rectifier efficiency is defined as the ratio of output d.c. power to input a.c. power.

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

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

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

If $(R_f + R_s) << R_L$ as mentioned earlier, we get the maximum theoretical efficiency of half wave rectifier as,

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

Thus in half wave rectifier, maximum 40.6% a.c. power gets converted to d.c. power in the load. If the efficiency of rectifier is 40% then what happens to the remaining 60% power. It is present interms of ripples in the output which is fluctuating component present in the output. Thus more the rectifier efficiency, less are the ripple contents in the output.

Ripple Factor (γ)

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**. Ideally there should not be any ripples in the rectifier output. The measure of such ripples present in the output is with the help of a factor called **ripple factor** denoted by γ. It tells how smooth is the output. Smaller the ripple factor closer is the output to a pure d.c. The ripple factor expresses how much successful the circuit is, in obtaining pure d.c. from a.c. input.

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

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

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

Now $\quad \text{Ripple factor} = \frac{I_{ac}}{I_{DC}} \quad$ as per definition

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

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

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

Now for a half wave circuit,

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

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

$$\therefore \quad \boxed{\gamma = 1.211}$$

This indicates that the ripple contents in the output are 1.211 times the d.c. component i.e. 121.1 % of d.c. component. The ripple factor for half wave is very high which indicates that the half wave circuit is a poor converter of a.c. to d.c. The ripple factor is minimised using filter circuits along with the rectifiers.

Transformer Utilization Factor (TUF)

The factor which indicates how much is the utilization of the transformer in the circuit is called Transformer Utilization Factor (T.U.F.)

The T.U.F. is defined as the ratio of d.c. power delivered to the load to the a.c power rating of the transformer. While calculating the a.c. power rating, it is necessary to consider r.m.s. value of a.c. voltage and current.

The T.U.F. for half wave rectifier can be obtained as,

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

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

Remember that the secondary voltage is purely sinusoidal hence its r.m.s. value is $1/\sqrt{2}$ times maximum while the current is half sinusoidal hence its r.m.s. value is 1/2 of the maximum, as derived earlier.

$$\text{D.C. power delivered to the load} = I_{DC}^2 R_L = \left(\frac{I_m}{\pi}\right)^2 R_L$$

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

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

Neglecting the drop across R_f and R_s we can write,

$$E_{sm} = I_m R_L$$

$$\therefore \quad \text{T.U.F} = \frac{I_m{}^2}{\pi^2} \cdot \frac{R_L \cdot 2\sqrt{2}}{I_m{}^2 R_L} = \frac{2\sqrt{2}}{\pi^2} = 0.287$$

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

Load Current

The load current i_L which is composed of a.c. and d.c. components can be expressed using Fourier series as,

$$i_L = I_m \left[\frac{1}{\pi} + \frac{1}{2}\sin\omega t - \frac{2}{3\pi}\cos 2\omega t - \frac{2}{15\pi}\cos 4\omega t \ \ldots\right]$$

This expression shows that the current may be considered to be the sum of an infinite number of current components, according to Fourier series.

The first term of the series is the average or d.c. value of the load current. The second term is a varying component having frequency same as that of a.c. supply voltage. This is called fundamental component of the current having frequency same as the supply. The third term is again a varying component having frequency twice the frequency of supply voltage. This is called second harmonic component. Similarly all the other terms represent the a.c. components and are called harmonics.

Thus ripple in the output is due to the fundamental component alongwith the various harmonic components. And the average value of the total pulsating d.c. is the d.c. value of the load current, given by the constant term in the series, I_m / π

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}. This is shown in the Fig. 1.5

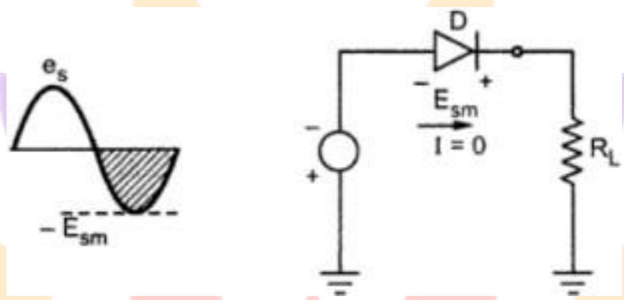


Fig. 1.5 PIV rating of Diode

Thus PIV occurs at the peak of each negative half cycle of the input, when **diode is** reverse biased and not conducting.

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

This is called PIV rating of a diode. So diode must be selected based on this PIV rating and the circuit specifications.

Voltage Regulation

The secondary voltage should not change with respect to the load current. The voltage regulation is the factor which tells us about the change in the d.c. output voltage as load changes from no load to full load condition.

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

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

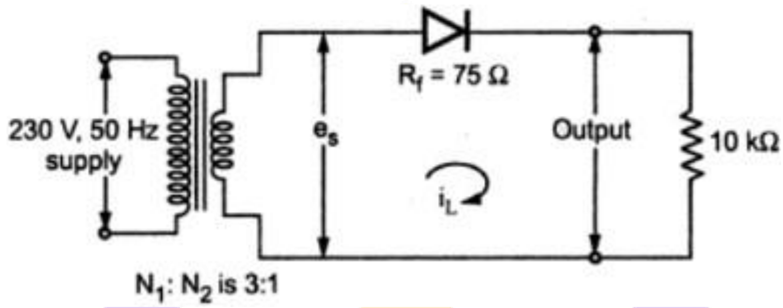
then voltage regulation is defined as,

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

Key Point: *Less the value of voltage regulation, better is the performance of rectifier circuit.*

Example 1 : ***A half wave rectifier circuit is supplied from a 230 V, 50 Hz supply with a step down ratio of 3:1 to a resistive load of 10 kΩ. The diode forward resistance is 75 Ω while transformer secondary resistance is 10 Ω. Calculate maximum, average, RMS values of current, D.C. output voltage, efficiency of rectification and ripple factor.***

Solution:



The given values are,

$R_f = 75\ \Omega,\ R_L = 10\ k\Omega,\ R_s = 10\ \Omega$

The given supply voltages are always r.m.s. values.

$$E_p(RMS) = 230\ V, \quad \frac{N_1}{N_2} = \frac{3}{1} \text{ i.e. } \frac{N_2}{N_1} = \frac{1}{3}$$

$$\frac{N_2}{N_1} = \frac{E_s(RMS)}{E_p(RMS)}$$

$$\therefore \quad \frac{1}{3} = \frac{E_s(RMS)}{230}$$

$$\therefore \quad E_s(RMS) = 76.667\ V$$

This is r.m.s. value of the transformer secondary voltage.

$$\therefore \quad E_{sm} = \sqrt{2}\,E_s(RMS) = \sqrt{2} \times 76.667 = 108.423\ V$$

$$\therefore \quad I_m = \frac{E_{sm}}{R_s + R_f + R_L} = \frac{108.423}{10 + 75 + 10 \times 10^3}$$

$$= \mathbf{10.75\ mA}$$

$$\therefore \quad I_{av} = I_{DC} = \frac{I_m}{\pi} = \frac{10.75}{\pi} = \mathbf{3.422\ mA}$$

$$I_{RMS} = \frac{I_m}{2} \quad \text{for half wave}$$

$$= \frac{10.75}{2} = \mathbf{5.375\ mA}$$

$$E_{DC} = \text{d.c output voltage} = I_{DC} R_L$$

$$= 3.422 \times 10^{-3} \times 10 \times 10^3 = \mathbf{34.22\ V}$$

$$P_{DC} = \text{d.c. output power} = E_{DC} I_{DC} = 34.22 \times 3.422 \times 10^{-3}$$

$$= 0.1171\ W$$

This also can be obtained as,

$$P_{DC} = \frac{I_m^2}{\pi^2} R_L = \frac{(10.75\times10^{-3})^2}{\pi^2}\times10\times10^3$$
$$= 0.1171 \text{ W}$$
$$P_{AC} = \text{a.c. input power} = I_{RMS}^2[R_s + R_f + R_L]$$
$$= (5.375\times10^{-3})^2[10+75+10\times10^3] = 0.2913 \text{ W}$$
$$\therefore \quad \%\eta = \frac{P_{DC}}{P_{AC}}\times100 = \frac{0.1171}{0.2913}\times100 = \mathbf{40.19\ \%}$$

The ripple factor is constant for half wave rectifier and is 1.21.

$$\therefore \quad \gamma = \mathbf{1.21}$$

Example 2 : *A half wave rectifier with $R_L = 1$ kΩ is given an input of 10 V peak from step down transformer. Calculate D.C. voltage and load current for ideal and silicon diode.*

Solution : Given values are R_L = 1 kΩ, V_m = 10 V peak

Case i) Ideal diode

Cut in voltage $V_\gamma = 0$ V, $R_f = 0\ \Omega$

$$\therefore \quad E_{DC} = \frac{V_m}{\pi} = \frac{10}{\pi} = \mathbf{3.18\ V}$$

$$\therefore \quad I_{DC} = \frac{E_{DC}}{R_L} = \frac{3.18}{1\times10^3} = \mathbf{3.18\ mA}$$

Case ii) Silicon diode

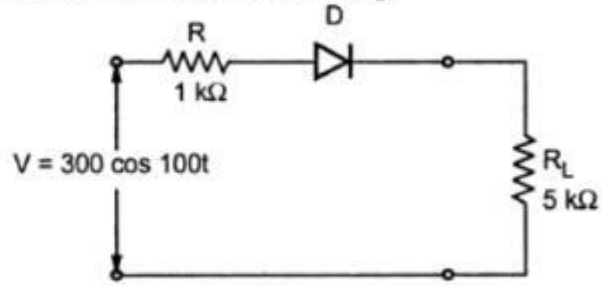
Cut in voltage $V_\gamma = 0.7$ V

$$\therefore \quad E_{DC} = \frac{V_m - V_\gamma}{\pi} = \frac{10-0.7}{\pi} = \mathbf{2.96\ V}$$

$$\therefore \quad I_{DC} = \frac{E_{DC}}{R_L} = \mathbf{2.96\ mA}$$

Example 3 : *A voltage $V = 300 \cos 100t$ is applied to a half wave rectifier, with $R_L = 5\,k\Omega$. The rectifier may be represented by ideal diode in series with a resistance of 1 kΩ. Calculate : i) I_m ii) D.C. power iii) A.C. power iv) Rectifier efficiency and v) Ripple factor.*

Solution : The diode circuit is as shown in the Fig.



The given voltage is V = 300 cos 100t volts

Compare with, $E = E_{sm} \sin \omega t$

$$E_{sm} = 300 \text{ volts}$$

$$R = 1 \text{ k}\Omega = \text{resistance in series with diode}$$

$$R_L = 5 \text{ k}\Omega, R_s = R_f = 0\ \Omega$$

i) $$I_m = \frac{E_{sm}}{R+R_L+R_f+R_L} = \frac{300}{6\times10^3}$$

$$= \mathbf{50\ mA}$$

ii) $$I_{DC} = \frac{I_m}{\pi} = \frac{50}{\pi} = \mathbf{15.9154\ mA}$$

∴ $$P_{DC} = I_{DC}^2 R_L = (15.9154\times10^{-3})^2 \times 5 \times 10^3$$

$$= \mathbf{1.2665\ watts}$$

iii) $$P_{AC} = I_{RMS}^2 (R + R_L + R_s + R_f)$$

$$= \left(\frac{I_m}{2}\right)^2 (R + R_L + R_s + R_f) \quad \text{as } I_{RMS} = \frac{I_m}{2} \text{ for half wave}$$

$$= \left(\frac{50\times10^{-3}}{2}\right)^2 \times 6\times10^3 = \mathbf{3.75\ watts}$$

iv) $$\eta = \frac{P_{DC}}{P_{AC}}\times100 = \frac{1.2665}{3.75}\times100$$

$$= \mathbf{33.77\ \%}$$

v) $$\text{Ripple factor} = \sqrt{\left(\frac{I_{RMS}}{I_{DC}}\right)^2 - 1} = \sqrt{\left(\frac{25\times10^{-3}}{15.9154\times10^{-3}}\right)^2 - 1}$$

$$= \mathbf{1.211}$$

Disadvantages of half wave rectifier circuit

The various disadvantages of the half wave rectifier circuit are,

1. The ripple factor of half wave rectifier circuit is 1.21, which is quite high. The output contains lot of varying components.
2. The maximum theoretical rectification efficiency is found to be 40%. The practical value will be less than this. This indicates that half wave rectifier circuit is quite inefficient.

3. The circuit has low transformer utilization factor, showing that the transformer is not fully utilized.
4. The d.c. current is flowing through the secondary winding of the transformer which may cause dc saturation of the core of the transformer. To minimize the saturation, transformer size have to be increased accordingly. This increases the cost.

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 center 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. 1.6

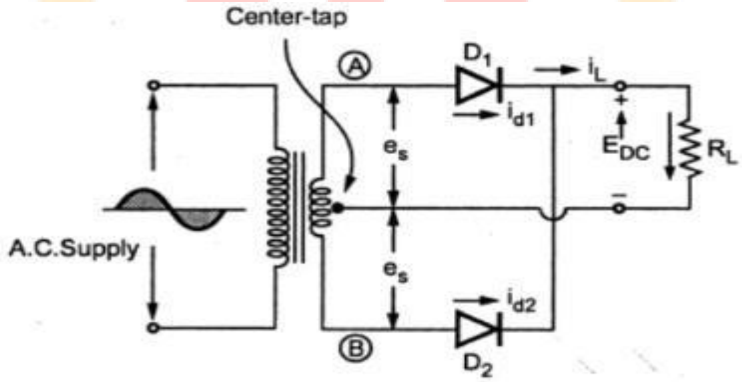


Fig. 1.6 Full Wave Rectifier Circuit

For the proper operation of the circuit, a **center-tap** on the secondary winding of the transformer is essential.

Operation of Full Wave Rectifier

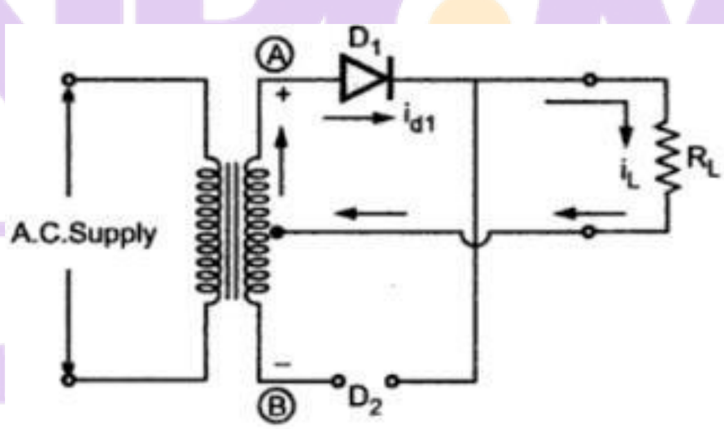


Fig. 1.7 Current flow during positive half cycle

Consider the positive half cycle of ac 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. This is illustrated in the Fig. 1.7

The diode D_1 supplies the load current, i.e. $i_L = i_{d1}$ .This current is flowing through upper half of secondary winding while the lower half of secondary winding of the transformer carries no current since diode D_2 is reverse biased and acts as an open circuit.

In the next half cycle of ac voltage, polarity reverses and terminal (A) becomes negative and (B) positive. The diode D_2 conducts, being forward biased, while D_1 does not, being reverse biased. This is shown in the Fig. 1.8 .

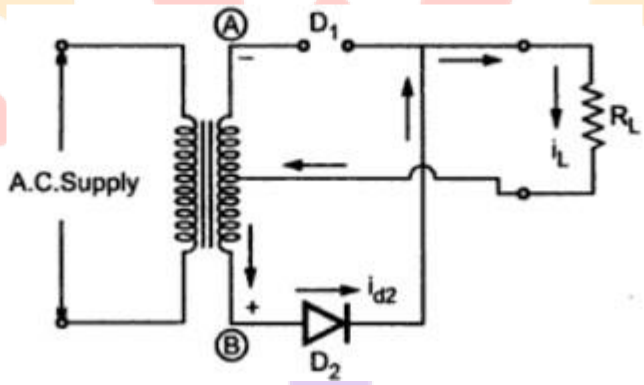


Fig. 1.8 Current flow during negative half cycle

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 but the upper half does not.

It is noted that the **load current flows in both the half cycles of ac 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 individual diode currents and the load current are shown in the Fig. 1.9

Thus the full wave rectifier circuit essentially consists of two half-wave rectifier circuits working independently (working in alternate half cycles of a c) of each other but feeding a common load. The output load current is still pulsating d.c. and not pure d.c.

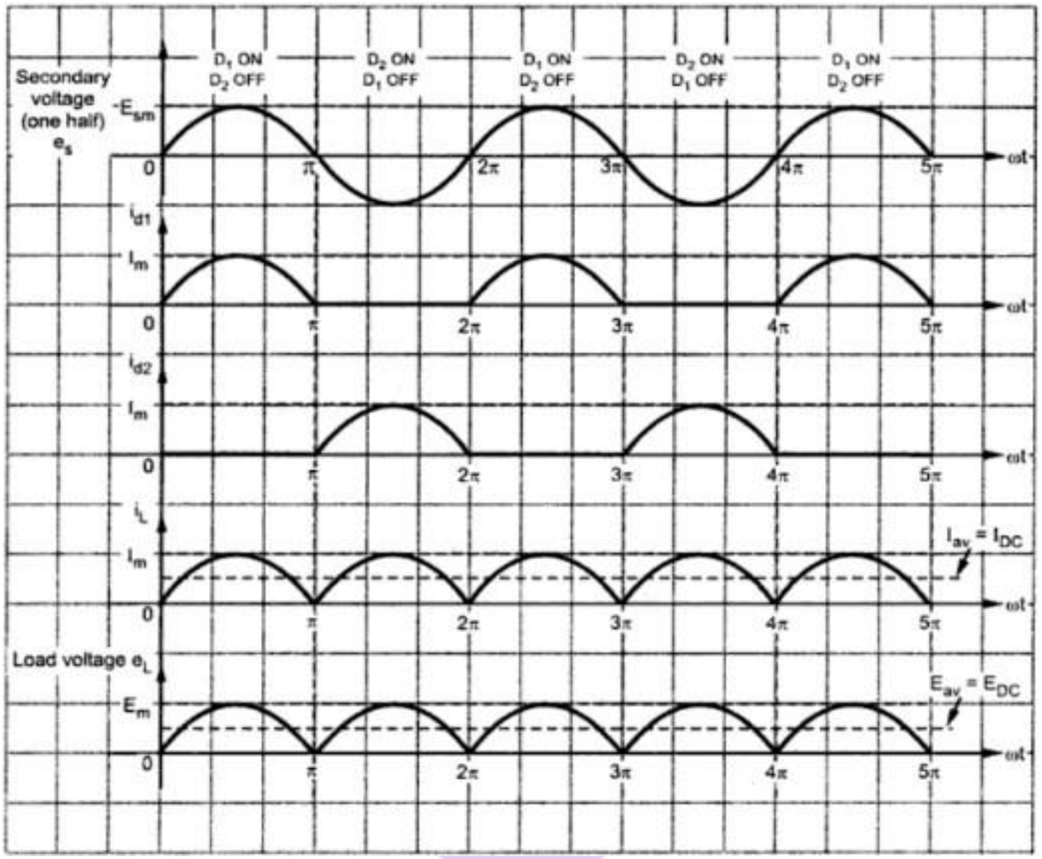
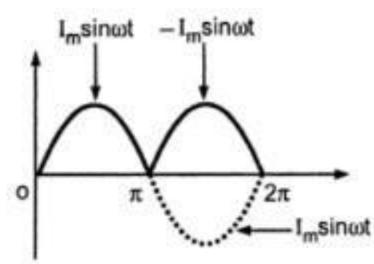


Fig. 1.9 Load current and voltage waveforms for full wave rectifier

Average DC Load Current (I_{DC})



Consider one cycle of load current i_L from 0 to 2π to obtain the average value which is d.c. value of load current.

$$i_L = I_m \sin \omega t \qquad 0 \le \omega t \le \pi$$

But for π to 2π, the current i_L is again positive while sin ω t term is negative during π to 2π . Hence in the region π to 2π the positive i_L can be represented as negative of I_m sin (ω t).

$$\therefore \quad i_L = -I_m \sin \omega t \qquad \pi \le \omega t \le 2\pi$$

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

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

$$= \frac{I_m}{2\pi}\left[\int_0^{\pi} \sin \omega t \, d(\omega t) - \int_{\pi}^{2\pi} \sin \omega t \, d(\omega t)\right]$$

$$= \frac{I_m}{2\pi}\left[(-\cos \omega t)_0^{\pi} - (-\cos \omega t)_{\pi}^{2\pi}\right]$$

$$= \frac{I_m}{2\pi}[-\cos \pi + \cos 0 + \cos 2\pi - \cos \pi]$$

but $\cos\pi = -1$

$$= \frac{I_m}{2\pi}[-(-1)+1+1-(-1)] = \frac{4I_m}{2\pi}$$

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

For half wave it is I_m/π and full wave rectifier is the combination of two half wave circuits acting alternately in two half cycles of input. Hence obviously the d.c. value for full wave circuit is $2\ I_m/\pi$.

Average DC Load Voltage (E_{DC})

The d.c. load voltage is,

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

Substituting value of I_m,

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

But as R_f and $R_s << R_L$ hence $\frac{R_f + R_s}{R_L} << 1$

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

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

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

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

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

$$I_{RMS} = \sqrt{\frac{2}{2\pi}\int_0^{\pi} [I_m \sin \omega t]^2 d(\omega t)}$$

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

$$\therefore \quad I_{RMS} = I_m\sqrt{\frac{1}{2\pi}\left[[\omega t]_0^{\pi} - \left(\frac{\sin 2\omega t}{2}\right)_0^{\pi}\right]} = I_m\sqrt{\frac{1}{2\pi}[\pi - 0]}$$

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

$$\therefore \quad \boxed{I_{RMS} = \frac{I_m}{\sqrt{2}}}$$

DC Power output (P_{DC})

$$\boxed{\text{D.C. Power output} = E_{DC}I_{DC} = I_{DC}^2 R_L}$$

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

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

Substituting value of I_m we get,

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

Note : Instead of remembering this formula, students can use the expression $E_{DC}I_{DC}$ or $I_{DC}^2 R_L$ to calculate P_{DC} while solving the problems.

AC Power input (P_{AC})

The a.c. power input is given by,

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

$$= \left(\frac{I_m}{\sqrt{2}}\right)^2 (R_f + R_s + R_L)$$

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

Substituting value of I_m we get,

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

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

Rectifier Efficiency (η)

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

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

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

But if $R_f + R_s << R_L$, neglecting it from denominator

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

$$\therefore \quad \% \eta_{max} = \frac{8}{\pi^2} \times 100 = 81.2 \%$$

This is the maximum theoretical efficiency of full wave rectifier.

Ripple Factor (γ)

As derived earlier in case of half wave rectifier the ripple factor is given by a general expression,

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

For full wave $I_{RMS} = I_m/\sqrt{2}$ and $I_{DC} = 2I_m/\pi$ so substituting in the above equation,

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

$$\therefore \quad \text{Ripple factor} = \gamma = 0.48$$

Key Point : *This indicates that the ripple contents in the output are 48 % of the d.c. component which is much less than that for the half wave circuit.*

Peak Inverse Voltage (PIV)

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

where E_{sm} = Maximum value of a.c. voltage across half the secondary of transformer.

If the diode drop is considered to be 0.7 V then the PIV of reverse biased diode is,

$$\text{PIV of diode} = 2E_{sm} - 0.7$$

This is because only one diode conducts at a time.

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 T.U.F is calculated for primary and secondary windings separately and then the average T.U.F. 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, $E_{sm} \approx I_m R_L$.

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

The primary of the transformer is feeding two half-wave rectifiers separately. These two half-wave rectifiers work independently of each other but feed a common load. We have already derived the T.U.F. for half wave circuit to be equal to 0.287. Hence

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

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

The average T.U.F for fullwave circuit will be

$$\text{Average T.U.F. for full wave rectifier circuit} = \frac{\text{T.U.F of primary} + \text{T.U.F of secondary}}{2}$$

$$= \frac{0.574 + 0.812}{2} = \mathbf{0.693}$$

∴ Average T.U.F. for full-wave rectifier = 0.693

Key Point: *Thus in full-wave circuit, transformer gets utilized more than the* ***half*** *wave rectifier circuit.*

Example 1 : *A full-wave rectifier circuit is fed from a transformer having a center-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) TUF of secondary.*

Solution:

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

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

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

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

$$= 42\ mA$$

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

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

$= \mathbf{0.715\ W}$

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

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

$= 26.74\ V$

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

$= \mathbf{0.97\ \%}$

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

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

$= 0.802$ **i.e. 80.2%**

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

$= \mathbf{0.89\ W}$

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

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

Bridge Rectifier

The bridge rectifier circuits are mainly used as,

a) a power rectifier circuit for converting a.c. power to d.c. power, and

b) a rectifying system in rectifier type a.c. meters, such as a.c. voltmeter, in which the a.c. voltage under measurement is first converted into d.c. and measured with conventional meter. In this system, the rectifying elements are either copper oxide type or selenium type.

