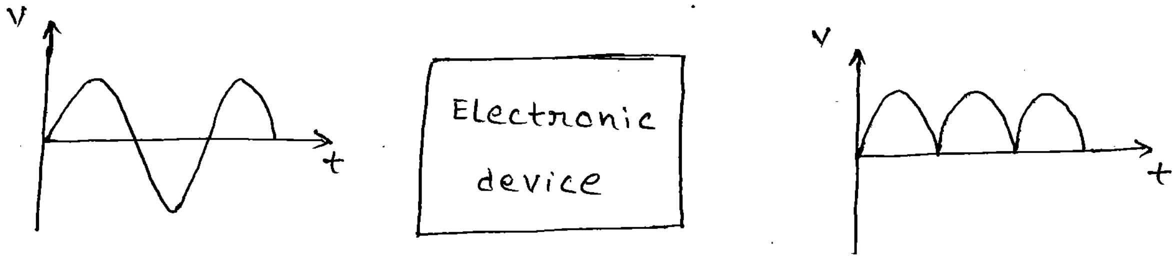
Electronics : The branch of Engineering which deals with current conduction through a vaccum or gas or semi conductor is known as Electronics.

Electronic Device : An electronic device is that in which current flows through a vaccum or gas or semi conductor.

Applications of Electronics :-

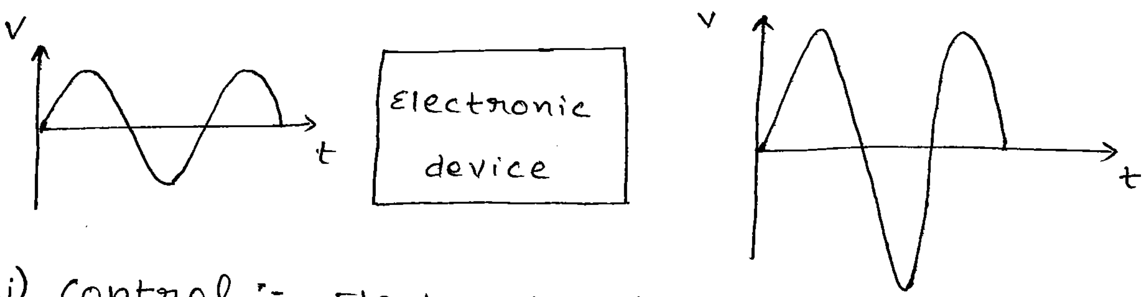
The Electronic devices are capable of Performing the following functions

i) **Rectification** : The conversion of a.c in to d.c is called rectification. Electronic devices can convert a.c power in to d.c power with very high efficiency. This d.c supply can be used for charging storage batteries, field supply of d.c generators etc.



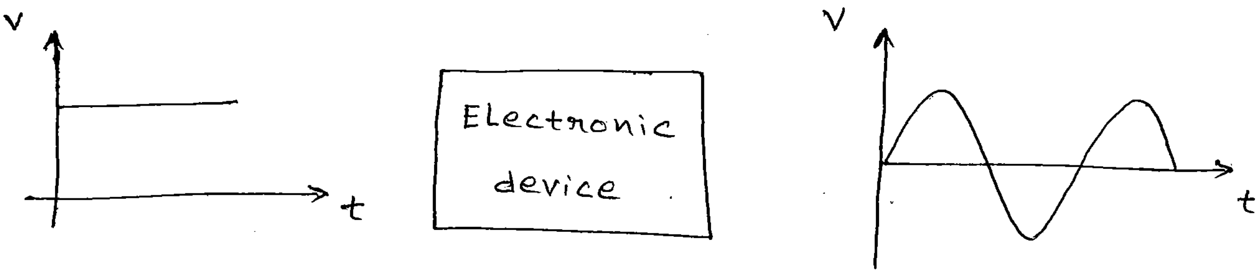
(ii) **Amplification** :- The process of raising the strength of a weak signal is known as Amplification.

Ex. Radio's, Televisions



iii) Control :- Electronic devices find wide applications in automatic control.
Ex speed of a motor, voltage across a refrigirator etc

iv) Generation :- Electronic devices can convert d.c power in to a.c power of any frequency. when performing this function, they are known as oscillators.



v) conversion of Light in to Electricity :- Electronic devices can convert Light in to Electricity. This conversion of light in to electricity is known as photo Electricity. Ex Burglar alarms etc

vi) conversion of Electricity in to Light :-
Electronic devices can convert electricity in to Light. This valuable property is utilised in television and radar.

Generally materials are classified in to 3 types

i) Insulators

ii) Metals

iii) Semiconductors

i) Insulators :- A very poor conductor of Electricity is called an Insulator

Ex wood, glass, Diamond, Mica etc

ii) Metals :- An Excellent conductor is a metal. Ex : copper, Alluminium etc

iii) Semi Conductor :- A material whose conductivity lies between that of conductors and insulators is called semi Conductors.

Ex: Silicon and Germanium.