The basic bridge rectifier circuit is shown in Fig. 1.10

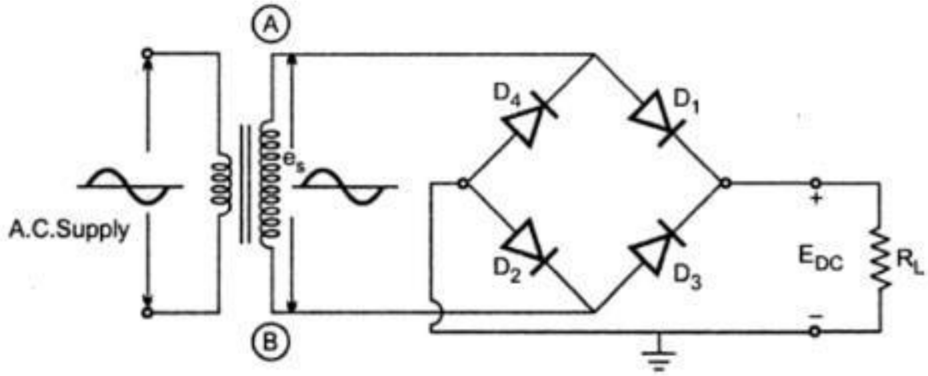


Fig. 1.10 Bridge rectifier circuit

The bridge rectifier circuit is essentially a full wave rectifier circuit, using four diodes, forming the four arms of an electrical bridge. To one diagonal of the bridge, the a.c. voltage is applied through a transformer if necessary, and the rectified d.c. voltage is taken from the other diagonal of the bridge. The main advantage of this circuit is that it does not require a center tap on the secondary winding of the transformer. Hence wherever possible, a.c. voltage can be directly applied to the bridge.

Operation of Bridge Rectifier

Consider the positive half of a.c. 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. 1.11

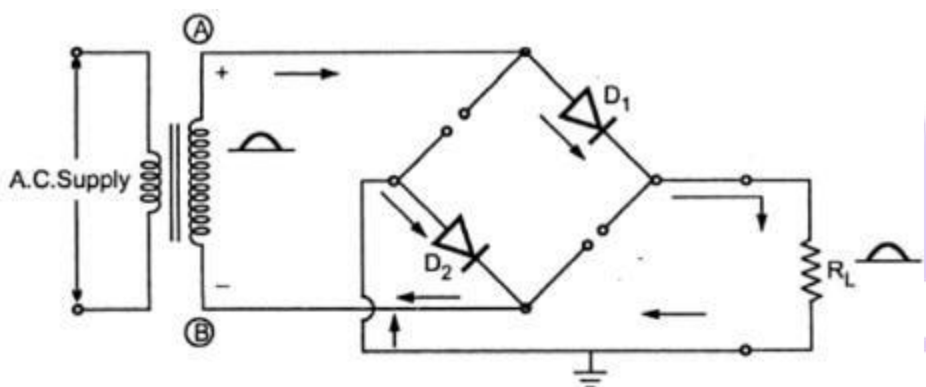


Fig. 1.11 Current flow during positive half cycle

In the next half cycle, when 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. 1.12

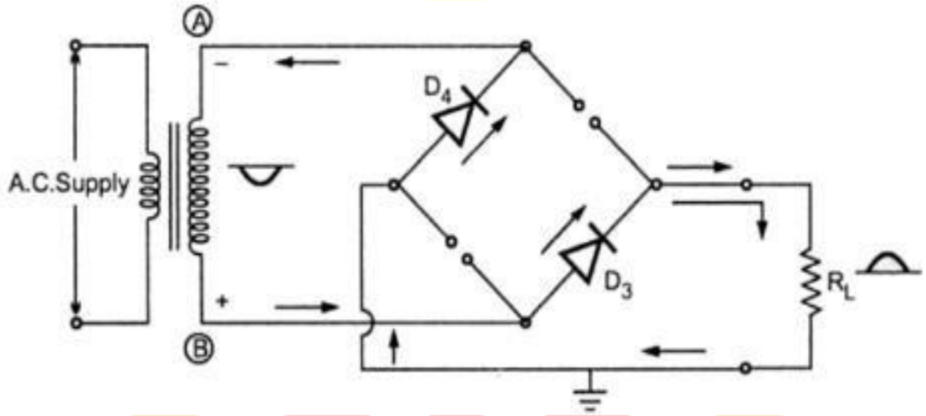


Fig. 1.12 Current flow during negative half cycle

It is seen that in both cycles of a.c., the load current is flowing in the same direction hence, we get a full wave rectified output.

The waveforms of load current and voltage remain exactly same as shown before for full wave rectifier.

Advantages of Bridge Rectifier

1) The current in both the primary and secondary of the power transformer flows for the entire cycle and hence for a given power output, power transformer of a small size and less cost may be used.
2) No center tap is required in the transformer secondary. Hence, wherever possible, ac voltage can directly be applied to the bridge.
3) The current in the secondary of the transformer is in opposite direction in two half cycles. Hence net d.c. component flowing is zero which reduces the losses and danger of saturation.
4) Due to pure alternating current in secondary of transformer, the transformer gets utilised effectively and hence the circuit is suitable for applications where large powers are required.
5) As two diodes conduct in series in each half cycle, inverse voltage appearing across diodes get shared. Hence the circuit can be used for high voltage applications. Such a peak reverse voltage appearing across diode is called peak inverse voltage rating (PIV) of diode.

Disadvantages of Bridge Rectifier

The only disadvantage of bridge rectifier is the use of four diodes as compared to two diodes in normal full wave rectifier. This causes additional voltage drop as indicated by term $2R_f$ present in expression of I_m instead of R_f . This reduces the output voltage.

Example 1 : *The four semiconductor diodes used in a bridge rectifier circuit each having a forward resistance of 0.1 Ω and infinite reverse resistance, feed a d.c. current of 10 A to a resistive load from a sinusoidally varying alternating supply of 30 V (r.m.s). Determine the resistance of the load and the efficiency of the circuit.*

Solution : The given values are,

$$R_f = 0.1\ \Omega,\ I_{DC} = 10\text{A},\ R_s = 0\ \Omega,\ E_s(\text{R.M.S.}) = 30\ \text{V}$$

Now
$$E_{sm} = E_{sm}(\text{R.M.S.}) \times \sqrt{2} = \sqrt{2} \times 30$$
$$= 42.4264\ \text{V}$$
$$I_{DC} = \frac{2I_m}{\pi}$$

∴
$$I_m = \frac{\pi \times I_{DC}}{2} = \frac{\pi \times 10}{2}$$
$$= 15.7079\ \text{A}$$

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

∴
$$15.7079 = \frac{42.4264}{2 \times 0.1 + R_L}$$

∴
$$R_L + 0.2 = 2.7$$

∴
$$R_L = \mathbf{2.5\ \Omega}$$

Now
$$P_{DC} = I_{DC}^2 R_L = (10^2) \times 2.5 = 250\ \text{W}$$
$$P_{AC} = I_{RMS}^2 (2R_f + R_s + R_L)$$

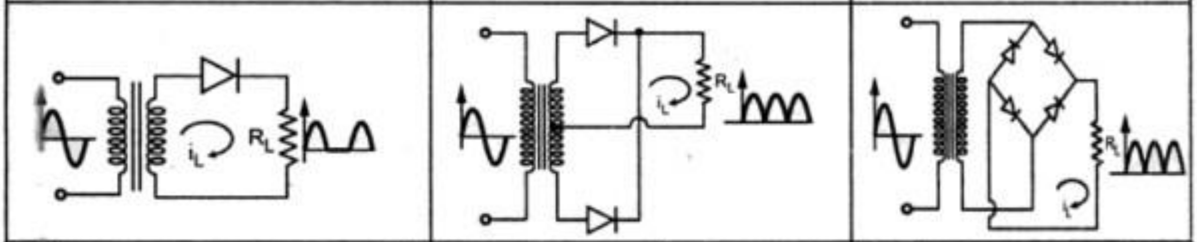
and
$$I_{RMS} = \frac{I_m}{\sqrt{2}} = \frac{15.7079}{\sqrt{2}} = 11.1071\ \text{A}$$

∴
$$P_{AC} = (11.1071)^2\ [2 \times 0.1 + 2.5] = 333.092\ \text{W}$$

∴
$$\%\eta = \frac{P_{DC}}{P_{AC}} \times 100 = \frac{250}{333.092} \times 100$$
$$= \mathbf{75.05\ \%}$$

Comparision of Rectifier Circuits

Circuit Diagrams		
Half Wave	Full Wave	Bridge



S.R.	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)	$\frac{E_{sm}}{R_s + R_f + R_L}$	$\frac{E_{sm}}{R_s + R_f + R_L}$	$\frac{E_{sm}}{R_s + 2R_f + R_L}$

FILTER CIRCUITS

It is seen that the output 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, filter circuits are used. These circuits are connected between the rectifier and load, as shown in the Fig. 1.13

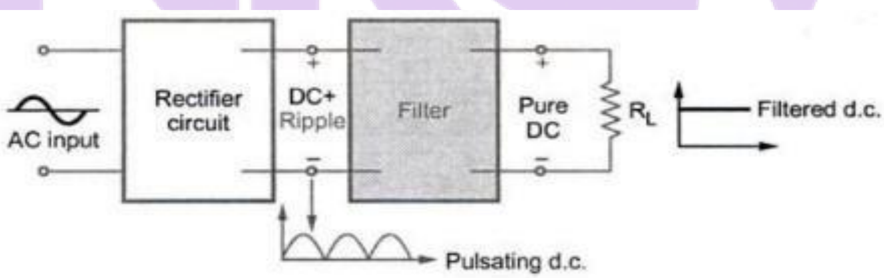


Fig. 1.13 Power supply using rectifier and filter

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. Practically, the filter circuit will try to minimize the ripple at the output, as far as possible.

Basically the ripple is a.c., i.e. varying with time, while d.c. is a constant w.r.t. time. Hence in order to separate d.c. from ripple, the filter circuit should use components which have widely different impedance for a.c. and d.c. Two such components are inductance and capacitance. Ideally, the inductance acts as a short circuit for d.c., but it has a large impedance for a.c.. Similarly, the capacitor acts as open for d.c. and almost short for a.c. if the value of capacitance is sufficiently large enough.

Since ideally, inductance acts as short circuit for d.c., it cannot be placed in shunt arm across the load, otherwise the d.c. will be shorted.

Key Point: *Hence, in a filter circuit, the inductance is always connected in series with the load.*

The inductance used in filter circuits is also called "**choke**".

Similarly, since the capacitance is open for d.c., i.e. it blocks d.c.; hence it cannot be connected in series with the load.

Key Point: *It is always connected in shunt arm, parallel to the load.*

Thus filter is an electronic circuit composed of capacitor, inductor or combination of both and connected between the rectifier and the load so as to convert pulsating d.c. to pure d.c.

There are basically two types of filter circuits,

- Capacitor input filter
- Choke input filter

Looking from the rectifier side, if the first element, in the filter circuit is capacitor then the filter circuit is called **capacitor input filter**. While if the first element is an inductor, it is called **choke input filter**. The choke input filter is not in use now a days as inductors are bulky, expensive and consume more power. Let us discuss the operation of a capacitor input filter.

Capacitor Input Filter

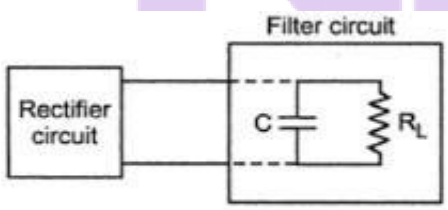


Fig. 1.14 Capacitor input filter

The block schematic of capacitor input filter is shown in the Fig. 1.14. Looking from the rectifier side the first element in filter is a capacitor.

Full wave rectifier with capacitor input filter

The same concept can now be extended to the capacitor filter used in full wave rectifier circuit as shown in the Fig. 1.19.

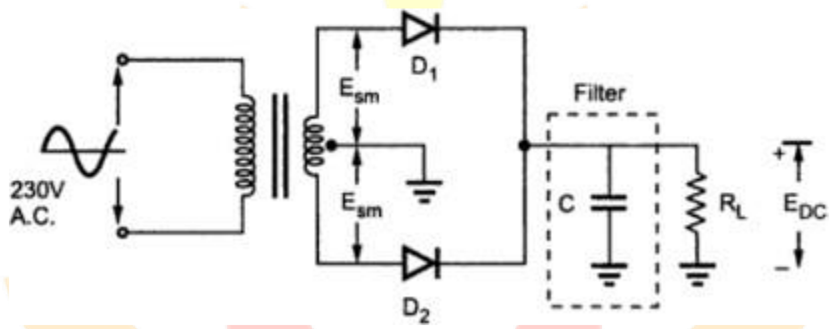


Fig.1.19 Full wave rectifier with capacitor input filter

Immediately 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 $\frac{\pi}{2}$ 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 $\frac{\pi}{2}$ to π, the capacitor C supplies the load current. It discharges to point B shown in the Fig. 1.20. At point B, lying in the quarter π to $\frac{3\pi}{2}$ 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. 1.20. At this point, the diode D_1 conducts to charge capacitor back to E_{sm}. The diode currents are shown shaded in the Fig. 1.20.

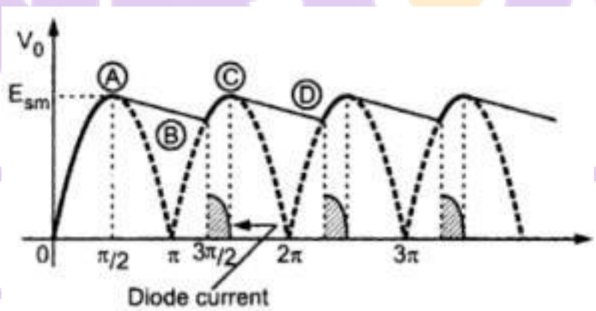


Fig.1.20 Charging and discharging of capacitor input filter

In this circuit, the two diodes are conducting in alternate half cycles of the output of the rectifier circuit. The diodes are not conducting for the entire half cycle but only for a part of the half cycle, during which the capacitor is getting charged. When the capacitor is discharging through the load resistance R_L, both the diodes are non-conducting. The capacitor supplies the load current. As the time required by capacitor to charge is very small and it discharges very little due to large time constant, hence ripple in the output gets reduced considerably. Though the diodes conduct partly, the load current gets maintained due to the capacitor. This filter is very popularly used in practice.

Expression for Ripple Factor

Consider an output waveform for a full wave rectifier circuit using a capacitor input filter, as shown in the Fig. 1.21.

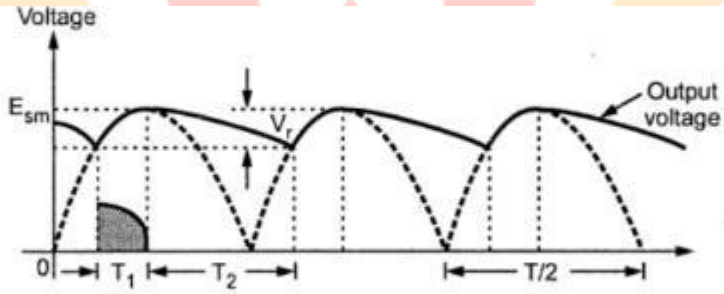


Fig.1.21 Derivation of ripple factor

Let T = Time period of the a.c. input voltage

$\frac{T}{2}$ = Half of the time period

T_1 = Time for which diode is conducting

T_2 = Time for which diode is nonconducting.

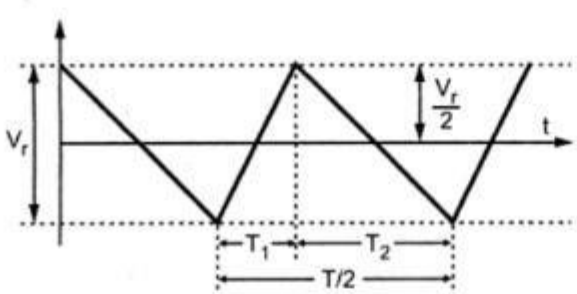


Fig. 1.22 Triangular approximation of ripple voltage

During time T_1, capacitor gets charged and this process is quick. During time T_2, capacitor gets discharged through R_L. As time constant R_LC is very large, discharging process is very slow and hence $T_2 >> T_1$.

Let V_r be the peak to peak value of ripple voltage, which is assumed to be triangular as shown in the Fig. 1.22

It is known mathematically that the r.m.s. value of such a **triangular waveform** is,

$$\boxed{V_{rms} = \frac{V_r}{2\sqrt{3}}}$$

During the time interval T_2, the capacitor C is discharging through the load resistance R_L. The charge lost is,

$$Q = CV_r$$

But $$i = \frac{dQ}{dt}$$

∴ $$Q = \int_0^{T_2} i\,dt = I_{DC}\,T_2$$

As integration gives average or d.c. value

Hence $$I_{DC}\,T_2 = CV_r$$

∴ $$V_r = \frac{I_{DC}\,T_2}{C}$$

Now, $$T_1 + T_2 = \frac{T}{2}$$ Normally, $T_2 >> T_1$

∴ $$T_1 + T_2 \approx T_2 = \frac{T}{2} \quad \text{where } T = \frac{1}{f}$$

∴ $$\boxed{V_r = \frac{I_{DC}}{C}\left[\frac{T}{2}\right] = \frac{I_{DC} \times T}{2C} = \frac{I_{DC}}{2\,fC}}$$

But $$I_{DC} = \frac{E_{DC}}{R_L}$$

∴ $$\boxed{V_r = \frac{E_{DC}}{2\,f\,C\,R_L} = \text{peak to peak ripple voltage}}$$

$$\text{Ripple factor} = \frac{V_{rms}}{E_{DC}} = \frac{\frac{E_{DC}}{2\,f\,C\,R_L}}{2\sqrt{3}} \times \frac{1}{E_{DC}}, \text{ Since } V_{rms} = \frac{V_r}{2\sqrt{3}}$$

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

For **half wave rectifier** with capacitor input filter the ripple factor is,

$$\boxed{\text{Ripple factor} = \frac{1}{2\sqrt{3}\,f\,C\,R_L} \quad \text{for half wave}}$$

The product CR_L is the time constant of the filter circuit.

Advantages and Disadvantages of Capacitor input filter

The **advantages** of capacitor input filter are,

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

The **disadvantages** of capacitor input filter are,

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

Example 1 : *A full wave rectifier is operated from 50 Hz supply with 120 V (rms). It is connected to a load drawing 50 mA and using 100 μF filter capacitor. Calculate the d.c. output voltage and the r.m.s. value of ripple voltage. Also calculate the ripple factor.*

Solution : $E_{s(rms)} = 120$ V, f = 50 Hz, $I_{DC} = 50$ mA, C = 100 μF

$$E_{sm} = \sqrt{2}\, E_{s(rms)} = \sqrt{2} \times 120 = 169.7056 \text{ V}$$

For full wave rectifier,

$$E_{DC} = E_{sm} - I_{DC}\left[\frac{1}{4\,fC}\right]$$

$$= 169.7056 - \frac{50 \times 10^{-3}}{4 \times 50 \times 100 \times 10^{-6}} = \mathbf{167.2056\ V}$$

$$V_{r(rms)} = \frac{I_{DC}}{4\sqrt{3}\, fC} = \frac{50 \times 10^{-3}}{4 \times \sqrt{3} \times 50 \times 100 \times 10^{-6}}$$

$$= \mathbf{1.4433\ V}$$

The ripple factor is given by,

$$\gamma = \frac{V_{r(rms)}}{E_{DC}} = \frac{1.4433}{167.2056}$$

$$= 8.63 \times 10^{-3}$$

Inductor Filter or Choke Filter

In this type of filter, an inductor (choke) is connected in series with the load. It is known that 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. 1.23 (a) shows the circuit diagram while Fig. 1.23(b) shows the current waveform obtained by using choke filter with full wave rectifier.

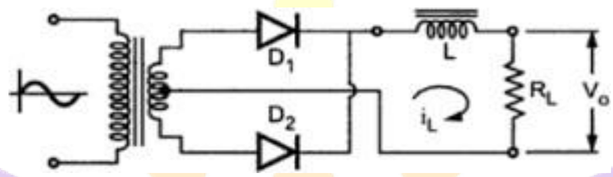


Fig.1.23 (a) Circuit diagram of choke filter

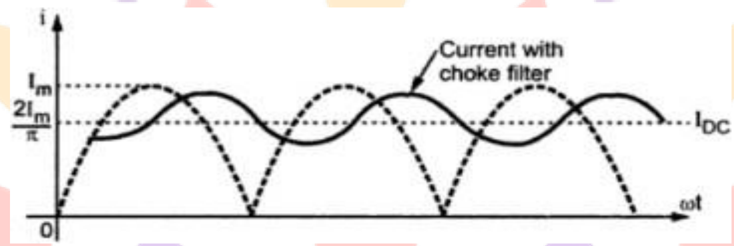


Fig.1.23 (a) Current waveform of choke filter

Operation 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. While 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.

We know that the fourier series for the load current for full wave rectifier as,

$$i_L = I_m \left[\frac{2}{\pi} - \frac{4}{3\pi} \cos 2\omega t - \frac{4}{15\pi} \cos 4\omega t \right]$$

Neglecting higher order harmonics we get,

$$i_L = \frac{2 I_m}{\pi} - \frac{4 I_m}{3\pi} \cos 2\omega t$$

Neglecting diode forward resistances and the resistance of choke and transformer secondary we can write the d.c. component of current as

$$\frac{2 I_m}{\pi} = \frac{2 V_m}{\pi R_L}$$

as $$I_m = \frac{V_m}{R_L}$$

While the second harmonic component represents a.c. component or ripple present and can be written as,

$$I_m = \frac{V_m}{Z} \quad \text{for a.c. component}$$

Now $Z = R_L + j2X_L = \sqrt{R_L^2 + 4\omega^2 L^2} \angle \phi$

where $\phi = \tan^{-1} \frac{2\omega L}{R_L}$

$$\therefore \quad \boxed{I_m = \frac{V_m}{\sqrt{R_L^2 + 4\omega^2 L^2}}}$$

The ripple present is the second harmonic component having frequency 2ω.

Key Point: *Hence while calculations the effective inductive reactance must be calculated at 2ω hence represented as $2X_L$ in the above expression.*

Hence equation (1) modifies as,

$$\boxed{i_L = \frac{2V_m}{\pi R_L} - \frac{4V_m}{3\pi\sqrt{R_L^2 + 4\omega^2 L^2}} \cos(2\omega t - \phi)}$$

Expression for the ripple factor

Ripple factor is given by ,

$$\text{Ripple factor} = \frac{I_{rms}}{I_{DC}}$$

where $I_{rms} = \frac{I_m}{\sqrt{2}}$ of a.c. component

$$I_{rms} = \frac{4V_m}{3\sqrt{2}\pi\sqrt{R_L^2 + 4\omega^2 L^2}}$$

while $I_{DC} = \frac{2V_m}{\pi R_L}$

$$\therefore \text{Ripple factor} = \frac{\frac{4V_m}{3\sqrt{2}\pi\sqrt{R_L^2 + 4\omega^2 L^2}}}{\frac{2V_m}{\pi R_L}}$$

$$= \frac{2}{3\sqrt{2}} \cdot \frac{1}{\sqrt{1 + \frac{4\omega^2 L^2}{R_L^2}}}$$

Initially on no load condition, $R_L \to \infty$ and hence $\frac{4\omega^2 L^2}{R_L^2} \to 0$.

$$\therefore \text{Ripple factor} = \frac{2}{3\sqrt{2}} = 0.472$$

This is very close to normal full wave rectifier without filtering.

But as load increases, R_L decreases hence $\frac{4\omega^2 L^2}{R_L^2} >> 1$. So neglecting 1 we get,

$$\text{Ripple factor} = \frac{2}{3\sqrt{2}} \cdot \frac{1}{\sqrt{\frac{4\omega^2 L^2}{R_L^2}}}$$

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

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

Key Point: *Smaller the value of R_L, smaller is the ripple hence the filter is suitable for low load resistances i.e. for high load current applications.*

Example 1 *(a). What should be the value of inductance to use in an inductor filter connected to a full-wave rectifier operating at 50 Hz, if the ripple is not to exceed 5% for a 100 Ω load.*

(b). Repeat the above problem for the standard aircraft power frequency of 400 Hz.