Structure of an Atom :-

→ All the protons and neutrons are bound together at the centre of an atom, which is called nucleus, while all the electrons are moving around the nucleus

→ the electrons are arranged in the different orbits at fixed distances from the nucleus

→ In general, an orbit or a shell can contain a maximum number of $2n^2$ electrons, where 'n' is the number of the shell.

→ Each shell has energy level associated

→ Closer the shell to the nucleus, more tightly it is bound to the nucleus and posesses Lower energy level.

→ The outermost shell is called valence shell and the electrons in this shell are called valence electrons.

→ The valence electrons revolving in the outer most shell are said to be having highest energy level

→ The amount of energy required to extract the valence electron from the outer shell is very less

→ An electron which is not subjected to the force of attraction of the nucleus is called a free electron. Such free electrons are basically responsible to the flow of current.

→ more the number of free electrons better is the conductivity of the metal.

Energy band theory :-

A material can be placed into insulators, conductors and semi conductors depending upon its energy band structure.

The energy band diagram consists of three bands

(1) valence band (2) conduction band (3) Forbidden band

(1) Valence band :- The valence electrons possess highest energy level. when such electrons form the covalent bonds due to the coupling between valence electrons of adjacent atom, the energy band formed due to merging of energy levels associated with the valence electrons. ie. electrons in the last shell is called the valence band

(2) conduction band :- valence electrons form the covalent bond and are not free, but when certain energy is imparted to them they become free.

The energy band formed due to merging of energy levels associated with the free electrons is called conduction band.

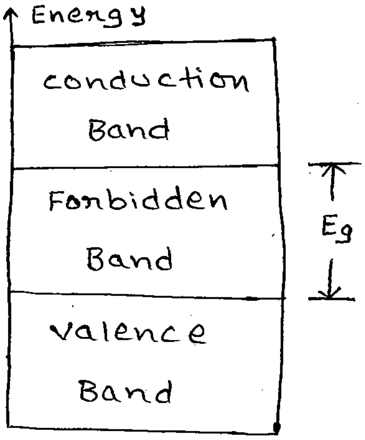
under normal conditions, the conduction band is empty and once energy is imparted the valence electrons jump from valence band to conduction band and become free.

(3) Forbidden band :-

while jumping from valence band to Conduction band the electrons have to cross an energy gap

The energy gap which is present separating the conduction band and the Valence band is called forbidden band or forbidden energy gap.

Insulators :- The energy band diagram of a insulator is shown in figure below.



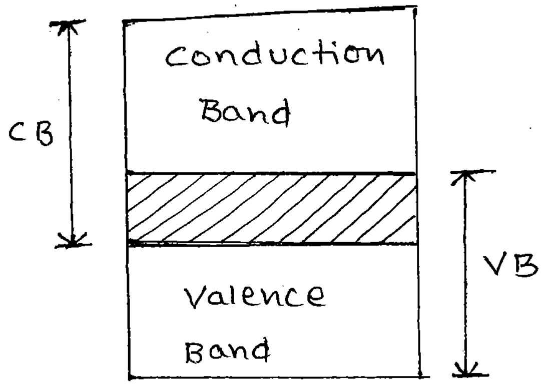
The valence band is fully filled and conduction band is almost empty and forbidden gap is more approximately of about 7eV

For a diamond, the forbidden gap is about 6eV

conduction is impossible in insulators even by applying additional energy.

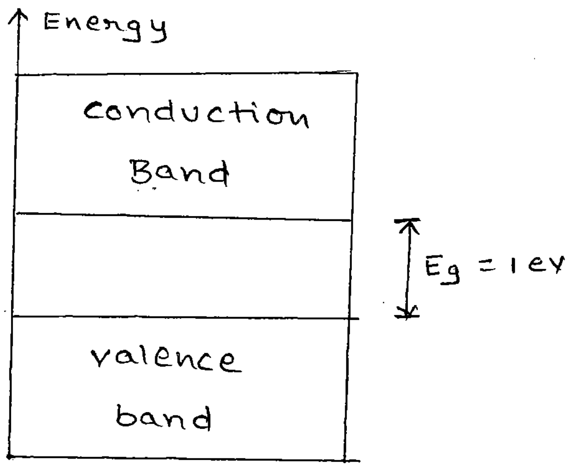
The resistivity of insulators is of the order of 10^7 ohm-meter.

Conductors : The energy band diagram of conductors is shown in figure below.



Here the valence band and conduction band overlap each other as shown in figure. As a result the electrons in the valence band can easily move in to the conduction band to make conduction easily. The resistivity is of the order of $10^{-8}\ \Omega$-m.

(3) Semi Conductors :- The energy band diagram of semi conductors is shown in figure below.



Here the valence band is almost filled and conduction band is almost empty. The energy gap between valence band and conduction band is very small and is about 1ev.

The resistivity of semi conductor is of the order of $10^{-4}\ \Omega$-m.

Hence smaller electric field is required to push the electrons from the valence band to the conduction band.

At low temperature, the valance band is completely full and conduction band is completely empty. therefore at low temperatures the

However even at room temperature, some of the valence electrons acquire thermal energy greater than Eg to overcome forbidden energy gap and jump in to the conduction band to make the conduction possible.