Solution. (*a*) Given: $f = 50$ Hz; $\gamma = 5\% = 0.05$ and $R_L = 100\ \Omega$.

We know that ripple factor (γ),

$$0.05 = \frac{R_L}{3\sqrt{2}\cdot\omega\cdot L} = \frac{100}{3\sqrt{2}\times(2\pi\times 50)\times L} = \frac{0.075}{L}$$

$$\therefore \quad L = 0.075/0.05 = 1.5 \text{ H } \textbf{Ans.}$$

(*b*) Given: $f = 400$ Hz; $\gamma = 0.05$ and $R_L = 100\ \Omega$.

We also know that ripple factor (γ),

$$0.05 = \frac{R_L}{3\sqrt{2}\cdot\omega\cdot L} = \frac{100}{3\sqrt{2}\times(2\pi\times 400)\times L} = \frac{1}{106.6\,L}$$

$$\therefore \quad L = 1/(106.6 \times 0.05) = 0.188 \text{ H Ans.}$$

Comparision of Filter Circuits

Parameter	Type of filter			
	L	C	LC	π
E_{DC}(no load)	0.636 E_{sm}	E_{sm}	E_{sm}	E_{sm}
E_{DC}(load I_{DC})	0.636 E_{sm}	$E_{sm} - \frac{I_{DC}}{4fC}$	0.636 E_{sm}	$E_{sm} - \frac{I_{DC}}{4fC}$
Ripple factor (γ)	$\frac{R_L}{3\sqrt{2}\omega L}$	$\frac{1}{4\sqrt{3}\, fRC}$	$\frac{1}{6\sqrt{2}\omega^2 LC}$	$\frac{\sqrt{2}}{8\omega^3 LC_1C_2R_L}$
PIV	2 E_{sm}	2 E_{sm}	2 E_{sm}	2 E_{sm}

Key Point: *Above comparison is for full wave rectifiers with filters and diode, transformer and filter element resistances are neglected.*

CLIPPERS

Clipping means cutting and removing a part. A clipping circuit is a circuit which removes the undesired part of the waveform and transmits only the desired part of the signal which is above or below some particular reference level, i.e. it is used to select for transmission that part of an arbitrary waveform which lies above or below some particular reference. Clipping circuits are also called voltage (or current) limiters, amplitude selectors or slicers.

Nonlinear wave shaping circuits may be classified as clipping circuits and clamping circuits. Clipping circuits may be single level clippers or two level clippers. Single level clippers may be series diode clippers with and without reference or shunt diode clippers with and without reference. Clipping circuits may use diodes or transistors.

Clamping circuits may be negative clampers (positive peak clampers) with and without reference or positive clampers (negative peak clampers) with and without reference.

Diode Clippers

Figure 2.1(a) shows the v-i characteristic of a practical diode. Figures 2.1(b), (c), (d), and (e) show the v-i characteristics of an idealized diode approximated by a curve which is piece wise linear and continuous. The break point occurs at Vr, where Vr = 0.2 V for Ge and Vr = 0.6 V for Si. Usually Vr is very small compared to the reference voltage VR and can be neglected.

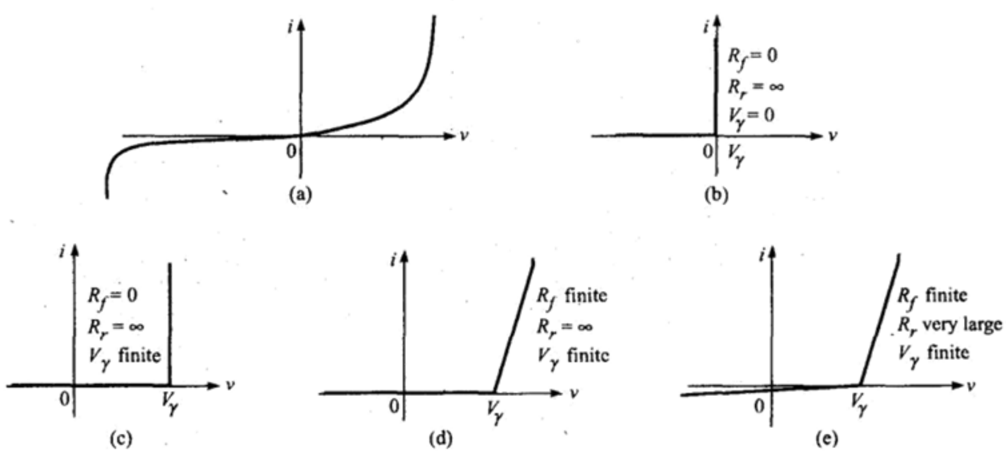


Figure 2.1 *v–i* characteristics of a diode.

Shunt Clippers

Clipping above reference level

Using the ideal diode characteristic of Figure 2.2(a), the clipping circuit shown in Figure 2.2(b), has the transmission characteristic shown in Figure 2.2(c). The transmission characteristic which is a plot of the output voltage v0 as a function of the input voltage v, also exhibits piece-wise linear discontinuity. The break point occurs at the reference voltage VR. To the left of the break point i.e. for vi < VR the diode is reverse biased (OFF) and the equivalent circuit shown in Figure 2.2(d) results. In this region the signal v, may be transmitted directly to the output, since there is no load across the output to cause a drop across the series resistor R. To the right of the break point i.e. for Vi > VR the diode is forward biased (ON) and the equivalent circuit shown in Figure 2,2(e) results and increments in the inputs are totally attenuated and the output is fixed at VR.

Figure 2.2(c) shows a sinusoidal input signal of amplitude large enough so that the signal makes excursions past the break point. The corresponding output exhibits a suppression of the positive peak of the signal. The output will appear as if the positive peak had been clipped off or sliced off.

Clipping below reference level

If this clipping circuit of Figure 2.2(b), is modified by reversing the diode as shown in Figure 2.3(a), the corresponding piece-wise linear transfer characteristic and the output for a sinusoidal input will be as shown in Figure 2.3(b). In this circuit, the portion of the waveform more positive than V_R is transmitted without any attenuation but the portion of the waveform less positive than V_R is totally suppressed. For Vi < VR, the diode conducts and acts as a short circuit and the equivalent circuit shown in Figure 2.3(c) results and the output is fixed at V_R. For vi > V_R, the diode is reverse biased and acts as an open circuit and the equivalent circuit shown in Figure 2.3(d) results and the output is the same as the input.

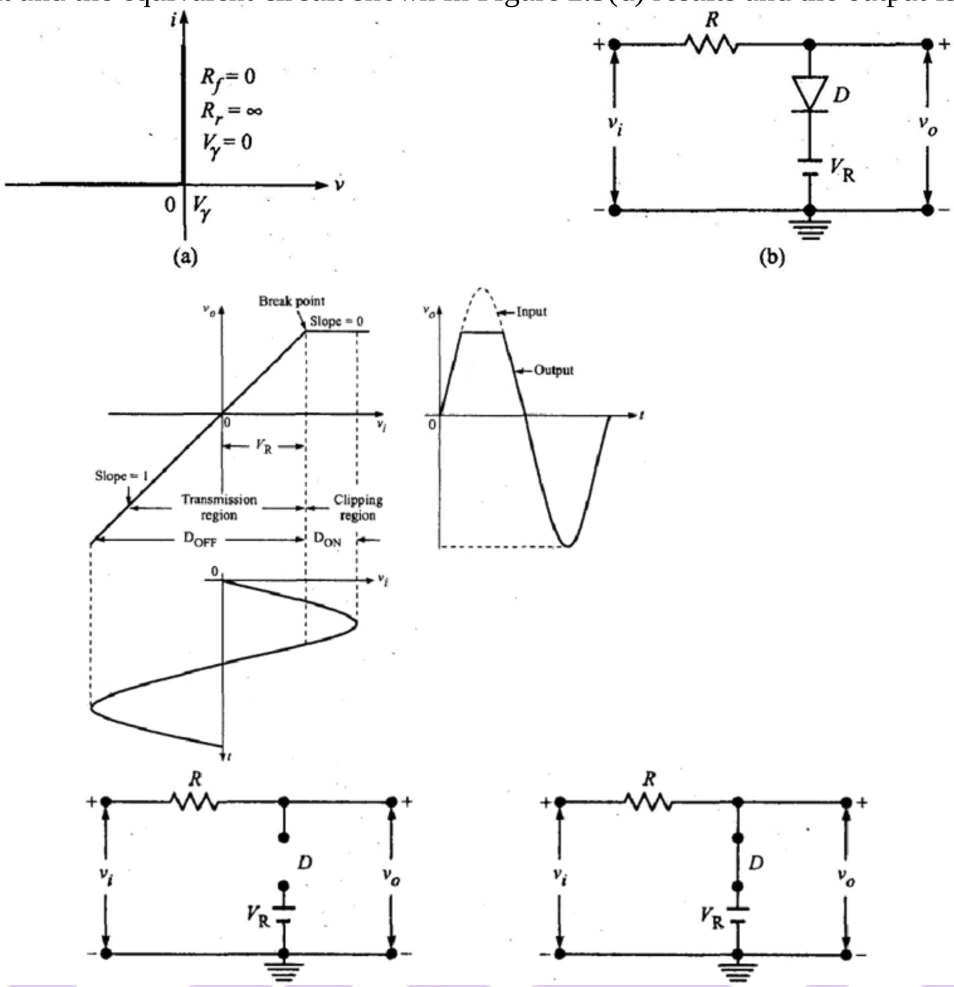


Figure 2.2 (a) v-i characteristic of an ideal diode, (b) diode clipping circuit, which removes that part of the waveform that is more positive than VR, (c) the piece-wise linear transmission characteristic of the circuit, a sinusoidal input and the clipped output, (d) equivalent circuit for vi < VR, and (e) equivalent circuit for vi > VR.

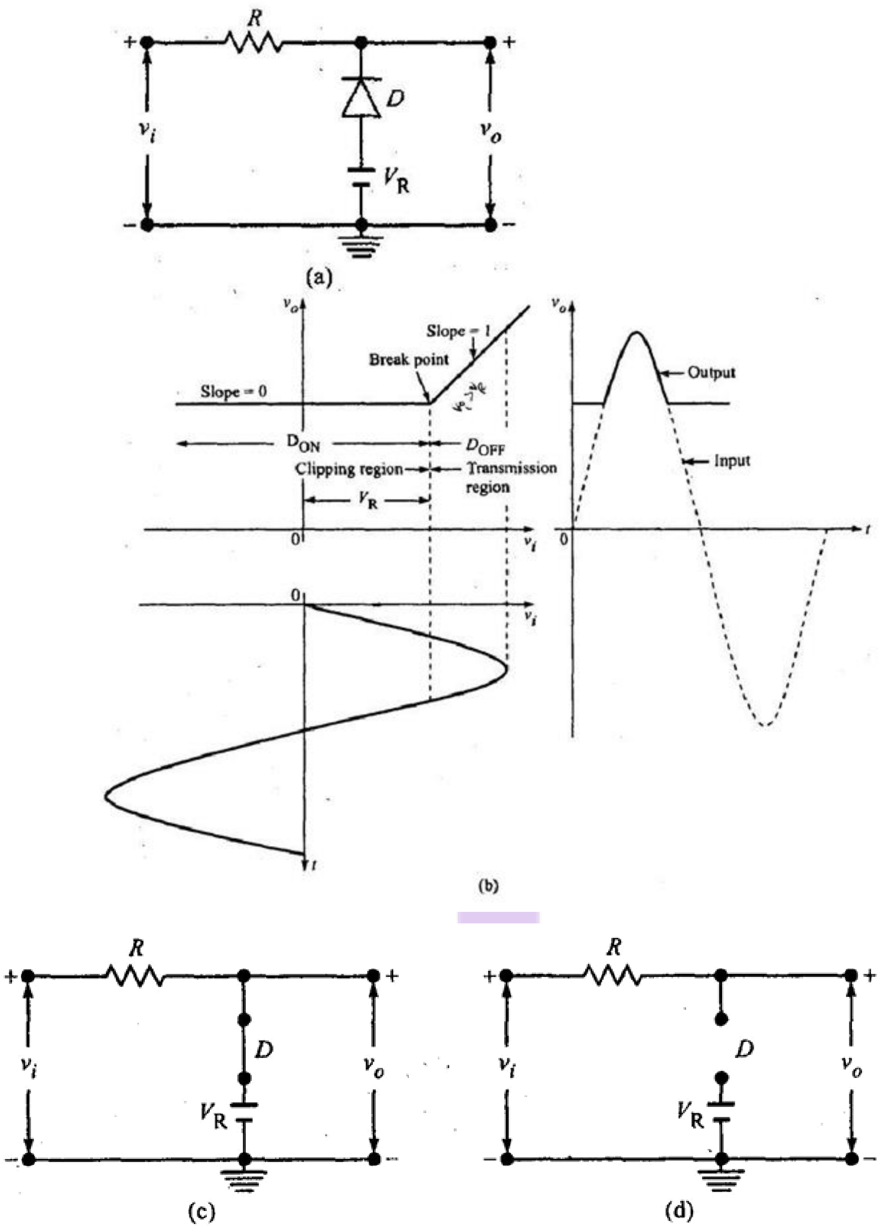


Figure 2.3 (a) A diode clipping circuit, which transmits that part of the sine wave that is more positive than V_R, (b) the piece-wise linear transmission characteristic, a sinusoidal input and the clipped output, (c) equivalent circuit for $V_i < V_R$, and (d) equivalent circuit for $V_i > V_R$.

In Figures 2.1(b) and 2.2(a), we assumed that Rr = ∞ and Rf = 0. If this condition does not apply, the transmission characteristic must be modified. The portions of those curves which are indicated as having unity slope must instead be considered as having a slope of Rr/(Rr + R), and those, having zero slope as having a slope of Rf/(Rf + R),. In the transmission region of a diode clipping circuit, it is required that Rr » R, i.e. Rr = kR, where k is a large number, and in the attenuation region, it is required that R » Rf. From these equations we can deduce that R = $\sqrt{(Rr \times Rf)}$, i.e. the external resistance R is to be selected as the geometric mean of Rf and Rr. The ratio Rr/Rf serves as a figure of merit for the diodes used in these applications. A zener diode may also be used in combination with a p-n junction diode to obtain single-ended clipping, i.e. one-level clipping.

Series Clippers

Clipping above the reference voltage V_R

Figure 2.4(a) shows a series clipper circuit using a p-n junction diode. VR is the reference voltage source. The diode is assumed to be ideal ($R_r = \infty$ and $R_f = 0$, $V\gamma = 0$) so that it acts as a short circuit when it is ON and as a open circuit when it is OFF. Since the diode is in the series path connecting the input and the output it is called a series clipper. The v_0 versus v_i, characteristic called the transfer characteristic is shown in Figure 2.4(b). The output for a sinusoidal input is shown in Figure 2.4(c).

The circuit works as follows:

For vi < VR, the diode D1 is forward biased because its anode is at a higher potential than its cathode. It conducts and acts as a short circuit and the equivalent circuit shown in Figure 2.4(d) results. The difference voltage between the input V_i and the reference voltage V_R i.e. (VR – vi) is dropped across R. Therefore v0 = vi and the slope of the transfer characteristic for vi < VR is 1. Since the input signal is transmitted to the output without any change, this region is called the transmission region.

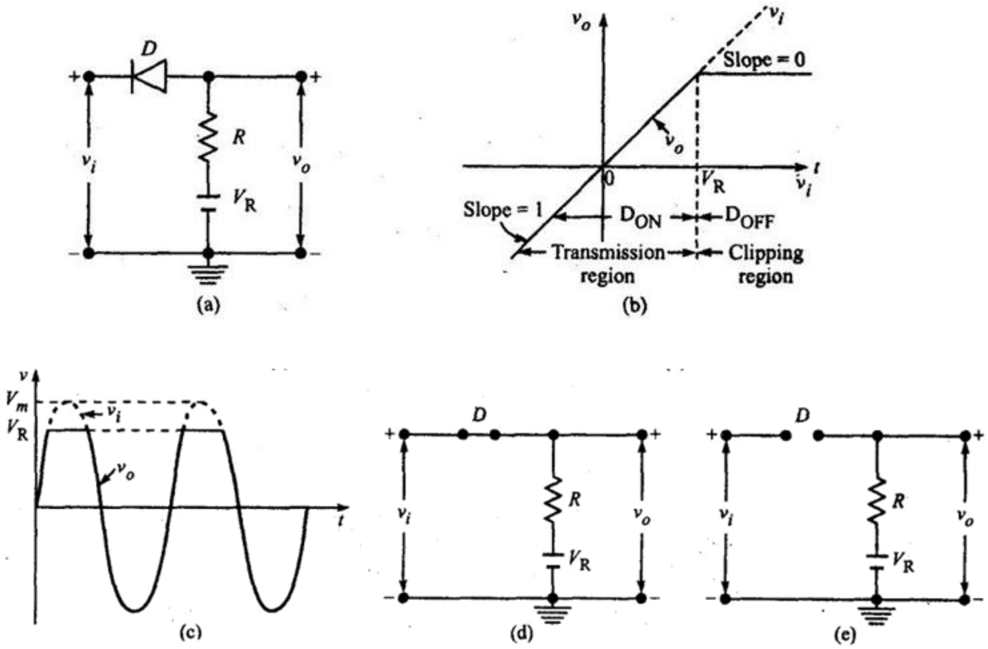


Figure 2.4 (a) Diode series clipper circuit diagram, (b) transfer characteristic, (c) output waveform for a sinusoidal input, (d) equivalent circuit for Vi< VR, and (e) equivalent circuit for Vi > VR.

For Vi> VR, the diode is reverse biased because its cathode is at a higher potential than its anode, it does not conduct and acts as an open circuit and the equivalent circuit shown in Figure 2.4(e) results. No current flows through R and so no voltage drop across it. So the output voltage v0 = VR and the slope of the transfer characteristic is zero. Since the input signal above V R is clipped OFF for Vi > VR, this region is called the clipping region.

The equations V0=Vi for Vi < VR and V0= VR for Vi > VR are called the transfer characteristic equations.

Clipping below the reference voltage Vr

Figure 2.5(a) shows a series clipper circuit using a p-n junction diode and a reference voltage source VR. The diode is assumed to be ideal ($R_f = 0$, $R_r = \infty$, $V\gamma = 0$) so that it acts as a short circuit when it is ON and as a open circuit when it is OFF. Since the diode is in the series path connecting the input and the output it is called a series clipper. The transfer characteristic is shown in Figure 2.5(b). The output for a sinusoidal input is shown in Figure 2.5(c).

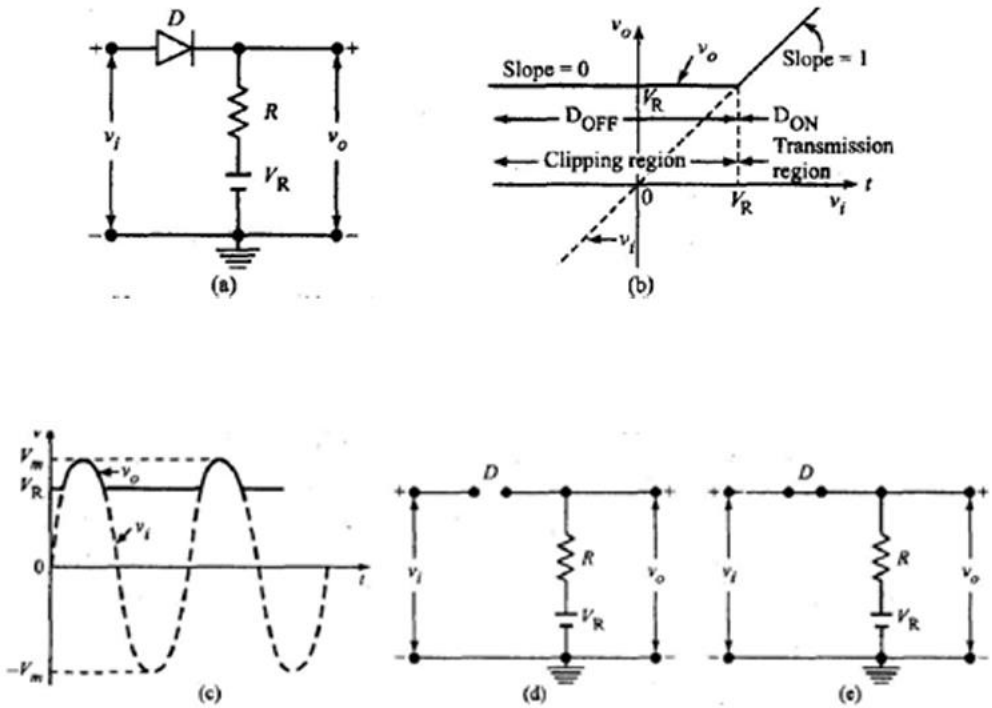


Figure 2.5 (a) Diode series clipper circuit diagram, (b). transfer characteristics, (c) output for a sinusoidal input, (d) equivalent circuit for vi < VR, and (e) equivalent circuit for vi > V_R.

The circuit works as follows:

For vi < V_R, D is reversed biased because its anode is at a lower potential than its cathode. The diode does not conduct and acts as an open circuit and the equivalent circuit shown in Figure 2.5(d) results. No current flows through R and hence no voltage drop across R and hence vo = V_R. So the slope of the transfer characteristic is zero for vi < V_R. Since the input is clipped off for vi < V_R, this region is called the clipping region.

For vi > VR, the diode is forward biased because its anode is at a higher potential than its cathode. The diode conducts and acts as a short circuit and the equivalent circuit shown in Figure 2.5(e) results. Current flows through R and the difference voltage between the input and the output voltages vi - VR drops across R and the output v0 = vi. The slope of the transfer characteristic for vi > VR is unity. Since the input is transmitted to the output for vi> VR, this region is called the transmission region. The equations are called the transfer characteristic equations.

$$v_o = V_R \text{ for } v_i < V_R$$
$$v_o = v_i \text{ for } v_i > V_R$$

Clipping at Two Independent Levels

A parallel, a series, or a series-parallel arrangement may be used in double-ended limiting at two independent levels. A parallel arrangement is shown in Figure 2.7. Figure 2.8 shows the transfer characteristic and the output for a sinusoidal input. The input-output characteristic has two breakpoints, one at v0 = vi = VR1 and the second at v0 = vi= -VR2 and has the following characteristics.

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

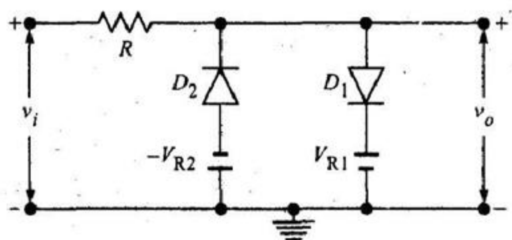


Figure 2.7 A diode clipper which limits at two independent levels.

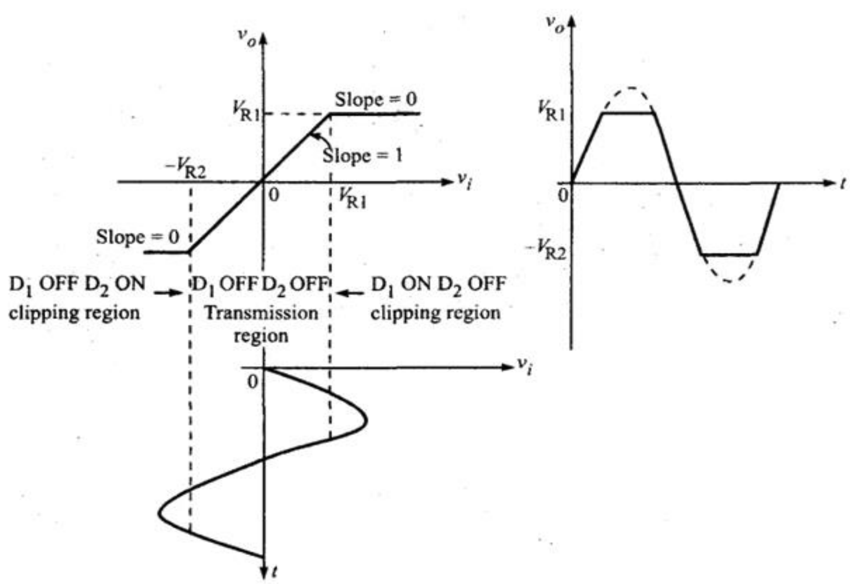


Figure 2.8 The piece-wise linear transfer curve, the input sinusoidal waveform and the corresponding output for the clipper of Figure 2.7.

The two level diode clipper shown in Figure 2.8 works as follows. For vi > VR1, DI is ON and D2 is OFF and the equivalent circuit shown in Figure 2.9(a) results. So the output v0 = VR1 and the slope of the transfer characteristic is zero.

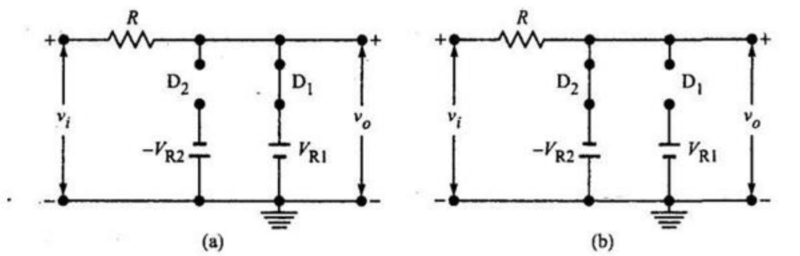


Figure 2.9 (a) Equivalent circuit for $v_i > V_{R1}$ and (b) equivalent circuit for $v_i < -V_{R2}$.

For vi < - VR2, D1 is OFF and D2 is ON and the equivalent circuit shown in Figure 2.9(b) results. So the output v0 = - VR2 and the slope of the transfer characteristic is zero. For-VR2 < Vi, < VRI, D1 is OFF and D2 is OFF and the equivalent circuit shown in Figure 2.10 results. So, the output v0 = vi and the slope of the transfer characteristic is one.

The circuit of Figure 2.7 is called a slicer because the output contains a slice of the input between two reference levels VR1and VR2. Looking at the input and output waveforms, we observe that this circuit may be used to convert a sine wave into a square wave, if $V_{R1} = V_{R2}$. and if the amplitude of the input signal is very large compared with the difference in the reference levels, the output will be a symmetrical square wave. Two zener diodes in series opposing may also be used to form a double-ended clipper. If the diodes have identical characteristics, then, a symmetrical limiter is obtained.

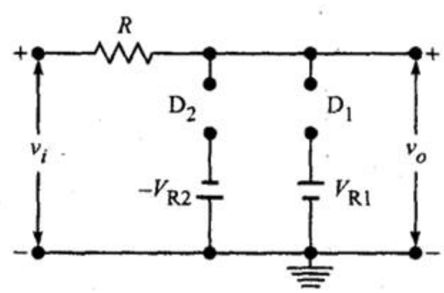


Figure 2.10 Equivalent circuit for $-V_{R2} < v_i < V_{R1}$.

CLAMPING CIRCUITS

Clamping circuits are circuits, which are used to clamp or fix the extremity of a periodic waveform to some constant reference level V_R. Under steady-state conditions, these circuits restrain the extremity of the waveform from going beyond V_R. Clamping circuits may be one way clamps or two-way clamps. When only one diode is used and a voltage change in only one direction is restrained, the circuits are called one-way clamps. When two diodes are used and the voltage change in both the directions is restrained, the circuits are called two-way clamps.

The Clamping Operation

When a signal is transmitted through a capacitive coupling network (RC high-pass circuit), it loses its dc component, and a clamping circuit may be used to introduce a dc component by fixing the positive or negative extremity of that waveform to some reference level. For this reason, the clamping circuit is often referred to as dc restorer or dc reinserter. In fact, it should be called a dc inserter, because the dc component introduced may be different from the dc component lost during transmission. The clamping circuit only changes the dc level of the input signal. It does not affect its shape

Classification of clamping circuits

Basically clamping circuits are of two types:

(1) positive-voltage clamping circuits and (2) negative-voltage clamping circuits.

In positive clamping, the negative extremity of the waveform is fixed at the reference level and the entire waveform appears above the reference level, i.e. the output waveform is positively clamped with reference to the reference level.

In negative clamping, the positive extremity of the waveform is fixed at the reference level and the entire waveform appears below the reference, i.e. the output waveform is negatively clamped with respect to the reference level. The capacitors are essential in clamping circuits. The difference between the clipping and clamping circuits is that while the clipper clipps off an unwanted portion of the input waveform, the clamper simply clamps the maximum positive or negative peak of the waveform to a desired level. There will be no distortion of waveform. Negative Clamper Figure 3.1 (a) shows the circuit diagram of a basic negative clamper. It is also termed a positive peak clamper since the circuit clamps the positive peak of a signal to zero level. Assume that the signal source has negligible output impedance and that the diode" is ideal, Rf= 0 n and $V\gamma = 0$ V in that, it exhibits an arbitrarily sharp break at 0 V, and that its input signal shown in Figure 2.71(b) is a sinusoid which begins at t = 0. Let the capacitor C be uncharged at t = 0**.**

During the first quarter cycle, the input signal rises from zero to the maximum value. The diode conducts during this time and since we have assumed an ideal diode, the voltage across it is zero. The capacitor C is charged through the series combination of the signal source and the diode and the voltage across C rises sinusoidally. At -the end of the first quarter cycle, the voltage across the capacitor, vc = Vm.When, after the first quarter cycle, the peak has been passed and the input signal begins to fall, the voltage vc across the capacitor is no longer able to follow the input, because there is no path for the capacitor to discharge. Hence, the voltage across the capacitor remains constant at vc = Vm, and the charged capacitor acts as a voltage source of V volts and after the first quarter cycle, the output is given by v0 = vi - Vm. During the succeeding cycles, the positive extremity of the signal will be clamped or restored to zero and the output.

Suppose that after the steady-state condition has been reached, the amplitude of the input signal is increased, then the diode will again conduct for at most one quarter cycle and the dc voltage across the capacitor would rise to the new peak value, and the positive excursions of the signal would be again restored to zero. Suppose the amplitude of the input signal is decreased after the steady-state condition has been reached. There is no path for the capacitor to discharge. To permit the voltage across the capacitor to decrease, it is necessary to shunt a resistor across C, or equivalently to shunt a resistor across D. In the latter case, the capacitor will discharge through the series combination of the resistor R across the diode and the resistance of the source, and in a few cycles the positive extremity would be again clamped at zero as shown in Figure 2.72(b). A circuit with such a resistor 'R is shown in Figure 2.72(a).

for $v_i = 0$, $v_o = -V_m$.

for $v_i = V_m$, $v_o = 0$,

for $v_i = -V_m$, $v_o = -2V_m$.

waveform shown in Figure 2.7 l(c) results. Therefore

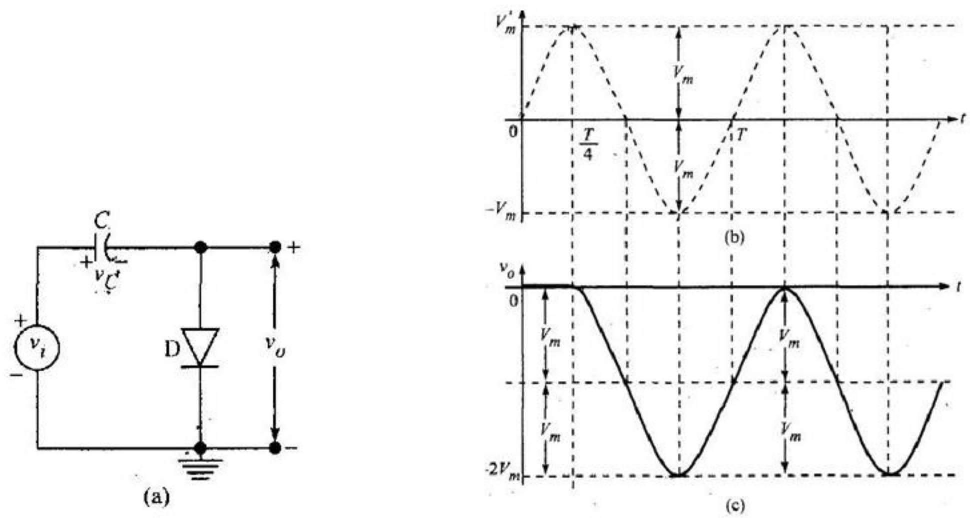


Figure 2.71 (a) A negative clamping circuit, (b) a sinusoidal input, and (c) a steady-state clamped output.

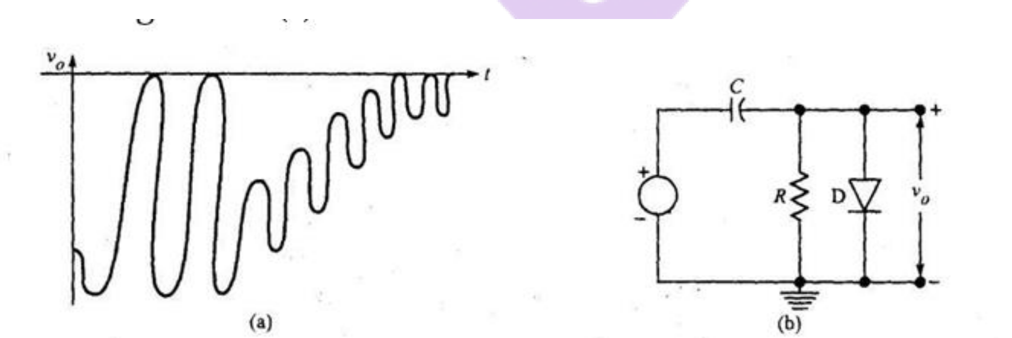


Figure 2.72 (a) Clamping circuit with a resistor R across the diode D and (b) output during transient period.

Positive Clamper Figure

2.73(a) shows a positive clamper. This is also termed as negative peak clamper since this circuit clamps the negative peaks of a signal to zero level. The negative peak clamper, i.e. the positive clamper introduces a positive dc.

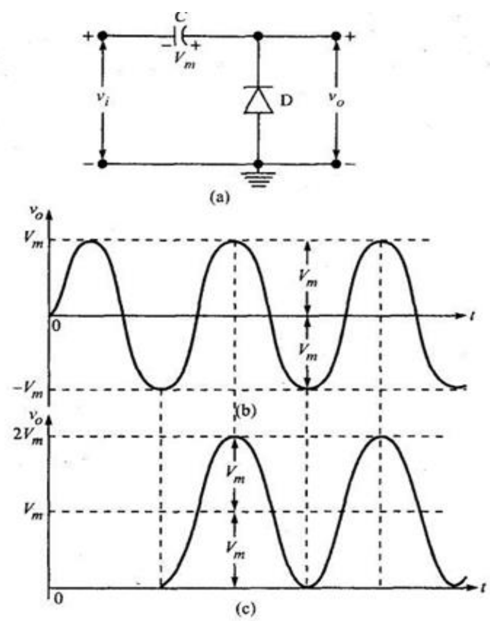


Figure 2.73 (a) A positive clamping circuit, (b) a sinusoidal input, and (c) a steady-state clamped output.

Let the input voltage be vi = Vm sin (ωt)as shown in Figure 2.73(b). When vi, goes negative, the diode gets forward biased and conducts and in a few cycles the capacitor gets charged to Vm with the polarity shown in Figure 2.73(a). Under steady-state conditions, the capacitor acts as a constant voltage source and the output is

$$v_o = v_i - (-V_m) = v_i + V_m.$$

Based on the above relation between v0 and v,, the output voltage waveform is plotted. As seen in Figure 2.73(c) the negative peaks of the input signal are clamped to zero level. Peak to-peak value of output voltage = peak-to-peak value of input voltage = 2Vm. There is no distortion of waveform. To accommodate for variations in amplitude of input, the diode D is shunted with a resistor as shown in Figure 2.74(a). When the amplitude of the input waveform is reduced, the output will adjust to its new value as shown in Figure 2.74(b).

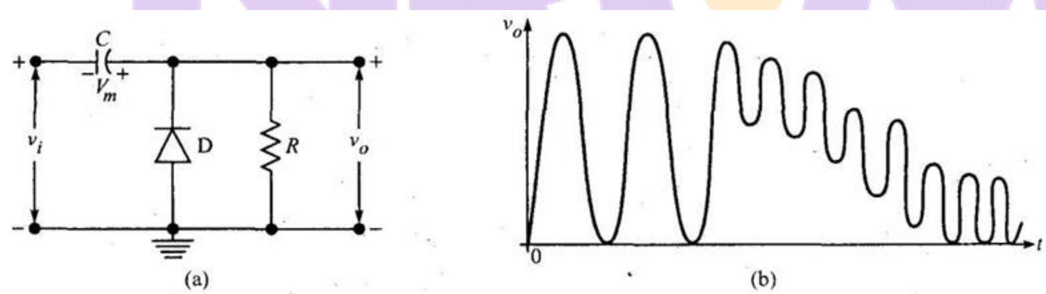


Figure 2.74 (a) Clamping circuit with a resistor *R* across D and (b) output during transient period.

Clamping Circuit Theorem

Under steady-state conditions, for any input waveform, the shape of the output waveform of a clamping circuit is fixed and also the area in the forward direction (when the diode conducts) and the area in the reverse direction (when the diode does not conduct) are related.

The clamping circuit theorem states that, **for any input waveform under steady-state conditions, the ratio of the area Af under the output voltage curve in the forward direction to that in the reverse direction Ar is equal to the ratio Rf/R.**

Clamping Circuit Taking Source and Diode Resistances Into Account In the discussion of the clamping circuit of Figure 2.71, we neglected the output resistance of the source as well as the diode forward resistance. Many times these resistances cannot be neglected. Figure 2.79 shows a more realistic clamping circuit taking into consideration the output resistance of the source Rs, which may be negligible or may range up to many thousands of ohms depending on the source, and the diode forward resistance Rf which may range from tens to hundreds of ohms. Assume that the diode break point Vy occurs at zero voltage.

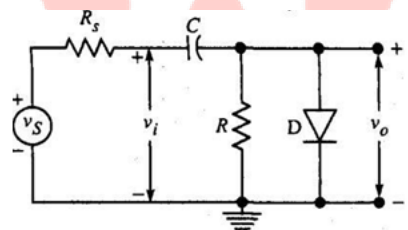


Figure 2.79 Clamping circuit considering the source resistance and the diode forward resistance.

The precision of operation of the circuit depends on the condition that R » Rf, and Rr » R. When the input is positive, the diode is ON and the equivalent circuit shown in Figure 2.80(a) results. When the input is negative, the diode is OFF and the equivalent circuit shown in Figure 2.80(b) results.

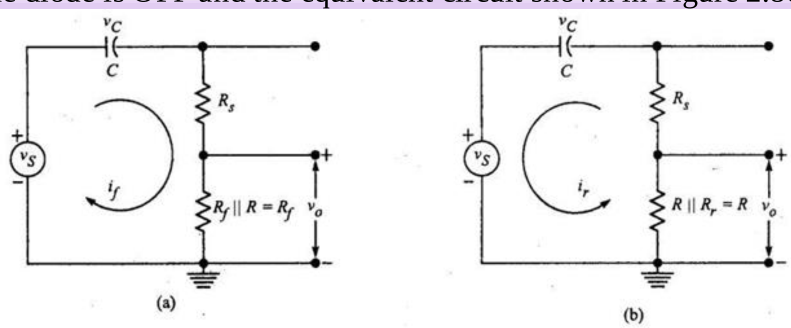


Figure 2.80 (a) Equivalent circuit when the diode is conducting and (b) the equivalent circuit when the diode is not conducting.

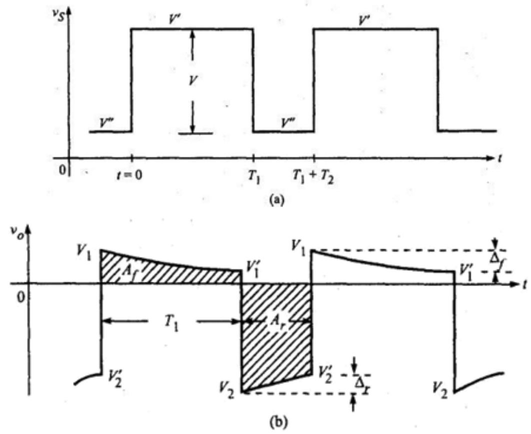


Figure 2.82 (a) A square wave input signal of peak-to-peak amplitude *V,* (b) the general form of the steady-state output of a clamping circuit with;' the input as in (a).

This theorem applies quite generally independent of the input waveform and the magnitude of the source resistance. The proof is as follows:

Consider the clamping circuit of Figure 2.79, the equivalent circuits in Figures 2.80(a) and 2.80(b), and the input and output waveforms of Figures 2.82(a) and 2.82(b) respectively.

In the interval $0 < t < T$, the input is at its upper level, the diode is ON, and the equivalent circuit of Figure 2.80(a) results. If v/(f) is the output waveform in the forward direction, then the capacitor charging current is $i_f(t) = \dfrac{v_f(t)}{R_f}$ Therefore, -the charge gained by the capacitor during

$$Q_g = \int_0^{T_1} i_f(t)dt = \frac{1}{R_f}\int_0^{T_1} v_f(t)dt = \frac{A_f}{R_f}$$

the forward interval is

In the interval $T1 < t < T1+T2$ the input is at its lower level, the diode is OFF, and the equivalent circuit of Figure 2.80(b) results. If $v_r(t)$ is the output voltage in the reverse direction, then the current which discharges the capacitor is $i_r(t) = \dfrac{v_r(t)}{R}$

Therefore, the charge lost by the capacitor during the reverse interval is

$$Q_l = \int_{T_1}^{T_1+T_2} i_r(t)dt = \frac{1}{R}\int_{T_1}^{T_1+T_2} v_r(t)dt = \frac{A_r}{R}$$

Under steady-state conditions, the net charge acquired by the capacitor over one cycle must be equal to zero. Therefore, the charge gained in the interval $0 < t < T$}, will be equal to the charge lost in the interval $T_1 < t < T_1 + T_2$, i.e. $Q_g = Q_l$

$$\frac{A_f}{R_f} = \frac{A_r}{R} \qquad \text{i.e.} \qquad \frac{A_f}{A_r} = \frac{R_f}{R}$$

INTRODUCTION

- The transistor was developed by Dr.Shockley along with Bell Laboratory steam in 1951
- The transistor is a main building block of all modern electronic systems
- It is a three terminal device whose output current, voltage and power are controlled by its input current
- In communication system sit is the primary component in the amplifier
- An amplifier is a circuit that is used to increase the strength of an ac signal
- Basically there are two types of transistors
    - Bipolar junction transistor
    - Field effect transistor
- The important property of the transistor is that it can raise the strength of a weak signal
- This property is called amplification
- Transistors are used in digital computers, satellites, mobile phones and other communication systems, control systems etc.,
- A transistor consists of two P-N junction
- The junction are formed by sand witching either p-type or n-type semiconductor layers between a pair of opposite types which is shown below

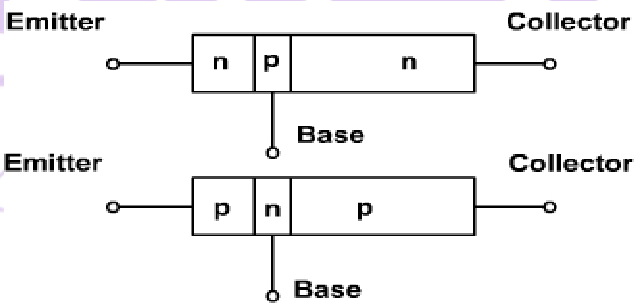
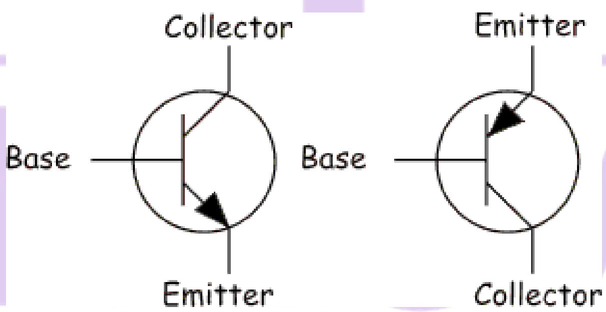


Fig: transistor

TRANSISTOR CONSTRUCTION

- A transistor has three regions known as emitter, base and collector
  - **Emitter :** it is a region situated in one side of a transistor ,which supplies charge carriers (ie., electrons and holes) to the other two regions
  - Emitter is heavily doped region
  - **Base :** It is the middle region that forms two P-N junction in the transistor
  - The base of the transistor is thin as compared to the emitter and is a lightly doped region
  - **Collector:** It is a region situated in the other side of a transistor (ie., side opposite to the emitter) which collects the charge carriers
  - The collector of the transistor is always larger than the emitter and base of a transistor
  - The doping level of the collector is intermediate between the heavy doping of emitter and the light doping of the base

TRANSISTOR SYMBOLS



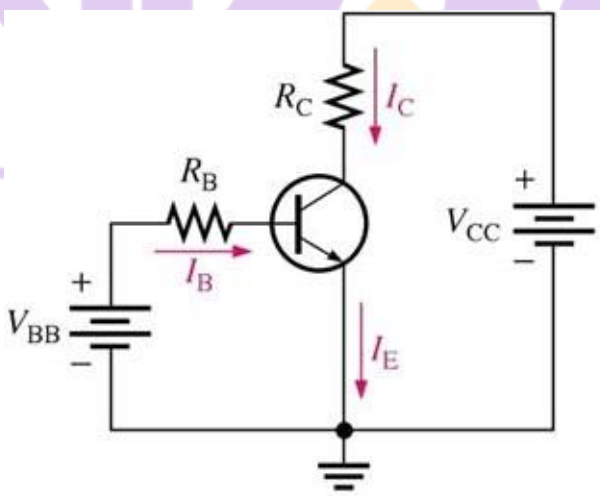
- The transistor symbol carries an arrow head in the emitter pointing from the P-region towards the N-region
- The arrow head indicates the direction of a conventional current flow in a transistor
- The direction of arrow heads at the emitter in NPN and PNP transistor is opposite to each other
- The PNP transistor is a complement of the NPN transistor
- In NPN transistor the majority carriers are free electrons ,while in PNP

Transistor these are the holes.

UNBIASEDTRANSISTORS

- A transistor with three terminals (Emitter, Base, Collector) left open is called an unbiased transistor or an open–circuited transistor
- The diffusion of free electrons across the junction produces two depletion layers.
- The barrier potential of three layers is approximately 0.7v for silicon transistor and 0.3v for germanium transistor.
- Since the regions have different doping levels therefore the layers do not have the same width.
- The emitter base depletion layer penetrates slightly into the emitter as it isa heavily doped region where as it penetrates deeply into the base as it is a lightly doped region.
- Similarly the collector- base depletion layer penetrates more into the base region and less into the collector region.
- The emitter-base depletion layer width is smaller than that of the collector base depletion layer.
- The unbiased transistor is never used in actual practice. Because of this we went for transistor biasing.

OPERATIONOFNPNTRANSISTOR



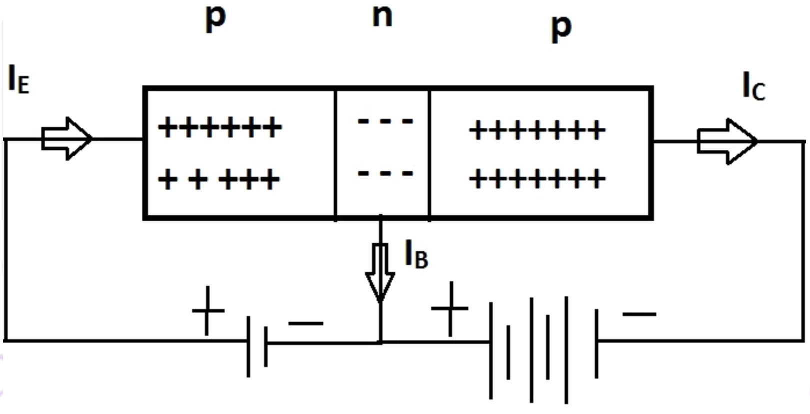
(a) *npn*

- The NPN transistor is biased in forward active mode i.e., emitter—base of

Transistor is forward biased and collector base junction is reverse biased

- The emitter–base junction is forward biased only if V is greater than barrier potential which is 0.7v for silicon and 0.3v for germanium transistor
- The forward bias on the emitter- base junction causes the free electrons in the N –type emitter to flow towards the base region. This constitutes the emitter current. Direction of conventional current is opposite to the flow of electrons
- Electrons after reaching the base region tend to combine with the holes
- If these free electrons combine with holes in the base, they constitute base current ().
- Most of the free electrons do not combine with the holes in the base
- This is because of the fact that the base and the width is made extremely small and electrons do not get sufficient holes for recombination
- Thus most of the electrons will diffuse to the collector region and constitutes collector current. This collector current is also called injected current ,because of this current is produced due to electrons injected from the emitter region
- There is another component of collector current due to the thermal generated carriers.
- This is called as reverse saturation current and is quite small

OPERATION OF PNP TRANSISTOR



p-n-p transistor

- Operation of a PNP transistor is similar to npn transistor
- The current within the PNP transistor is due to the movement of holes whereas, in an NPN transistor it is due to the movement of free electrons

- In PNP transistor, its emitter–base junction is forward biased and collector base junction is reverse biased.
- The forward bias on the emitter—base junction causes the holes in the emitter region to flow towards the base region.
- This constitutes the emitter current ( ).
- The hole after reaching the base region combines with the electrons in the base and constitutes base current.
- Most of the holes do not combine with the electrons in the base region.
- This is due to the fact that base width is made extremely small, and a hole does not get sufficient electrons for recombination.
- Thus most of the holes diffuse to the collector region and constitutes collector region.
- This current is called injected current, because it is produced due to the holes injected from the emitter region.
- There is small component of collector current due to the thermally generated carriers.
- This is called reverse saturation current.

TRANSISTOR CURRENTS

- We know that direction of conventional current is always opposite to the electron current in any electronic device.
- However, the direction of a conventional current is same as that of ahole current in a PNP transistor
- Emitter current
- Base current
- Collector current

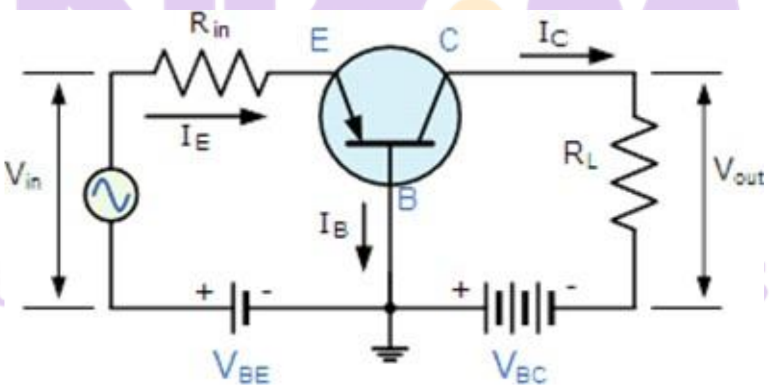
- Since the base current is very small

TRANSISTORCONFIGURATIONS

- A transistor is a three terminal device, but we require four terminals (two for input and two for output) for connecting it in a circuit.

- Hence one of the terminals is made common to the input and output circuits.
- The common terminal is grounded.
- There are three types of configuration for the operation of a transistor.
  - **Common base configuration**
    - This is also called grounded base configuration.
    - In this configuration emitter is the input terminal, collector is the output terminal and base is the common terminal.
  - **Common emitter configuration(CE)**
    - This is also called grounded emitter configuration.
    - In this configuration base is the input terminal, collector is the output terminal and emitter is the common terminal
  - **Common collector configuration (CC)**
    - This is also called grounded collector configuration.
    - In this configuration, base is the input terminal, emitter is the output terminal and collector is the common terminal.

- **Common base configuration (CB)**



- The input is connected between emitter and base and output is connected across collector and base
- The emitter–base junction is forward biased and collector–base junction is reverse biased.

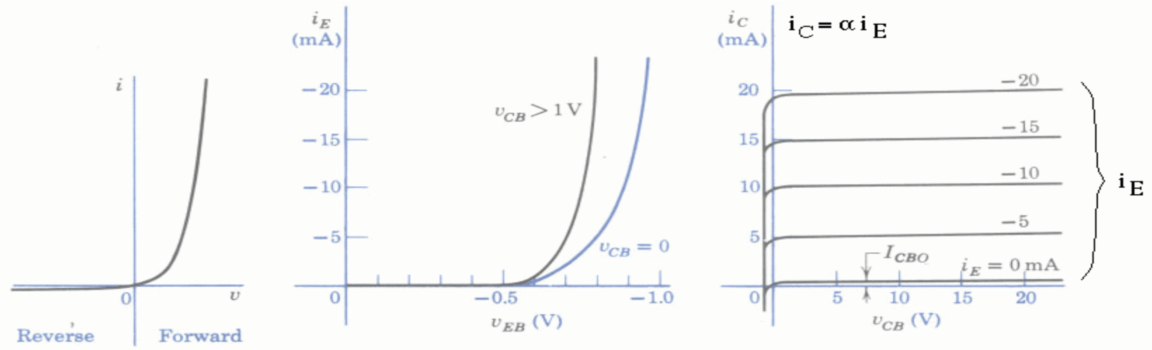
- The emitter current, flows in the input circuit and the collector current flows in the output circuit.
- The ratio of the collector current to the emitter current is called current amplification factor.
- If there is no input ac signal, then the ratio of collector current to emitter current is called dc alpha.
- The ratio of change in the collector current to change in the emitter current is known as ac alpha.
- Common-emitter current gain=Common-base current gain

$$= \frac{I_C}{I_B} \qquad = \frac{I_C}{I_E}$$

- The input characteristics look like the characteristics of a forward-biased diode .Note that V_{BE} varies only slightly, so we often ignore these characteristics and assume:
  - Common approximation: $V_{BE}=V_o=0.65to0.7V$
- The higher the value of better the transistor. It can be increased by making the base thin and lightly doped
- The collector current consists of two parts transistor action. Ie., component depending upon the emitter current, which is produced by majority carriers.
- The leakage current due to the movement of the minority carriers across base collector junction

CHARACTERISTICS OF CB CONFIGURATION

- The performance of transistors determined from their characteristic curves that relate different d.c currents and voltages of a transistor
- Such curves are known as static characteristics curves
- There are two important characteristics of a transistor
  - Input characteristics
  - Output characteristics



(a) Diode characteristic (b) Emitter characteristics (c) Collector characteristics

INPUT CHARACTERISTICS

- The curve drawn between emitter current and emitter — base voltage for a given value of collector— base voltage is known as input characteristics

Base width modulation (or) Early effect

- In a transistor, since the emitter— base junction is forward biased there is no effect on the width of the depletion region
- However, since collector–base junction is reverse biased as the reverse bias voltage across the collector–base junction increase the width of the depletion region also increases.
- Since the base is lightly doped the depletion region penetrates deeper into the base region.
- This reduces the effective width of the base region.
- This variation or modulation of the effective base width by the collector voltage is known as base width modulation or early effect.
- The decrease in base width by the collector voltage has the following three effects.
- It reduces the chances of recombination of electrons with the holes in the base region.Hence current gain increases with increase in collector–base voltage.
- The concentration gradient of minority carriers within the base increases. This increases the emitter current.
- For extremely collector voltage, the effective base width may be reduced to zero, resulting in voltage breakdown of a transistor
- This phenomenon is known as punch through
- The emitter current increases rapidly with small increase in voltage which means low input resistance.
- Because input resistance of a transistor is the reciprocal of the slope of the input characteristics.

Output characteristics

- The curve drawn between collector current and collector—base voltage, for a given value of emitter current is known as output characteristics.

ACTIVE REGION

- There is a very small increase in current i_c with increase in voltage $v_{cb.}$
- This is because the increase in expands the collector—base depletion region and shorten the distance between two depletion region.
- Hence due to the early effect does not increase very much with increase in voltage
- Although, the collector current is independent of it is increased beyond a certain value, eventually increases rapidly because of avalanche effects
- This condition is called punch–through or reach–through.
- When it occurs large current can flow destroying the device

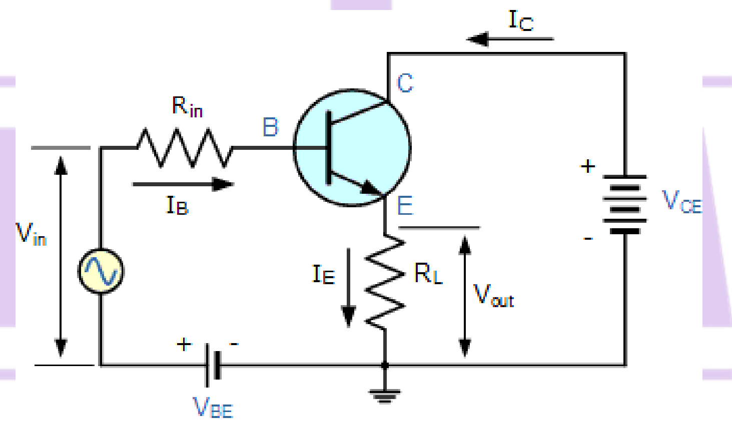
CUT–OFF REGION

- small collector current flows even when emitter current is open
- this is the collector leakage current

SATURATION REGION

- Collector current flows even when the external applied voltage is reduced to zero. There is a low barrier potential existing at the collector — base junction and this assists in the flow of collector current.

(II) COMMON–EMITTER CONFIGURATION



- The input is connected between base and emitter, while output is connected between collector and emitter
- Emitter is common to both input and output circuits.
- The bias voltage applied is Vce and Vbe.
- The emitter-base junction is forward biased and collector-emitter junction is reverse biased.
- The base current I_b is flows in the input circuit and collector current Ic flows in the output circuit.
- CE is commonly used because its current, Voltage, Power gain are quite high and

output to input impedance ratio is moderate.

- The rate of change in collector current to change in base current is called amplification factor β.
- The current gain in the common-emitter circuit is called BETA (β). Beta is the relationship of collector current (output current) to base current (input current).
- Two voltages are applied respectively to the base B and collector C with respect to the common emitter E.
- Same as the CB configuration, here in the CE configuration, the BE junction is forward biased while the CB junction is reverse biased. The voltages of CB and CE configurations are related by:

$$V_{CE} = V_{CB} + V_{BE}, \quad \text{or} \quad V_{CB} = V_{CE} - V_{BE}$$

- The base current is treated as the input current, and the collector current is treated as the output current:

$$I_C = \alpha I_E + I_{CB0} = \alpha(I_C + I_B) + I_{CB0} \approx \alpha(I_C + I_B)$$

- Solving this equation for collector current, we get the relationship between the output collector current and the input base current:

$$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CB0} = \beta I_B + (\beta + 1) I_{CB0} = \beta I_B + I_{ce0} \approx \beta I_B$$

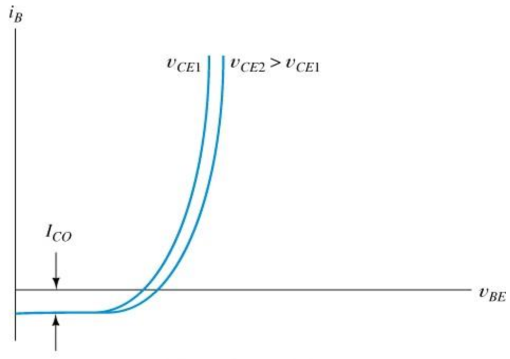
- Here we have also defined the CE *current gain* or *current transfer ratio*

$$\beta = \frac{\alpha}{1-\alpha} \approx \frac{I_C}{I_B}$$

- Which is approximately the ratio of the output current and the input current. The two parameters α and β are related by:

$$\beta = \frac{\alpha}{1-\alpha}, \quad \alpha = \frac{\beta}{1+\beta}, \quad 1+\beta = \frac{1}{1-\alpha}, \quad 1-\alpha = \frac{1}{1+\beta}$$

Characteristics of CE configuration



(a) Input characteristics

Input Characteristics

- Same as in the case of common-base configuration, the junction of the common-emitter configuration can also be considered as a forward biased diode, the current-voltage characteristics is similar to that of a diode:

$$I_B = f(V_{BE}, V_{CE}) \approx f(V_{BE}) = I_0(e^{V_{BE}/V_T} - 1)$$

- The Curve drawn between base current and base-emitter voltage for a given value of collector-emitter voltage is known as input characteristics.

- The input characteristics of CE transistors are similar to those of a forward biased diode because the base-emitter region of the transistor is forward-biased.
- Input Resistance is larger in CE configuration than in CB configuration.

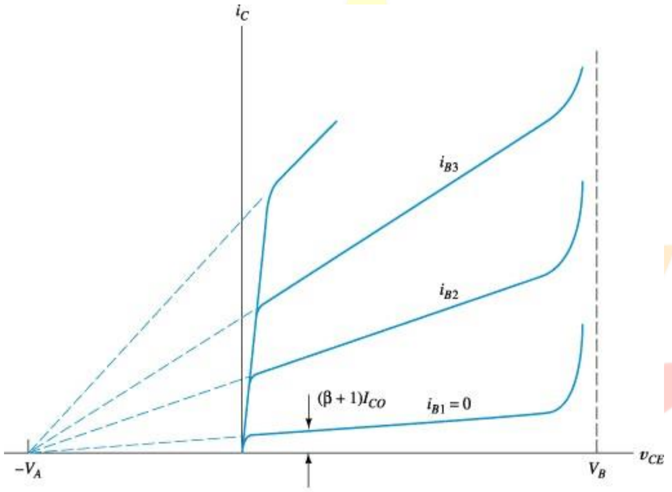
  This is because the I/P current increases less rapidly with increase in Vbe.
- An increment in value of Vce causes the input current to be lower for a given level of Vbe.
- This is explained on the basis of early effect.
- As a result of early effect, more charge carriers from the emitter flows across the collector-base junction and flow out through the based lead.

ii) Output Characteristics

$$I_C = f(I_B, V_{CE}) \approx f(I_B) = \beta I_B \qquad \text{(in linear region)}$$

- It is the curve drawn between collector current Ic and collector-emitter voltage Vce for a given value of base current Ib.

- The collector current Ic varies with Vce and becomes a constant.
- An output characteristic in CE configuration has some slope while CB configuration



(b) Output characteristics

has almost horizontal characteristics.
- This indicates that output resistance incase of CE configuration is less than that in CB configuration.

Active Region

- For small values of base current ,the effect of collector voltage Vco ver Ic is small but for large values of Ib,this effect increases.
- The shape of the characteristic is same as CB configuration
- The difference that Ic is larger than input current
- Thus, the current gain is greater than unity.

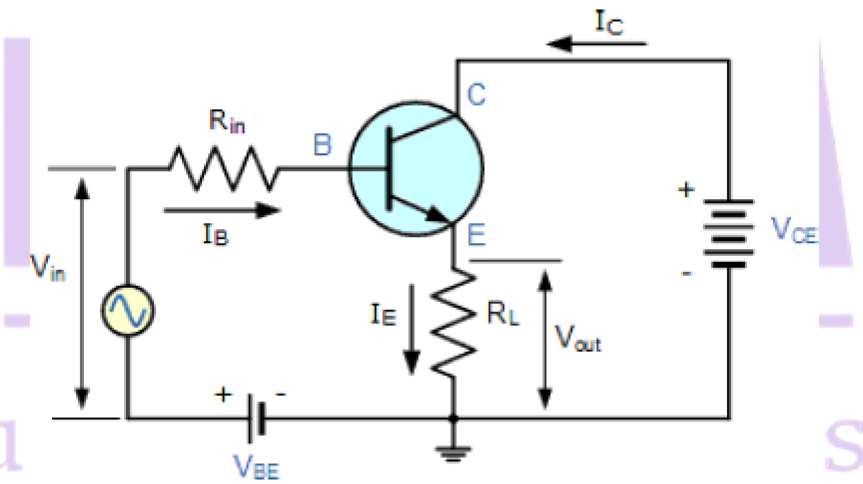
Saturation Region

- With low values of Vce, the transistor is said to be operated in saturation region and in this region, base current Ib does not correspond to Ic,

Cutoff Region

- A small amount of collector current Ic flows even when Ib=0, This is called emitter leakage current.

iii) Common Collector Configuration:



- Input is applied between base and collector while output is applied between emitter and collector.
- The collector forms the terminal common to both the input and output.

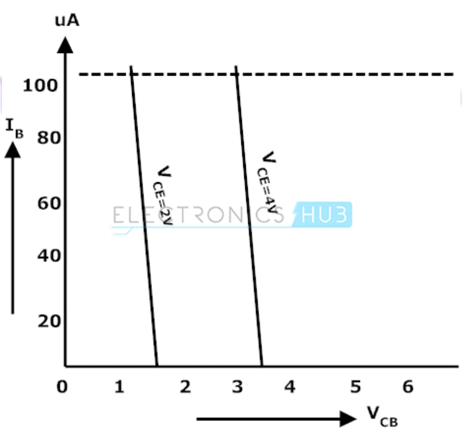
  GAIN is a term used to describe the amplification capabilities of an amplifier. It is basically a ratio of output to input. The current gain for the three transistor configurations (CB, CE, and CC) are ALPHA (α), BETA (β), and GAMMA (γ), respectively.

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

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

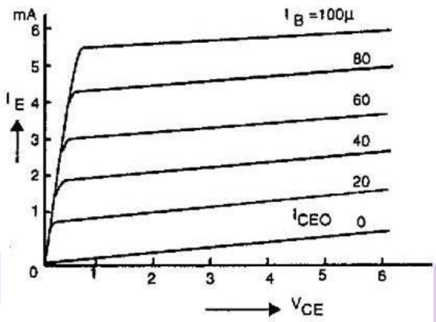
$$\gamma = \frac{\Delta I_E}{\Delta I_B}$$

i) Input Characteristics



- To determine the i/p characteristics Vce is kept at a suitable fixed value.
- The base collector voltage Vbc is increased in equal steps and the corresponding increase in Ib is noted.
- This is repeated for different fixed values of Vce.

ii) Output Characteristics



Current components in a Transistor

- As a result of biasing the active region current flows to drift and diffusion in various parts of transition.
- Due to forward bias a cross input junction, there across three phenomena.
  a) The generation and Recombination of electrons and holes Let, n -> Electron concentration P->Hole concentration Tn -> Life time of electron Tp ->Lifetime of Holes no -> Equilibrium density of electrons po->Equilibrium density of Holes

Transistor Current Components

- In the figure we show the various components which flow across the forward-based emitter junction and the reverse-biased collector junction.
- The emitter current I_E consists of hole current I_{pE} (holes crossing from the emitter into base) and electron current I_{nE} (electron crossing from base into the emitter).
- The ratio of hole to electron currents, I_{pE}/ I_{nE}, crossing the emitter junction is proportional to the ratio of the conductivity of the p material to that of the n material.
- In the commercial transistor the doping of the emitter is made much larger than the doping of the base.
- This future ensures (in a p-n-p transistor) that the emitter current consists almost entirely of the holes.
- Such a situation is desired since the current which result from electrons crossing the emitter junction from base to emitter does not contribute carriers which can reach the collector.

- Not all the holes crossing the emitter junction J_E reach the collector junction J_c because some of them combine with the electrons in the n–type base.
- If I_{pc} is the hole current at J_c,there must be a bulk recombination current I_{pE} - I_{pC} leaving the base (actually, electrons enter the base region through the base lead to supply those charges which have been lost by recombination with the holes injected into the base across J_{E}).
- If the emitter were open-circuited so that I_E=0,then I_{pC} would be zero.
- Under these circumstances, the base and collector would act as a Reverse-biased diode, and the collector current I_c would equal the reverse saturation current I_{CO}. If $I_E \neq 0$, then
- From figure, we note that

$$I_c = I_{co} - I_{pC}$$

- For a p-n-p transistor, I_{co} consists of holes moving across J_c from left to right(base to collector) and electrons crossing J_c in the opposite direction.
- Since the assumed reference direction for I_{co} in figure is from right to left, then for a p-n-p transistor, I_{co} is negative. For an n-p-n transistor, I_{co} is positive.

Emitter Efficiency:-(γ)

- The emitter, or injection, efficiency γ is defined as γ≡

$$\gamma \equiv \frac{\text{Current of injected carriers at } J_E}{\text{Total emitter current}}$$

Transport Factor:-(β^*)

- The transport factor β^* is defined as

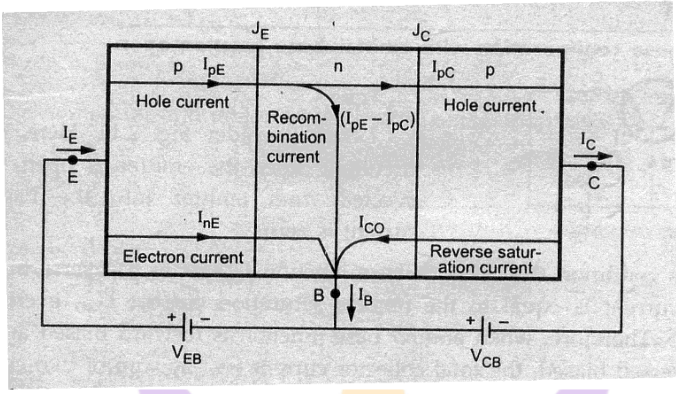
$$\beta^* \equiv \frac{\text{injected carrier current reaching } J_c}{\text{injected carrier current at } J_E}$$

In the caseof a p-n-p transistor we have β^*

$=I_{pC}/I_{pE}$

Large –signal current Gain :-(α)

- We define the ratio of the negative of the collector-current increment to the emitter-current change from zero (cutoff) to I_E as the large-signal currant gain of a common-base transistor,or



α=-I_c–I_{co}/I_E

- Since I_c and I_E have opposite signs, then α, as defined, is always positive Typical numerical values of α lies in the range of0.90 to0.995.

$\alpha = I_{pC}/I_E$

$= I_{pC}/I_{pE} . I_{pE}/I_E \alpha = \beta^* \gamma$

$I_C = -\alpha I_E + I_{co}$

$I_c = -\alpha I_E + I_{co}(1 - e^{Vc/Vr})$

TRANSISTOR AS A SWITCH

A transistor can be used as a switch. It has three regions of peration. When both emitter^ base and collector-base junctions are reverse biased, the transistor operates in the cut-off region and it acts as an open switch. When the emitter base junction is forward biased and the collector base junction is reverse biased, it operates in the active region and acts as auf amplifier. When both the emitter-base and collector-base junctions are forward biased, it operates in the saturation region and acts as a closed switch. When the transistor is switched from cut-off to saturation and from saturation to cut-off with negligible active region, the transistor is operated as a switch. When the transistor is in saturation, junction voltages are very small but the operating currents are large. When the transistor is in cut-off, the currents* are zero (except small leakage current) but the junction voltages are large.

In Figure 3.6a the transistor Q can be used to connect and disconnect the load *RL* from the source Vcc When Q is saturated it is like a closed switch from collector to emitter and when Q is cut- off it is like an open switch from collector to emitter.

$$I_C = \frac{V_{CC} - V_{CE}}{R_L} \quad \text{and} \quad I_B = \frac{V_{BB} - V_{BE}}{R_B}$$

Referring to the output characteristics shown in Figure 3.6(b), the region below the IB =0 curve is the cut-off region. The intersection of the load line with IB = 0 curve is the *cut-off point.* At this point, the base current is zero and the collector current is negligible. The emitter diode comes out of forward bias and the normal transistor action is lost, i.e, VCE(cut-off) = *Vcc.* The transistor appears like an open switch.

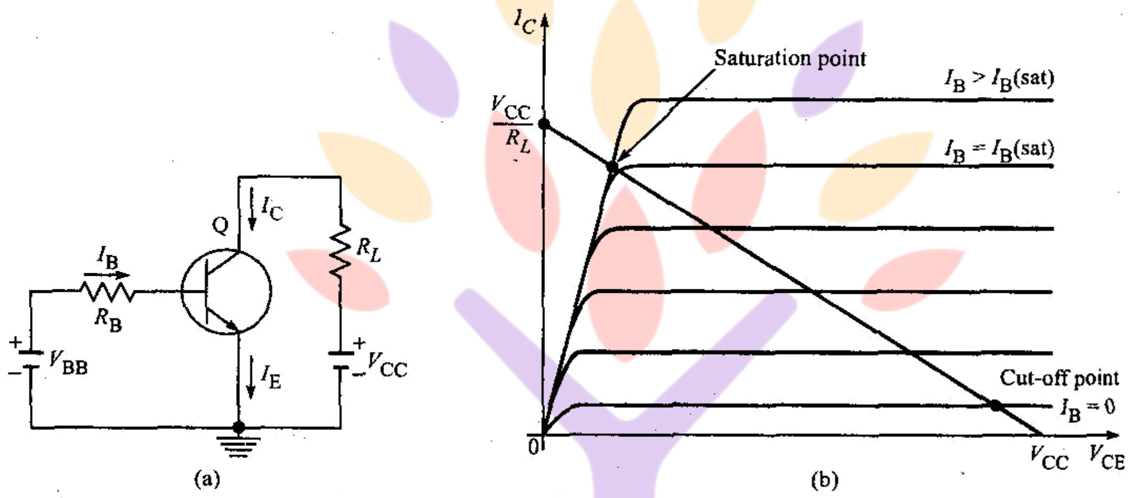


Figure 3.6 (a) Transistor used as a switch and (b) output characteristics with load line (dc).

The intersection of the load line with the IB - Ie(sat) curve is called the *saturation point.* At thispoint, the base current is IB(sat) and the collector current is maximum. 'At saturation, the collector diode comes out of cut-off and again the normal transistor action is lost, i.e. Ic(sat) = *Vcc/RL.I*e(sat) represents the minimum base current required to bring the transistor into saturation. For 0 < IB < IB(sat), the transistor operates in the active region. If the base current is greater than IB(sat), the collector current approximately equals VCC/IC and the transistor appears like a closed switch.

TRANSISTOR SWITCHING TIMES

When the transistor acts as a switch, it is either in cut-off or in saturation. To consider the behavior of the transistor as it makes transition from one state to the other, consider the circuit shown in Figure 3,7(a) driven by the pulse waveform shown in Figure 3.7(b). The pulse waveform makes transitions between the voltage levels V2 and V1. At V2 the transistor is at cut- off and at Vthe transistor is in saturation. The input waveform v; is applied between the base and the emitter througha resistor *RB*

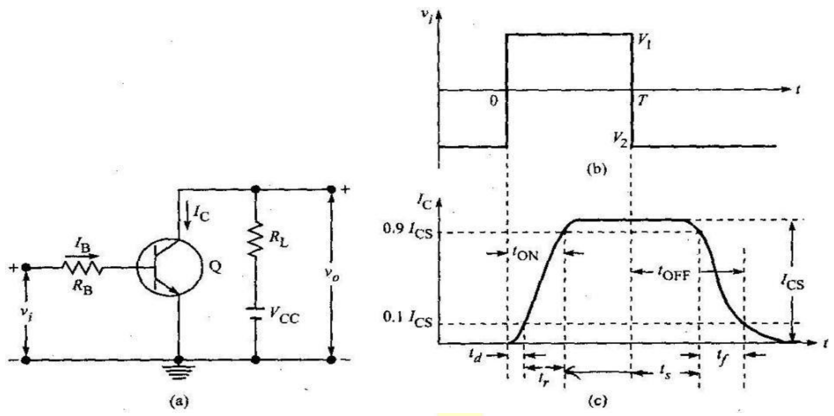


Figure 3.7 (a) Transistor as a switch, (b) input waveform, and (c) the response of collector current versus time

The response of the collector current Ic to the input waveform, together with its time relationship to the waveform is shown in Figure 3.7(c), The collector current does not immediately respond to the input signal. Instead there is a delay, and the time that elapses during this delay, together with the time required for the current to rise to 10% of its maximum(saturation) value (ICs = Vcc/Rc) is called the delay time *td*. The current waveform has a nonzero rise time tr, which is the rise time required for the current to rise from 10% to 90% of Ics- The total turn-on time TON is the sum of the *delay time* and the rise time, i.e. TON = *td* + *tr*.

When the input signal returns to its initial state, the collector current again fails to respond immediately. The interval which elapses between the transition of the input waveform and the time when Ic has dropped to 90% of ICs is called the *storage time ts*. The storage interval is followed by the fall time t_f, which is the time required for IC to fall from 90% to 10% of Ics. The turn-off time t_{OFF} is defined as the sum of the storage and fall times, i.e. TOFF = *tr* + *tf* We shall now consider the physical reasons for the existence of each of these times.

The delay time:

There are three factors that contribute to the delay time.

First there is a delay which results from the fact that, when the driving signal is applied to the transistor input, a non-zero time is required to charge up the junction capacitance so that the transistor may be brought, from cut-off to the active region.

Second, even when the transistor has been brought to the point where minority carriers have begun to cross the emitter junction into the base, a nonzero time is required before these carriers can cross the base region to the collector junction and be recorded as collector current.

Finally, a nonzero time is required before the collector current can rise to 10% of its maximum value. The rise time and fall time are due to the fact that, if a base current step is used to saturate the transistor or to return it from saturation into cut- off, the collector current must traverse the active region. The collector current increases or decreases along an exponential curve.

Storage time:

The failure of the transistor to respond to the trailing edge of the driving pulse for the time interval *ts*, results from the fact that a transistor in saturation has a saturation charge of excess minority carriers stored in the base. The transistor cannot respond until the saturation excess charge has been removed.

Junction FET (JFET):

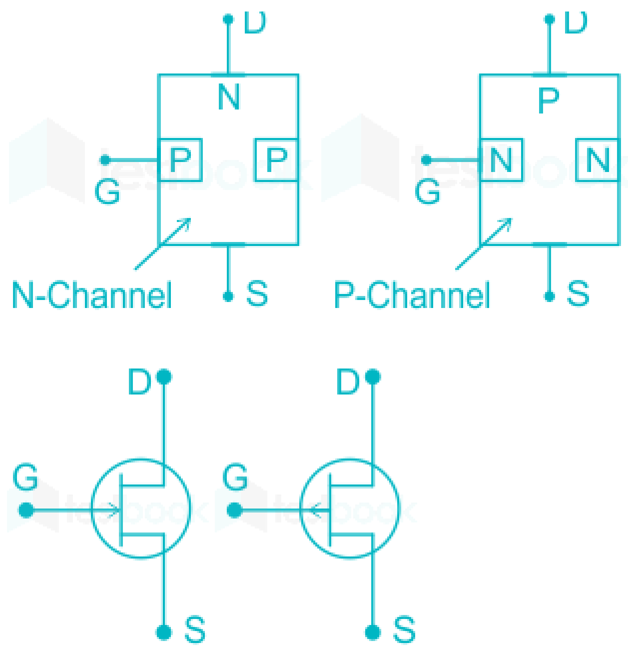
- The **Field Effect Transistor** is a three-terminal unipolar semiconductor device in which the condition of current is only due to the majority carrier.
- It has high input impedance and low output impedance and acts as a voltage-controlled device.
- It is a three-terminal device that is Gate, Drain, and Source.

Source: It is the terminal through which the **majority carriers enter**.

Drain: It is the terminal through which the **majority carriers leave.**

Gate: It is two internally connected heavily-doped impurity regions that form two P-N junctions.

Channel: It is the space between two gates through which majority carriers pass from source-to-drain when VDS is applied.

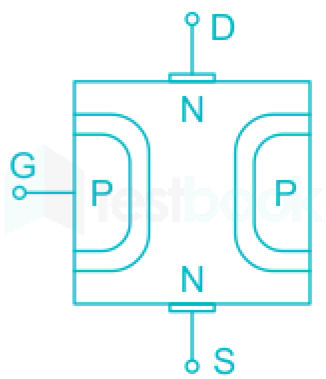


Operation of JFET:

- **NP region between Gate and Source are always reversed-biased**. Hence, gate current (I_G) is practically zero.
- The **source terminal is always connected to that end of the drain supply** which provides the necessary charge carriers.
- In an **N-channel JFET**, the **source terminal (S) is connected to the negative end of the drain voltage** supply for getting electrons.
- In a **P-channel JFET**, the **source terminal (S) is connected to the positive end of the drain voltage** supply for getting holes.
- Let us now consider an **N-channel** JFET and discuss its working when either V_{GS} or V_{DS} or both are changed.

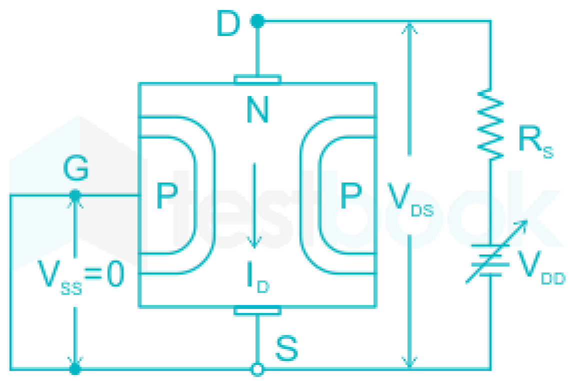
When V_{GS} = 0 and V_{DS} = 0:

- The **depletion regions around the P-N junctions are of equal thickness and symmetrical** as shown.



When V_{GS} = 0 and V_{DS} is increased from zero:

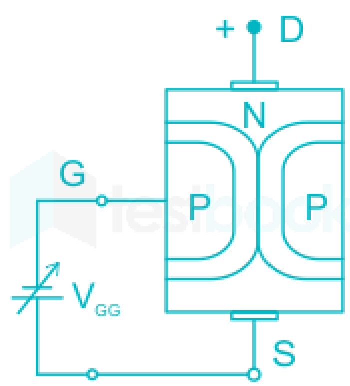
- In that case, the JFET is connected to the V_{DD} supply as shown.
- The **electrons flow from Source to Drain whereas conventional drain current I_D flows through the channel from D to S**.
- V_{DS} is gradually increased from zero, I_D increases proportionally as per Ohm's law.
- The ohmic relationship between V_{DS} and I_D continues till V_{DS} reaches a certain critical value called **pinch-off voltage.**
- Once **pinch-off voltage comes the Drain current (I_D) becomes constant**.



When v_{ds}=0 and v_{GS} is decreased from zero

-- --

- In this case, V_{GS} is made more and more negative.
- The **reverses bias at the gate terminal increases** which increases the thickness of the depletion regions.
- As the **negative value of V_{GS} is increased**, a stage comes when the **two depletion regions touch each other** as shown.
- In this condition, the **channel is said to be cut off**.
- This value of V_{GS} cuts off the channel and hence the **Drain current decreased to zero**.



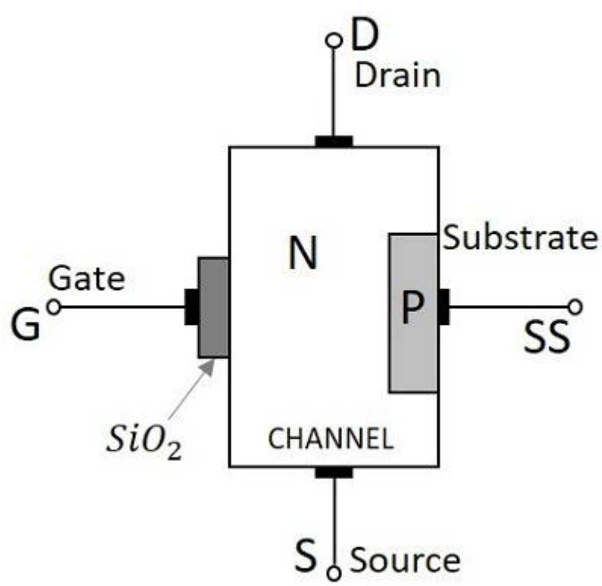
FETs have a few disadvantages like high drain resistance, moderate input impedance and slower operation. To overcome these disadvantages, the MOSFET which is an advanced FET is invented.

MOSFET stands for Metal Oxide Silicon Field Effect Transistor or Metal Oxide Semiconductor Field Effect Transistor. This is also called as IGFET meaning Insulated Gate Field Effect Transistor. The FET is operated in both depletion and enhancement modes of operation. The following figure shows how a practical MOSFET looks like.

Construction of a MOSFET

The construction of a MOSFET is a bit similar to the FET. An oxide layer is deposited on the substrate to which the gate terminal is connected. This oxide layer acts as an insulator (sio_2 insulates from the substrate), and hence the MOSFET has another name as IGFET. In the construction of MOSFET, a lightly doped substrate is diffused with a heavily doped region. Depending upon the substrate used, they are called as **P-type** and **N-type** MOSFETs.

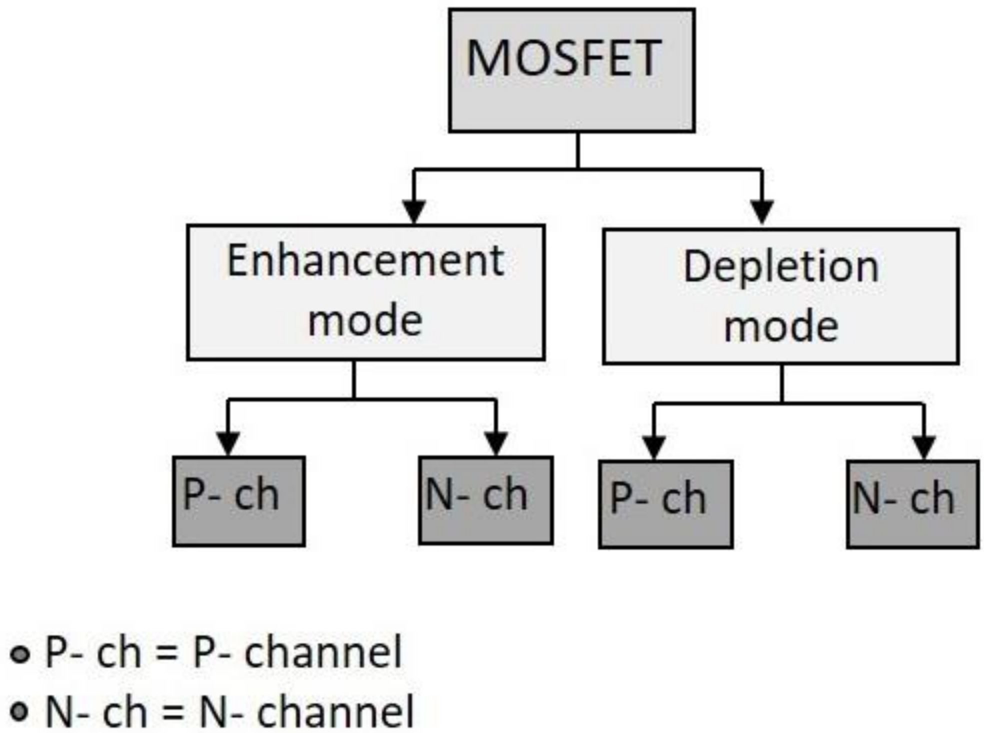
The following figure shows the construction of a MOSFET.



The voltage at gate controls the operation of the MOSFET. In this case, both positive and negative voltages can be applied on the gate as it is insulated from the channel. With negative gate bias voltage, it acts as **depletion MOSFET** while with positive gate bias voltage it acts as an **Enhancement MOSFET**.

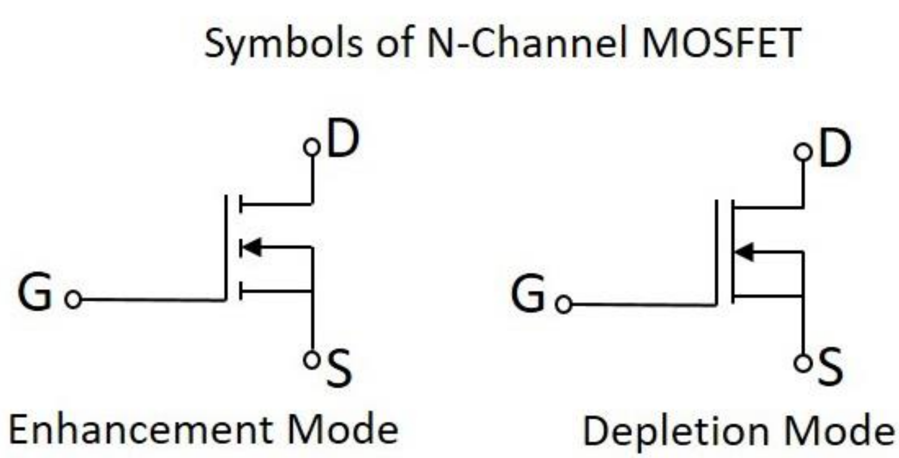
Classification of MOSFETs

Depending upon the type of materials used in the construction, and the type of operation, the MOSFETs are classified as in the following figure.

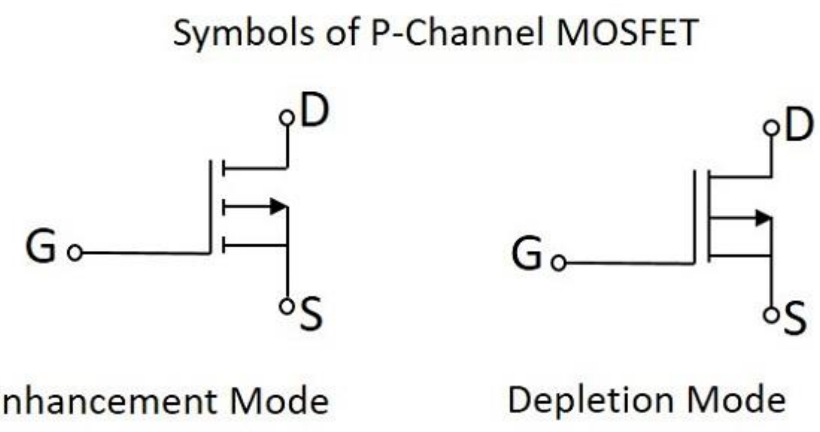


After the classification, let us go through the symbols of MOSFET.

The **N-channel MOSFETs** are simply called as **NMOS**. The symbols for N-channel MOSFET are as given below**.**



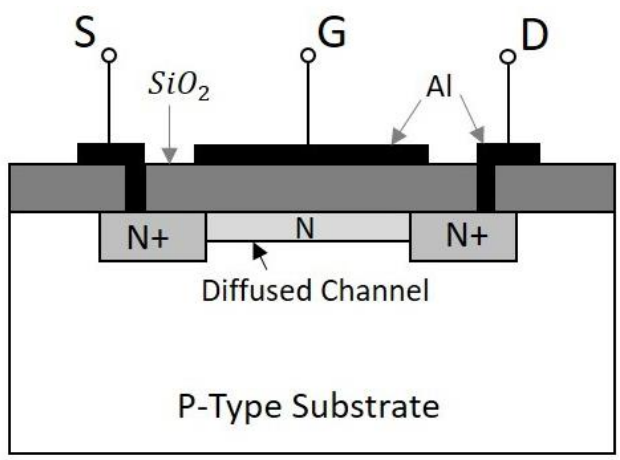
The **P-channel MOSFETs** are simply called as **PMOS**. The symbols for P-channel MOSFET are as given below.



Now, let us go through the constructional details of an N-channel MOSFET. Usually an N Channel MOSFET is considered for explanation as this one is mostly used. Also, there is no need to mention that the study of one type explains the other too.

Construction of N- Channel MOSFET

Let us consider an N-channel MOSFET to understand its working. A lightly doped P-type substrate is taken into which two heavily doped N-type regions are diffused, which act as source and drain. Between these two N+ regions, there occurs diffusion to form an N channel, connecting drain and source.



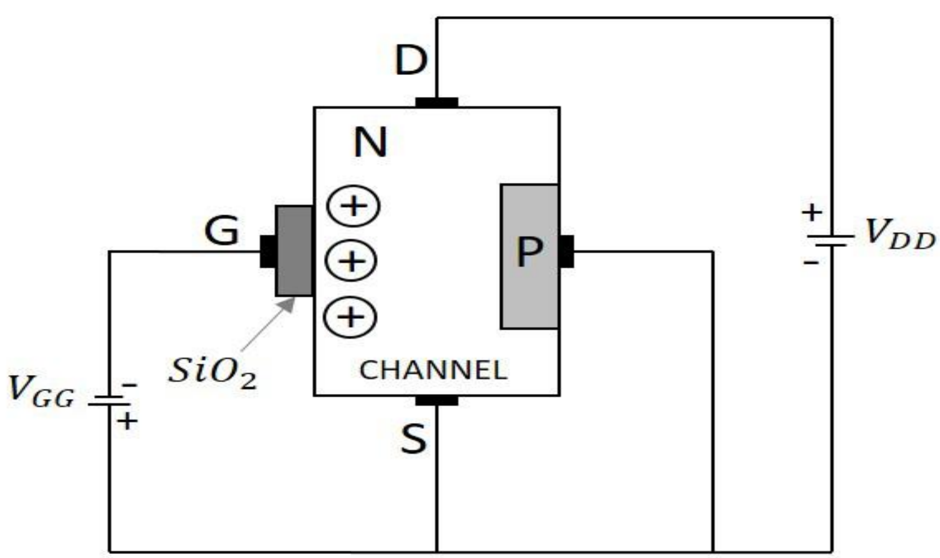
Structure of N-channel MOSFET

A thin layer of **Silicon dioxide (SiO_2)** is grown over the entire surface and holes are made to draw ohmic contacts for drain and source terminals. A conducting layer of **aluminum** is laid over the entire channel, upon this **SiO_2** layer from source to drain which constitutes the gate. The **SiO_2 substrate** is connected to the common or ground terminals.Because of its construction, the MOSFET has a very less chip area than BJT, which is 5% of the occupancy when compared to bipolar junction transistor. This device can be operated in modes. They are depletion and enhancement modes. Let us try to get into the details.

Working of N - Channel depletion mode MOSFET

For now, we have an idea that there is no PN junction present between gate and channel in this, unlike a FET. We can also observe that, the diffused channel N between two N+ regions, the **insulating dielectric SiO_2** and the aluminum metal layer of the gate together form a **parallel plate capacitor**.

If the NMOS has to be worked in depletion mode, the gate terminal should be at negative potential while drain is at positive potential, as shown in the following figure.



Working of MOSFET in depletion mode

When no voltage is applied between gate and source, some current flows due to the voltage between drain and source. Let some negative voltage is applied at **V_{GG}**.

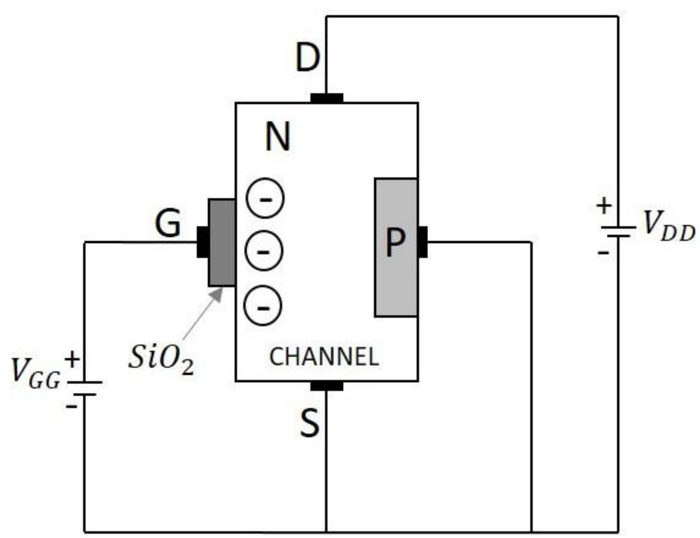
Then the minority carriers i.e. holes, get attracted and settle near **SiO_2** layer. But the majority carriers, i.e., electrons get repelled.

With some amount of negative potential at **V_{GG}** a certain amount of drain current **I_D** flows through source to drain. When this negative potential is further increased, the electrons get depleted and the current **I_D** decreases. Hence the more negative the applied **V_{GG}**, the lesser the value of drain current **I_D** will be.

The channel nearer to drain gets more depleted than at source like in FET and the current flow decreases due to this effect. Hence it is called as depletion mode MOSFET.

Working of N-Channel MOSFET Enhancement Mode

The same MOSFET can be worked in enhancement mode, if we can change the polarities of the voltage V_{GG}. So, let us consider the MOSFET with gate source voltage V_{GG} being positive as shown in the following figure.



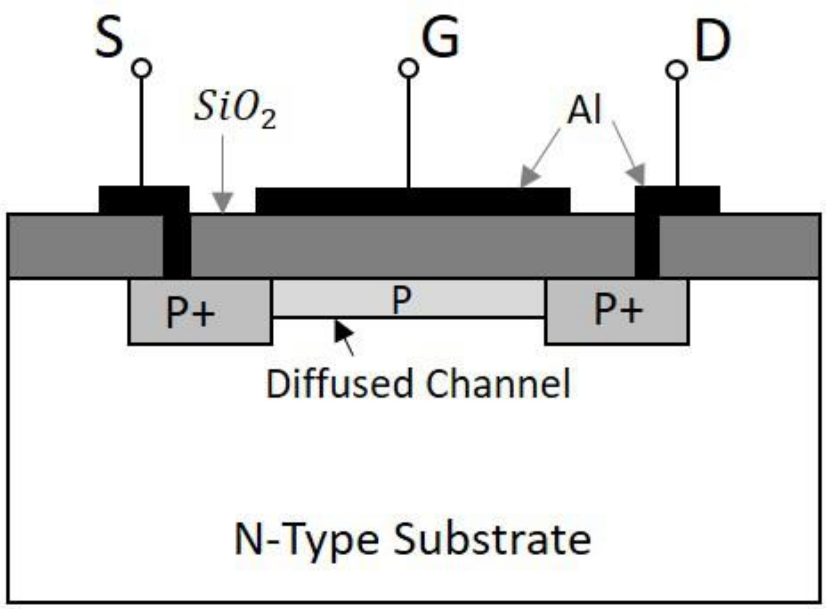
Working of MOSFET in Enhancement mode

When no voltage is applied between gate and source, some current flows due to the voltage between drain and source. Let some positive voltage is applied at **V_{GG}**. Then the minority carriers i.e. holes, get repelled and the majority carriers i.e. electrons gets attracted towards the **SiO_2** layer.

With some amount of positive potential at V_{GG} a certain amount of drain current I_D flows through source to drain. When this positive potential is further increased, the current I_D increases due to the flow of electrons from source and these are pushed further due to the voltage applied at V_{GG}. Hence the more positive the applied V_{GG}, the more the value of drain current I_D will be. The current flow gets enhanced due to the increase in electron flow better than in depletion mode. Hence this mode is termed as **Enhanced Mode MOSFET**.

P - Channel MOSFET

The construction and working of a PMOS is same as NMOS. A lightly doped **n-substrate** is taken into which two heavily doped **P+ regions** are diffused. These two P+ regions act as source and drain. A thin layer of **SiO_2** is grown over the surface. Holes are cut through this layer to make contacts with P+ regions, as shown in the following figure.



Structure of P-channel MOSFET

Working of PMOS

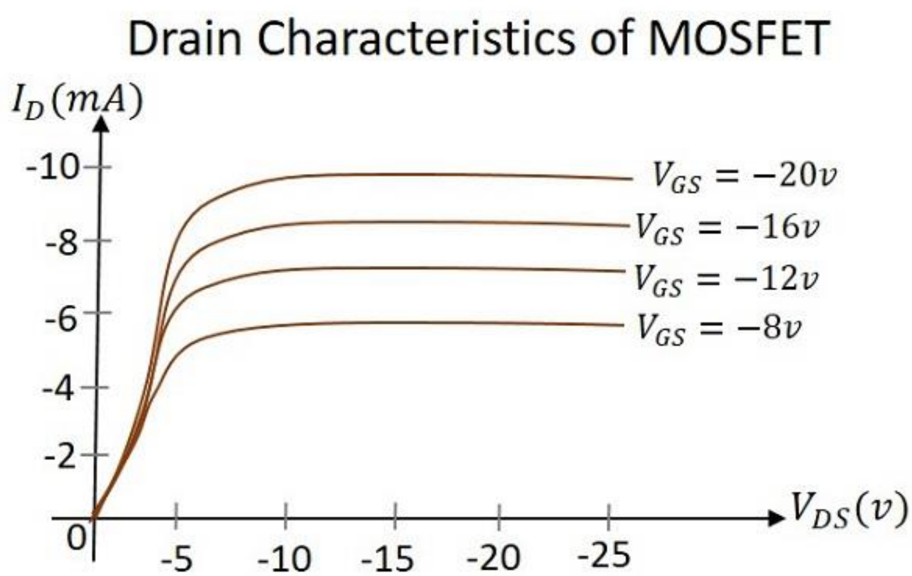
The diffused P channel and the PMOS works in **Enhancement Mode**.

When the gate terminal is given a positive potential at $\mathbf{V_{GG}}$ than the drain source voltage $\mathbf{V_{DD}}$, then due to the repulsion, the depletion occurs due to which the flow of current reduces. Thus PMOS works in **Depletion Mode**. Though the construction differs, the working is similar in both the type of MOSFETs. Hence with the change in voltage polarity both of the types can be used in both the modes.

This can be better understood by having an idea on the drain characteristics curve.

Drain Characteristics

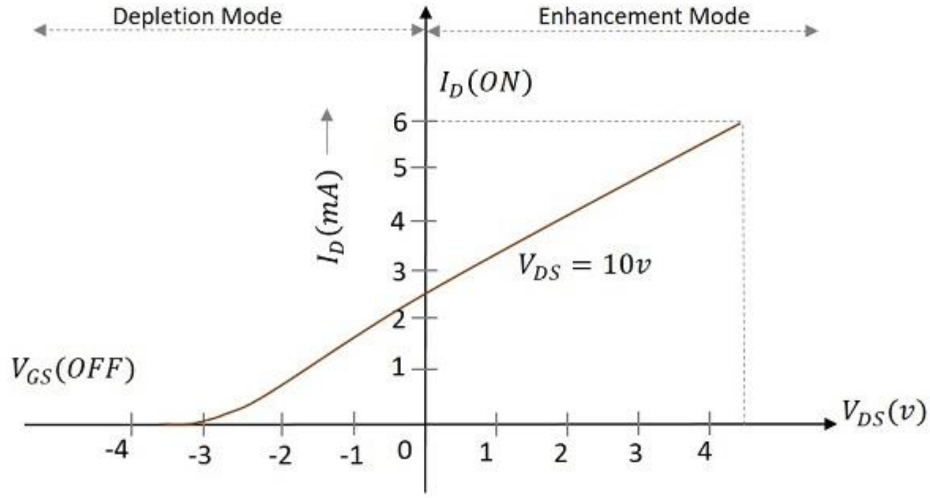
The drain characteristics of a MOSFET are drawn between the drain current $\mathbf{I_D}$ and the drain source voltage $\mathbf{V_{DS}}$. The characteristic curve is as shown below for different values of inputs.



Actually when $\mathbf{V_{DS}}$ is increased, the drain current $\mathbf{I_D}$ should increase, but due to the applied $\mathbf{V_{GS}}$, the drain current is controlled at certain level. Hence the gate current controls the output drain current.

Transfer Characteristics

Transfer characteristics define the change in the value of $\mathbf{V_{DS}}$ with the change in $\mathbf{I_D}$ and $\mathbf{V_{GS}}$ in both depletion and enhancement modes. The below transfer characteristic curve is drawn for drain current versus gate to source voltage.



Transfer Characteristics of a MOSFET

Comparison between BJT, FET and MOSFET

Now that we have discussed all the above three, let us try to compare some of their properties.

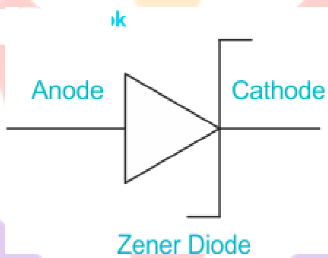
TERMS	BJT	FET	MOSFET
Device type	Current controlled	Voltage controlled	Voltage Controlled
Current flow	Bipolar	Unipolar	Unipolar
Terminals	Not interchangeable	Interchangeable	Interchangeable
Operational modes	No modes	Depletion mode only	Both Enhancement and Depletion modes
Input impedance	Low	High	Very high
Output resistance	Moderate	Moderate	Low

Operational speed	Low	Moderate	High
Noise	High	Low	Low
Thermal stability	Low	Better	High

Zener Diode

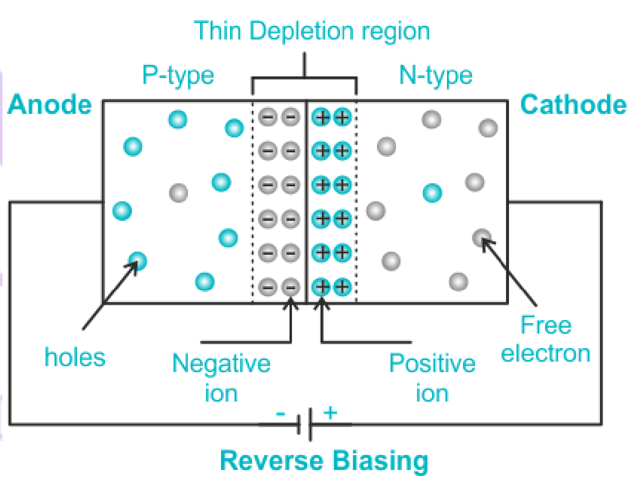
A Zener diode can be defined as a heavily doped semiconductor device that is designed to operate the electric circuit in the reverse direction. It is also called a breakdown diode. It is a heavily doped semiconductor diode that is designed to operate the electric circuit in the reverse direction.

When some voltage passes through the terminals of a Zener diode then it gets reversed and the potential of the circuit reaches the Zener Voltage or knee voltage, which is the forward voltage of a flowing current. Then the junction breaks down and the current starts to flow in the reverse direction. This effect in an electric circuit is known as the Zener Effect. The image below represents the Zener Diode symbol.



Working Principle of Zener Diode

The working principle is such that if the reverse bias voltage is less than the breakdown voltage, or if it is forward biased then it acts as an ordinary diode. This means that forward bias allows current to flow and reverse bias blocks the current from flowing. After this, the voltage surpasses the breakdown point in reverse bias, and the diode falls in the Zener region, where it gets conducted without getting damaged. Current in this region is known as avalanche current but for a Zener diode, it is also known as a Zener current.



When the voltage decreases in the circuit the diode maintains its non-conducting condition and gets back to its natural properties. This specific property of the Zener diode of being functional in the reverse bias and with avalanche current is given by the rich doping of the semiconductor material present in it.

Further, by controlling the amount of doping of the semiconductor material and by doing this the thickness of the depletion region in the PN junction and the breakdown voltage can be set to any value according to the need of the appliance.

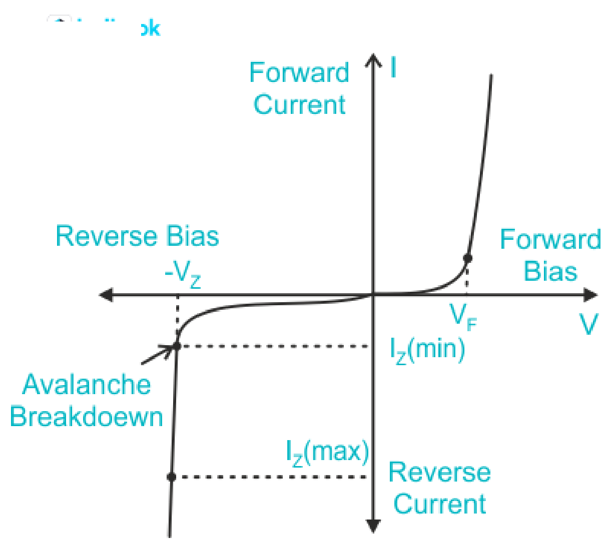
Avalanche Breakdown

Avalanche breakdown occurs in a Zener diode when the reverse bias voltage is increased to a point where the electric field across the depletion region becomes strong enough to knock electrons from their valence bonds into the conduction band. These electrons then collide with other atoms, knocking more electrons free, and the process continues in a chain reaction known as an avalanche. This avalanche of electrons causes a sudden increase in current through the diode, and the voltage across the diode drops to a constant value known as the breakdown voltage.

Zener Breakdown

Zener breakdown is a tunneling effect that occurs in a Zener diode with a narrow depletion region. When the reverse bias voltage is increased to a point where the electric field across the depletion region is strong enough, some of the valence electrons in the p-type material can tunnel through the depletion region and into the conduction band of the n-type material. This tunneling of electrons causes a sudden increase in current through the diode, and the voltage across the diode drops to a constant value known as the breakdown voltage.

V-I Characteristics of Zener Diode



The V-I characteristics of a Zener diode are divided into two parts which are mentioned as follows:

Forward Characteristics of Zener Diode

The first quadrant of the graph depicts the forward characteristics of a Zener diode, and from which we can understand that it is almost similar to the forward characteristics of any other normal PN junction diode.

Reverse Characteristics of Zener Diode

When a reverse voltage is applied to a Zener voltage, a small reverse saturation current which is Io flows across the whole diode. This current is present due to thermally generated minority carriers present in the diode. As the reverse voltage starts to increase, at a certain value of reverse voltage the reverse current also starts to increase drastically and sharply.This is proof that the breakdown in the diode has occurred. This voltage is known as breakdown voltage in zener diode or Zener voltage and is denoted byVz. Its range is also mentioned in the above characteristics.

Applications of Zener Diode

Zener Diode as Voltage Regulator

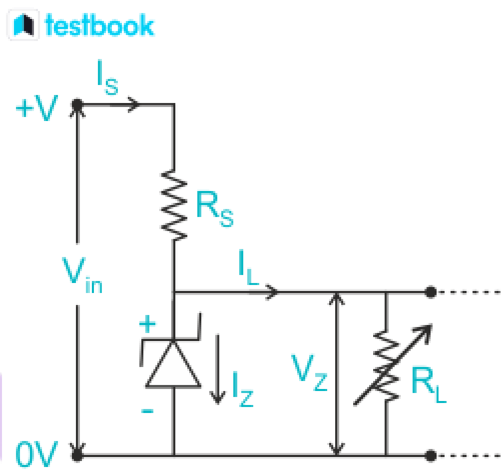
Zener Diode in Over-Voltage Protection

Zener Diode in Clipping Circuits

Working of Zener Diode as a Voltage Regulator

The capacity of a Zener diode to keep a constant voltage regardless of changes in source or load current is critical in this application. A voltage regulation device's general role is to give a constant output voltage to a load connected in parallel to it, regardless of variations in the load's energy drawn (Load current) or fluctuations and instability in the supply voltage. If the current remains within the limit of the min and max reverse currents, the Zener diode will produce a constant voltage.

To restrict the current that flows through the Zener diode, a resistor Rs is connected in series with the diode, and also the input voltage Vin is connected across as shown in the image, and the output voltage Vout is chosen to take across the Zener diode with Vout=Vz. Because the reverse bias features of the Zener diode are required to control the voltage, it is wired in reverse bias mode, and with a cathode linked to the circuit's positive rail.



Whenever the load is connected, a small valued resistor would result in a big diode current and electricity, which would raise the power dissipation need of the diode, which could exceed the Zener's maximum power rating and harm it.

The value of the resistor can be determined by the formula

RS=(Vin−VZ)Iz

Where, RS is the value of series resistance and Vin is the input voltage and Vz is Zener voltage.

Using this method, it is simple to assure that the resistor value chosen does not result in a current flow greater than the Zener can tolerate.

One minor issue with Zener diode-based regulatory circuits is that although attempting to moderate the input voltage, the Zener might generate electrical noise just on the supply rail. Although it may not be a problem in most cases, a big value decoupling capacitor placed across the diode may address the problem. This helps to keep the Zener's output stable.

Application of Zener Diode as a Voltage Regulator

The following are some of the most important applications of a Zener voltage regulator.

- Within the emitter follower regulator, a Zener voltage regulator is used.
- It is utilised with a modest load current range and maintains a steady output DC voltage.
- It is used to control or change the circuit's output voltage.
- It is employed in analog and digital circuits that need to be precise with their references.
- It is utilised in current source and sink circuits.
- It is used to fine-tune linear and switch power supply voltage and current.
- Error amplifiers use it as well

Difference between PN Junction and Zener Diode

The differences between a Zener diode and a PN junction diode is mentioned as follows:

Zener Diode	PN Junction Diode
It allows the current to flow in both directions which means that its current can flow forward as well as in the reverse direction.	A PN junction diode allows current to pass only in one direction which is a forward direction.
Zener diode has high doping.	PN junction diode has low doping.
A reverse current has no effect on a Zener diode.	A reverse current effect on a PN junction diode by damaging its junctions.
A breakdown occurs at a lower voltage in a Zener diode.	A breakdown occurs at a higher voltage in a PN junction diode.
A Zener diode does not follow Ohm's law.	A PN junction diode does follow Ohm's law.

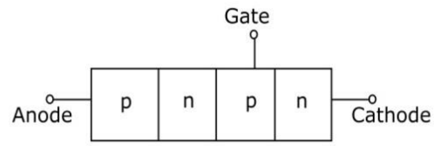
Silicon Controlled Rectifier – Working Principle and Applications

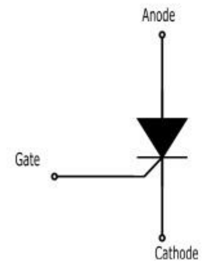
An **SCR** is a three-terminal, three-junction, and four-layer **semiconductor device** that is used to perform switching functions in power circuits.

Sometimes the SCR is also called as Thyristor.

Constructional Details of SCR

The SCR has three pn – junctions, and four layer of **p and n type semiconductor** joined alternatively to get pnpn device. The three terminals are taken – one from outer p – type layer called anode (A), second from the outer n – type layer called cathode (K) and the third from the internal p –type layer called gate (G).



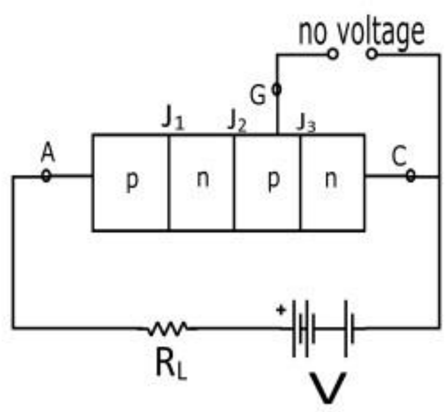


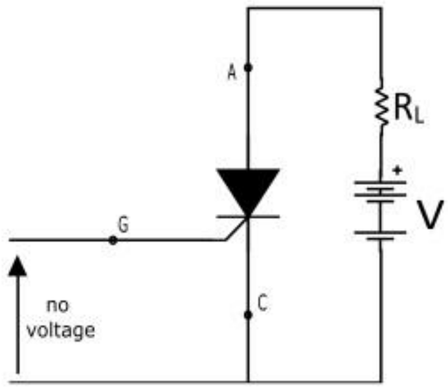
Working of SCR

In a SCR, the load is connected in series with the anode. The anode is always kept positive with respect to cathode.

When Gate is Open Circuited

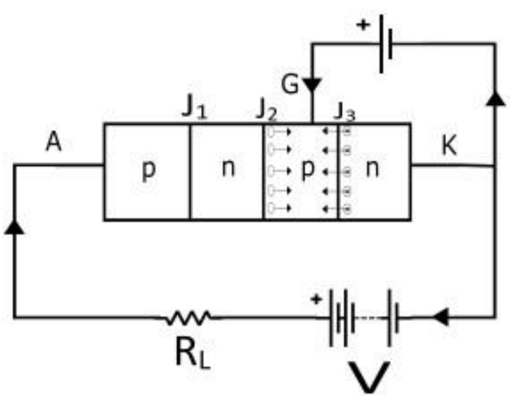
When no voltage applied to gate terminal, junction J2, is reverse biased and the junctions J1 and J3 are forward biased. Since one of the three junctions is reverse biased so there is no current can flow through the load, hence the SCR is OFF. However if the applied voltage is gradually increased, a stage is reached, when reverse biased junction (J2) breaks down. The SCR now, starts conducting and become ON. The value of applied voltage at which the reverse biased junction breaks down and the SCR becomes ON is known as Breakover Voltage

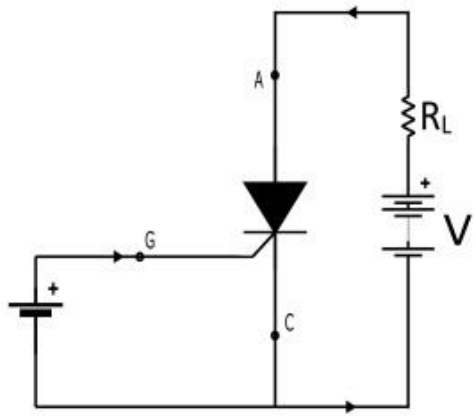




When Gate is Positive with Respect to Cathode

The SCR can be turned ON at smaller applied voltage by the application of a small positive voltage at the gate terminal. When gate voltage is applied the junction J3 is forward biased and junction J2 is reverse biased. Thus, the electrons from n – type layer starts moving across the junction J3 toward p –type material and the holes from p –type material towards the n – type material. Due to the movement of holes and electrons across the junction J3 the gate current starts flowing. Because of gate current the anode current increases. The increased anode current makes the more electrons available at the junction J2. As a result of this process, in a small time, the junction J2 breaks down and the SCR is turn ON.





Even if the voltage at the gate terminal is removed, the SCR the anode current does not decrease. The SCR can only be turned off by reducing the applied voltage to zero.

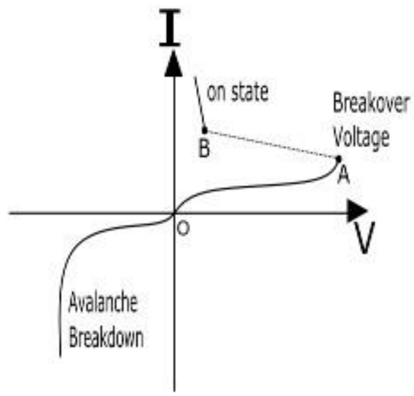
Parameters of SCR

- **Break Over Voltage** − It is the minimum value of the applied voltage at which the SCR is turned ON, provided the gate voltage is not applied. For commercially available SCRs the range of break over voltage is 50 V to 500 V.
- **Peak Reverse Voltage (PRV)** − It is the maximum reverse voltage (i.e. cathode made positive with respect to the anode) that can be applied to the SCR without conducting in the reverse direction. The commercially available SCRs have PRV up to 2.5 kV.
- **Holding Current** − With gate being open, it is the maximum value of anode current at which SCR is turned OFF from ON state.
- **Forward Current Rating** − It is maximum value of the anode current that an SCR can pass through it without destruction.
- **Circuit Fusing Rating** − It indicates the maximum forward surge current capability of the SCR. It is defined as the product of square of forward surge current and the time duration of the surge.

If the circuit fusing rating is exceeded in the SCR circuit, the device is destroyed by excessive power dissipation.

I–V Characteristics of SCR

It is the curve plotted between the anode – cathode voltage (V) and anode current (I) of the SCR at constant gate current.



- **Forward Characteristics** − When the anode is made positive with respect to the cathode, then the curve between V and I is called as forward characteristics of the SCR. If the supply voltage is increased from zero, a point is reached (Point A, the voltage is called breakover voltage) when the SCR starts conducting. Under this condition, the voltage across SCR decreases suddenly (shown by dotted line in the curve) and the most of the supply voltage appears across the load.
- **Reverse Characteristics** − When anode is made negative with respect to the cathode, the curve plotted between V and I is called as reverse characteristics. If the reverse voltage is increased gradually, at first the anode current remains small (called leakage current) and at some reverse voltage, the avalanche breakdown occurs and the SCR starts conducting in the reverse direction (Shown by the curve in third quadrant). The maximum reverse voltage at which the SCR starts conducting in the reverse direction is called as Reverse Breakdown Voltage.

Applications of SCR

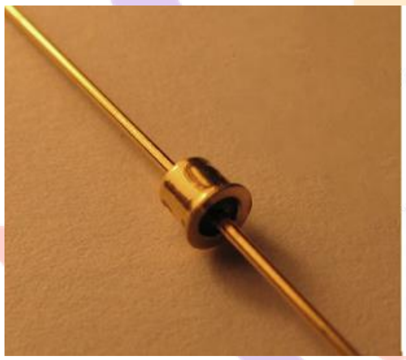
The SCR can be used in following application −

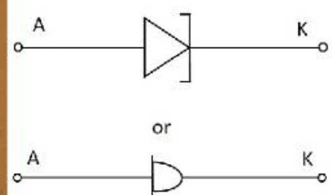
- Power Switching Circuit
- Controlled Rectifier
- AC power control circuits
- Speed control of DC shunt motor
- SCR Crowbar
- Computer logic circuits
- Timing Circuits
- Inverters
- Battery Charging Regulators
- Temperature control systems

Tunnel diode

If the impurity concentration of a normal PN junction is highly increased, this **Tunnel diode** is formed. It is also known as **Esaki diode**, after its inventor.

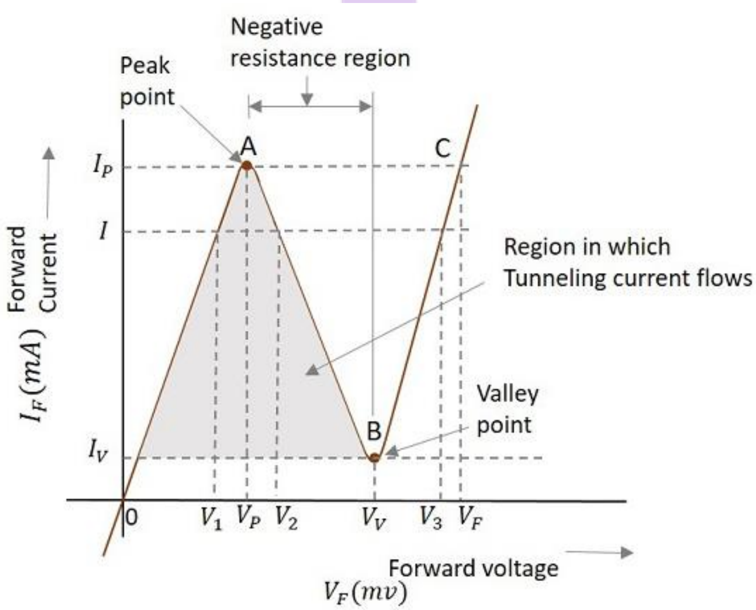
When the impurity concentration in a diode increases, the width of depletion region decreases, extending some extra force to the charge carriers to cross the junction. When this concentration is further increased, due to less width of the depletion region and the increased energy of the charge carriers, they penetrate through the potential barrier, instead of climbing over it. This penetration can be understood as **Tunneling** and hence the name, **Tunnel diode**.





Symbol of Tunnel diode

The Tunnel diodes are low power devices and should be handled with care as they easily get affected by heat and static electricity. The Tunnel diode has specific V-I characteristics which explain their working. Let us have a look at the graph below.



V – I Characteristics of a Tunnel diode

Consider the diode is in **forward-biased condition**. As forward voltage increases, the current increases rapidly and it increases until a peak point, called as **Peak Current**, denoted by I_P. The voltage at this point is called as **Peak Voltage**, denoted by V_P. This point is indicated by **A** in the above graph.

If the voltage is further increased beyond V_P, then the current starts decreasing. It decreases until a point, called as **Valley Current**, denoted by I_V. The voltage at this point is called as **Valley Voltage**, denoted by V_V. This point is indicated by **B** in the above graph.

If the voltage is increased further, the current increases as in a normal diode. For larger values of forward voltage, the current increases further beyond.

If we consider the diode is in **reverse-biased condition**, then the diode acts as an excellent conductor as the reverse voltage increases. The diode here acts as in a negative resistance region.

Applications of Tunnel diode

There are many applications for tunnel diode such as –

- Used as a high-Speed Switching device
- Used as a memory storage device
- Used in Microwave oscillators
- Used in relaxation oscillators

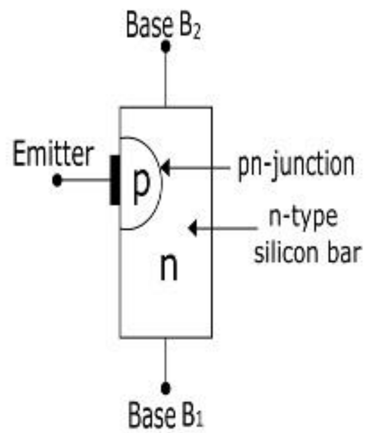
Unijunction Transistor – Construction, Working Principle, and Characteristic Features

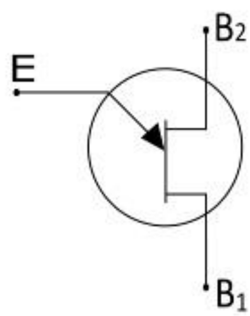
A **Unijunction Transistor (UJT)** is a three-terminal **semiconductor device**. The main characteristics of UJT is when it is triggered, the emitter current increases re-generatively until it is limited by emitter power supply. Due to this characteristic feature, it is used in applications like switching pulse generator, saw-tooth wave generator etc.

Construction of UJT

The UJT consists of an n-type silicon semiconductor bar with an electrical on each end. The terminals of these connections are called Base terminals (B_1 and B_2). Near to base B_2, a pn-junction is formed between a p-type emitter and the n-type silicon bar. The terminal of this junction is called emitter terminal (E).

Since the device has three terminals and one pn-junction, for this region this is called as a Unijunction Transistor (UJT).



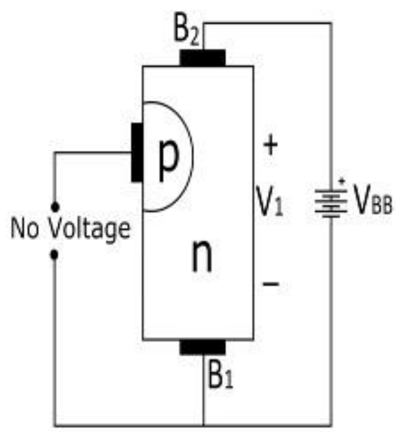


The device has only pn-junction so it forms a diode. Because the two base leads are taken from one section of the diode, hence the device is also called as **Double-Based Diode**.

The emitter is heavily doped while the n-region is lightly doped. Thus, the resistance between base terminals is very high when emitter terminal is open.

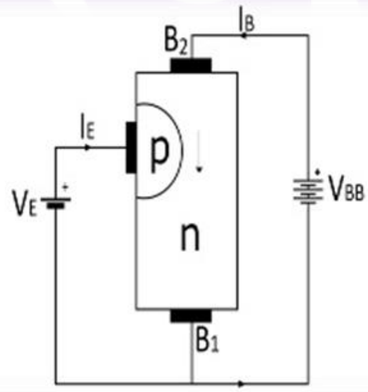
Operation of UJT With Emitter Open

When the voltage V_{BB} is applied with emitter open. A potential gradient is established along the n-type silicon bar. As the emitter is located close to the base B_2, thus a major part of VBB appears between the emitter and base B_1. The voltage V_1 between emitter and B_1, establishes a reverse bias on the pn-junction and the emitter current is cut off, but a small leakage current flows from B_2 to emitter due to minority charge carriers. Thus, the device is said to be in OFF state.

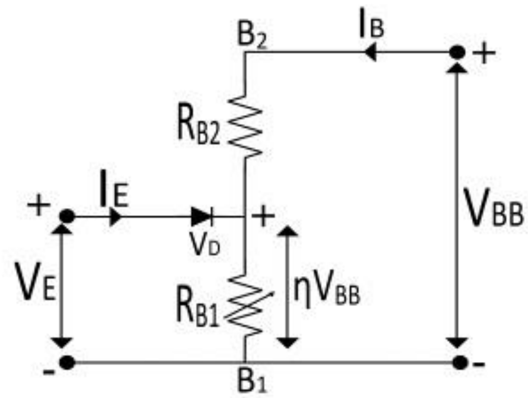


With Emitter at Positive Potential

When a positive voltage is applied at the emitter terminal, the pn-junction will remain reverse biased till the input voltage is less than V_1. A soon as the input voltage at emitter exceeds V_1, the pn-junction becomes forward biased. Under this condition, holes are supplied from p-type region into the n-type bar. These holes are repelled by positive B_2 terminal and attracted towards the B_1 terminal. This increase in the number of holes in the emitter to B_1 region results in the decrease of resistance of this section of the bar. Because of this, the internal voltage drop from emitter to B_1 region is reduced, thus the emitter current (I_E) increases. As more holes are supplied, a condition of saturation is reached. At the point of saturation, the emitter current is limited by the emitter power supply. Now, the device is conducting, hence said to be in ON state.



Equivalent Circuitof UJT



- The resistance of silicon bar is called as the **inter-base resistance** (has a value from 4 kΩ to 10 kΩ).
- The resistance R_{B1} is the resistance of the bar between emitter and B_1 region. The value of this is variable and depends upon the bias voltage across the pn-junction.
- The resistance R_{B2} is the resistance of the bar between emitter and B_2 region.
- The emitter pn-junction is represented by a diode.
- With no voltage applied to the UJT, the value of inter-base resistance is given by $R_{BB}=R_{B1}+R_{B2}$
- The intrinsic **stand-off ration (η)** of UJT is given by

$$\eta=V_1/V_{BB}=R_{B1}/(R_{B1}+R_{B2})$$

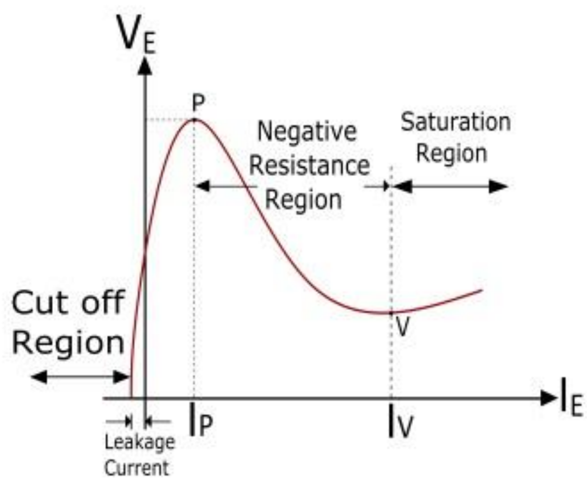
The voltage across R_{B1} is $V1=\frac{RB1}{RB1+RB2}V_{BB}=\eta\ V_{BB}$

- The value of η generally lies between 0.51 and 0.82.
- The **Peak Point Voltage (V_P)** of the UJT

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

Characteristics of UJT

The curve between emitter voltage (V_E) and emitter current (I_E) of UJT, at a given value of V_{BB} is known as emitter characteristics of UJT.



Important points from the characteristics are −

- At first, in the cut off region, when the emitter voltage increases from zero, due to the minority charge carriers, a small current flows from terminal B_2 to emitter. This is called as leakage current.
- Above the definite value of V_E, the emitter current (I_E) starts to flow and increases until the peak (V_P and I_P) is reached at point P.
- After point P, an increase in V_E causes a sudden increase in I_E with a corresponding decrease in V_E. This is the **Negative Resistance Region** of the curve as with the increase in I_E, V_E decreases.
- The negative resistance region of the curve ends at the **valley-point (V)**, having valley-point voltage V_V and current I_V. After the valley-point the device is driven to saturation.

Advantages of UJT

- Low cost
- Excellent characteristics
- Low power absorbing device under normal operating conditions

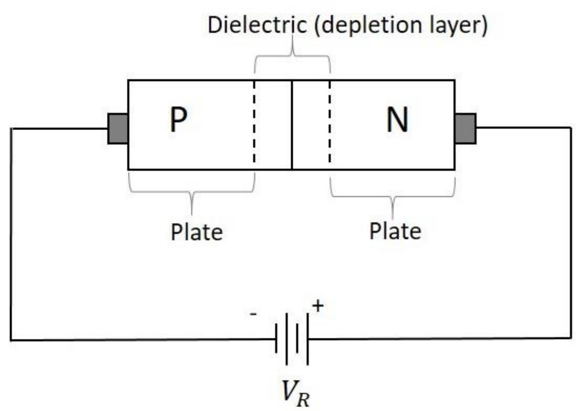
Applications of UJT

- Oscillators
- Trigger Circuits
- Saw tooth generator
- Bi-stable networks
- Pulse and voltage sensing circuits
- UJT relaxation oscillators
- Over voltage detectors

Varactor Diode

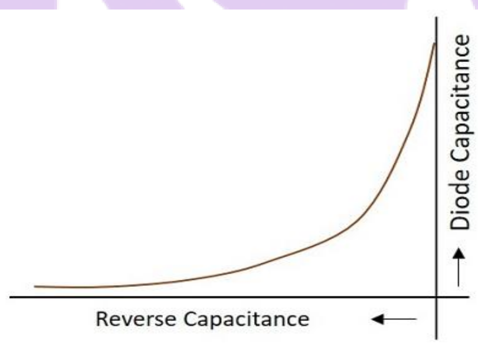
A junction diode has two potentials on both sides where the depletion region can act as a dielectric. Hence there exists a capacitance. The Varactor diode is a special case diode that is operated in reverse bias, where the junction capacitance is varied.

The Varactor diode is also called as **Vari Cap** or **Volt Cap**. The following figure shows a Varactor diode connected in reverse bias.



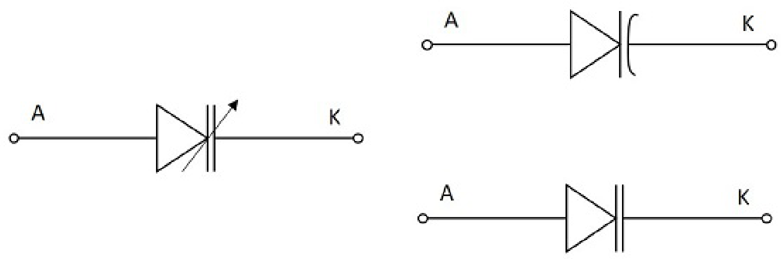
Reverse biased PN junction

If the reverse voltage applied is increased, the **width** of the dielectric region **increases**, which **reduces** the **junction capacitance**. When the reverse voltage decreases, the width of the dielectric decreases, which increases the capacitance. If this reverse voltage is completely null, then the **capacitance** will be at its **maximum**.



Capacitance versus Reverse voltage

The following figure shows various symbols used for Varactor diode which represents its function.



Symbol for Varactor diode

Though all diodes have this junction capacitance, the Varactor diode is mainly manufactured to make use of this effect and increase the variations in this junction capacitance.

A Practical Varactor diode

Applications of Varactor diode

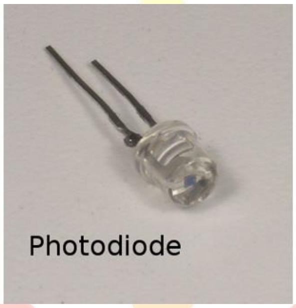
This diode has many applications such as −

- It is used as a Voltage variable capacitor.
- It is used in variable LC tank circuit.
- Used as Automatic frequency control.
- Used as Frequency Modulator.
- Used as RF Phase shifter.
- Used as frequency multiplier in local oscillator circuits.

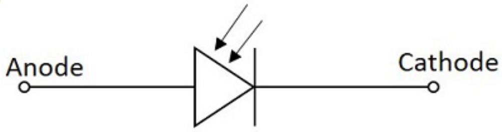
Photo Diode

Photo diode, as the name implies, is a PN junction which works on light. The intensity of light affects the level of conduction in this diode. The photo diode has a P type material and an N-type material with an **intrinsic** material or a **depletion region** in between.

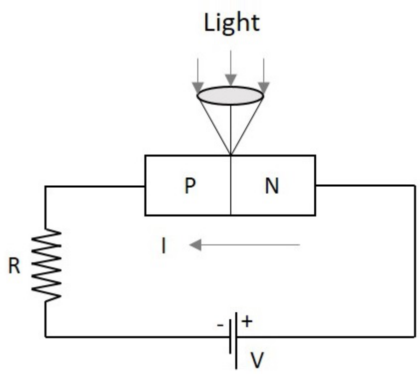
This diode is generally operated in **reverse bias** condition. The light when focused on the depletion region, electron-hole pairs are formed and flow of electron occurs. This conduction of electrons depends upon the intensity of light focused. The figure below shows a practical Photo diode.



The figure below indicates the symbol for a photodiode.



When the diode is connected in reverse bias, a small reverse saturation current flows due to thermally generated electron hole pairs. As the current in reverse bias flows due to minority carriers, the output voltage depends upon this reverse current. As the light intensity focused on the junction increases, the current flow due to minority carriers increase. The following figure shows the basic biasing arrangement of a photo diode.



The Photo diode is encapsulated in a glass package to allow the light to fall onto it. In order to focus the light exactly on the depletion region of the diode, a lens is placed above the junction, just as illustrated above.

Even when there is no light, a small amount of current flows which is termed as **Dark Current**. By changing the illumination level, reverse current can be changed.

Advantages of Photo diode

Photo diode has many advantages such as −

- Low noise
- High gain
- High speed operation
- High sensitivity to light
- Low cost
- Small size
- Long lifetime

Applications of Photo diode

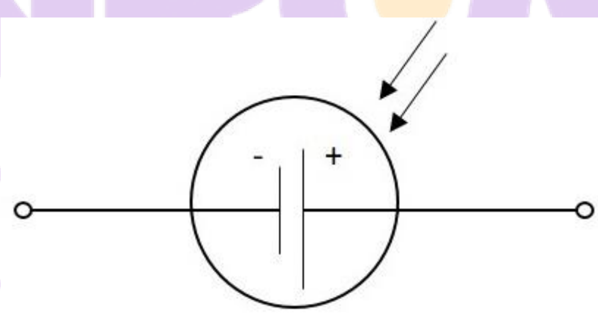
There are many applications for photo diode such as −

- Character detection
- Objects can be detected visible or invisible
- Used in circuits that require high stability and speed.
- Used in Demodulation
- Used in switching circuits
- Used in Encoders
- Used in optical communication equipment

Solar Cell

The light dependent diodes include Solar cell, which is a normal PN junction diode but has its conduction by the rush of photons which are converted into the flow of electrons. This is similar to a photo diode but it has another objective of converting maximum incident light into energy and storing it.

The figure below represents the symbol of a solar cell.



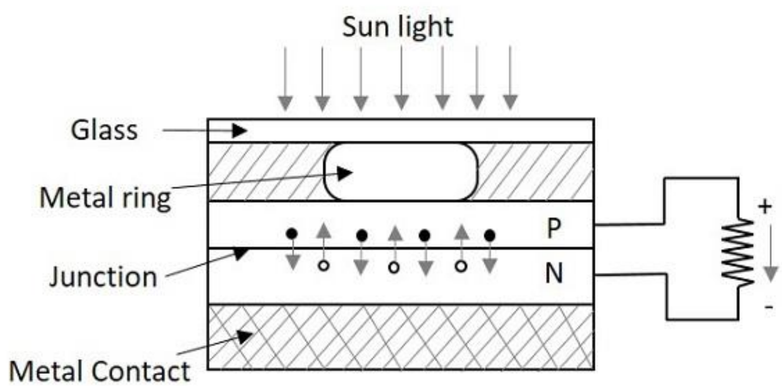
Symbol of Solar Cell

A solar cell has its name and symbol indicating storing of energy though it is a diode. The feature of extracting more energy and storing of it is concentrated in the solar cell.

Construction of a Solar cell

A PN junction diode with an intrinsic material in the deletion region is made to encapsulate in a glass. The light is made to incident on maximum area possible with thin glass on the top so as to collect maximum light with minimum resistance.

The following figure shows the construction of a Solar cell.



When the light is incident on the solar cell, the photons in the light collide with valence electrons. The electrons are energized to leave the parent atoms. Thus a flow of electrons is generated and this current is directly proportional to the light intensity focused onto the solar cell. This phenomenon is called as the **Photo-Voltaic effect**.

The following figure shows how a solar cell looks like and how a number of solar cells together are made to form a solar panel.


Solar panel


Solar cell

Difference between a Photo diode and Solar cell

Photo Diode works faster and concentrates on switching rather than providing more power at the output. It has a low capacitance value because of this. Also the area of incidence of light energy is lesser in Photo diode, according to its applications.

A Solar cell concentrates on delivering high output energy and storing the energy. This has **high capacitance** value. The operation is a bit slower than photo diode. According to the purpose of the solar cell, the area of incidence of light is larger than photo diode.

Applications of Solar Cell

There are many applications for Solar cell such as −

Science and Technology

- Used in Solar panels for Satellites
- Used in telemetry
- Used in Remote lighting systems etc.

Commercial Use

- Used in Solar panels for storage of electricity
- Used in Portable power supplies etc.
- Used in household uses such as cooking and heating using solar energy

Electronic

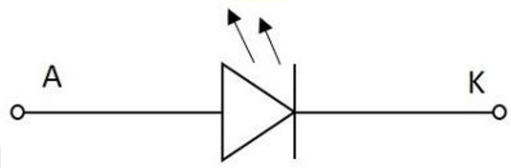
- Watches
- Calculators
- Electronic Toys, etc.

Some diodes emit light according to the voltage applied. There are two main types of diodes in this category. They are LEDs and Laser diodes

LED Light Emitting Diodes

This one is the most popular diodes used in our daily life. This is also a normal PN junction diode except that instead of silicon and germanium, the materials like gallium arsenide, gallium arsenide phosphide are used in its construction.

The figure below shows the symbol of a Light emitting diode.



Symbol of LED

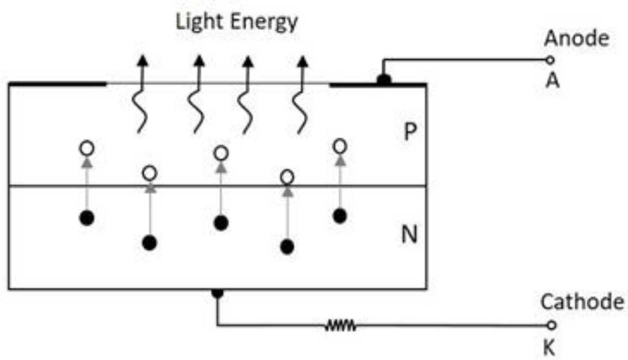
Like a normal PN junction diode, this is connected in forward biascondition so that the diode conducts. The conduction takes place in a LED when the free electrons in the conduction band combine with the holes in the valence band. This process of recombination emits **light**. This process is called as **Electroluminescence**. The color of the light emitted depends upon the gap between the energy bands.

The materials used also effect the colors like, gallium arsenide phosphide emits either red or yellow, gallium phosphide emits either red or green and gallium nitrate emits blue light. Whereas gallium arsenide emits infrared light. The LEDs for non-visible Infrared light are used mostly in remote controls.

The following figure shows a how the practical LEDs of different colors looks like.

LED in the above figure has a flat side and curved side, the lead at the flat side is made shorter than the other one, so as to indicate that the shorter one is **Cathode** or negative terminal and the other one is **Anode** or the Positive terminal.

The basic structure of LED is as shown in the figure below.



Basic Structure of LED

As shown in the above figure, as the electrons jump into the holes, the energy is dissipated spontaneously in the form of light. LED is a current dependent device. The output light intensity depends upon the current through the diode.

Advantages of LED

There are many advantages of LED such as −

- High efficiency
- High speed
- High reliability
- Low heat dissipation
- Larger life span
- Low cost
- Easily controlled and programmable
- High levels of brightness and intensity
- Low voltage and current requirements
- Less wiring required
- Low maintenance cost
- No UV radiation
- Instant Lighting effect

Applications of LED

There are many applications for LED such as −

In Displays

- Especially used for seven segment display
- Digital clocks
- Microwave ovens
- Traffic signaling
- Display boards in railways and public places

- Toys

In Electronic Appliances

- Stereo tuners
- Calculators
- DC power supplies
- On/Off indicators in amplifiers
- Power indicators

Commercial Use

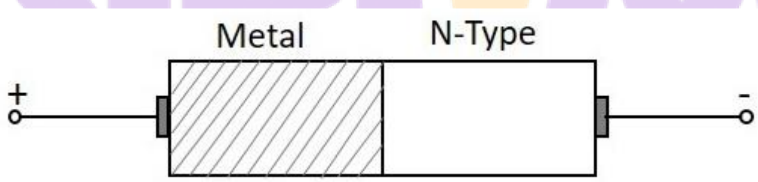
- Infrared readable machines
- Barcode readers
- Solid state video displays

Optical Communications

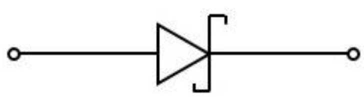
- In Optical switching applications
- For Optical coupling where manual help is unavailable
- Information transfer through FOC
- Image sensing circuits
- Burglar alarms
- In Railway signaling techniques
- Door and other security control systems

Schottky Diode

This is a special type of diode in which a PN junction is replaced by a metal semiconductor junction. The P-type semiconductor in a normal PN junction diode is replaced by a metal and N-type material is joined to the metal. This combination has no depletion region between them. The following figure shows the Schottky diode and its symbol.



Structure of a Schottky diode



Symbol of a Schottky diode

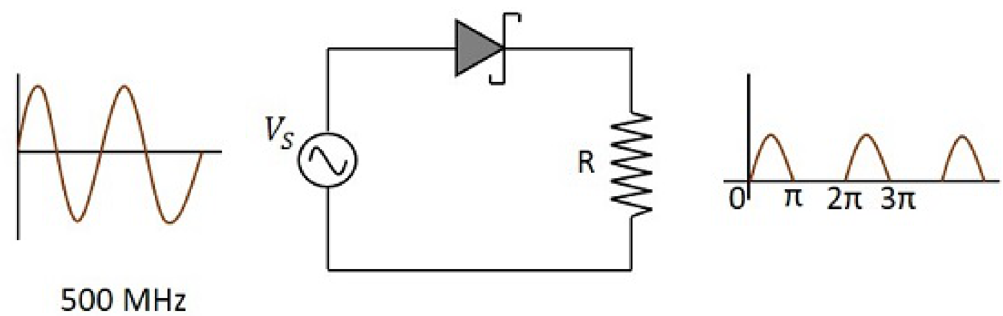
The metal used in this Schottky diode may be gold, silver, platinum or tungsten etc. As well, for the semiconductor material other than silicon, gallium arsenide is mostly used.

Image of a Schottky diode

Operation

When no voltage is applied or when the circuit is unbiased, the electron in the N-type material has lower energy level than the ones in the metal. If the diode is then forward biased, these electrons in the N-type gain some energy and move with some higher energy. Hence these electrons are called as **Hot Carriers**.

The following figure shows a Schottky diode connected in a circuit.



Advantages

There are many advantages of Schottky diode such as −

- It is a unipolar device and hence no reverse currents are formed.
- Its forward resistance is low.
- Voltage drops are very low.
- Rectification is fast and easy with the Schottky diode.
- There is no depletion region present and hence, no junction capacitance. So, the diode gets to OFF position quickly.

Applications

There are many applications of Schottky diode such as −

- Used as a detector diode
- Used as a Power rectifier
- Used in RF mixer circuits
- Used in power circuits
- Used as clamping diodes