Hence as the temperature increases, the conductivity of semiconductor increases ie. resistance decreases. Therefore semi conductors have negative resistance temperature coefficient.

At 0°K, the forbidden gap for Germanium is

$$\boxed{E_g = 0.785\ eV}$$

and for Silicon (Si) is $\boxed{E_g = 1.21\ eV}$

The forbidden energy gap depends on temperature.

At Room temp ie 300° K

For Ge $E_g = 0.72\ eV$

For Si $E_g = 1.1\ eV$

<u>Commonly used Semi Conductors</u> :

There are many semi conductors available, but very few of them have a practical application in electronics. The two most frequently used materials are Germanium and Silicon. It is because the energy required to break their covalent bond (ie the energy required to release an electron from their valence bonds) is very small being 0.72 eV for Ge and 1.1 eV for Si

1) <u>Germanium (Ge) :</u>

The atomic number of Ge is 32. Therefore it has 32 protons and 32 electrons. Two electrons are in the first orbit; eight electrons in the second, 18 electrons in the third and 4 electrons in the outer (or) valence orbit.

It is clear that Ge atom has 4 valence electrons ie it is a tetravalent element. It is shown in fig (a)

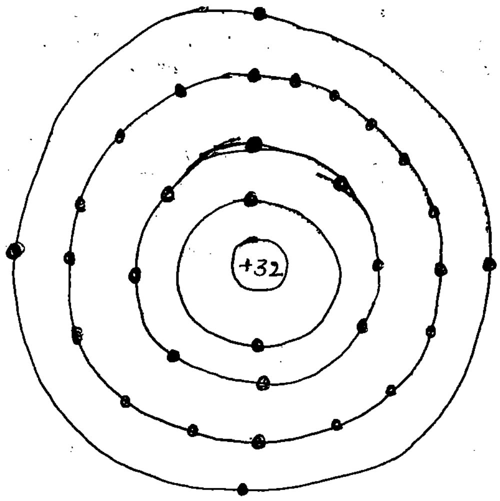


fig (a).

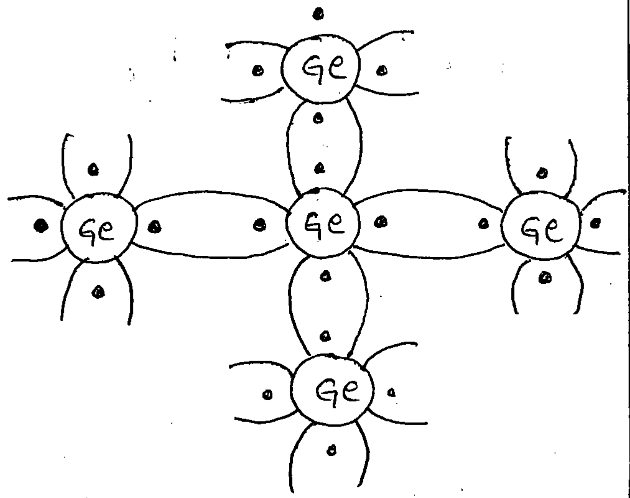


fig (b).

fig (b) shows how the various Germanium atoms are held through co-valent bonds. As the atoms are arranged in an orderly pattern, Ge has crystalline structure.

2) <u>Silicon (Si)</u> :- Silicon is an element ~~of~~ in most of the common rocks. Actually sand is silicon di oxide. And this is chemically reduced to silicon which is 100% pure for use as a semiconductor.

The atomic number of silicon is 14. Therefore it has 14 protons and 14 electrons. Two electrons are in the first orbit, eight electrons in the second orbit and four electrons in the ~~second~~ third orbit. This is shown in fig(a) below. It is clear that silicon atom has four valence electrons. ie. it is a tetravalent element.

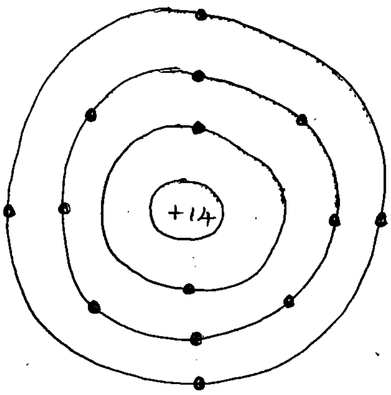


fig (a).

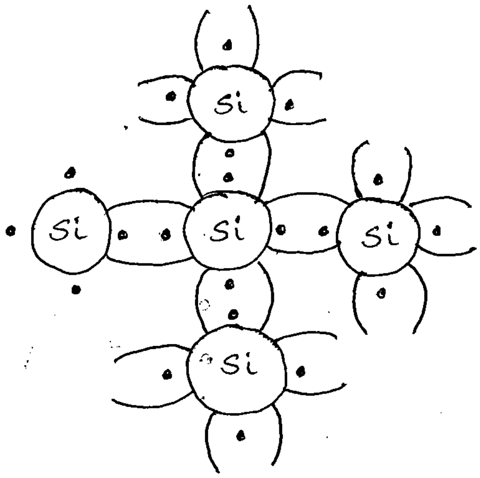


fig (b)

fig(b) shows how various silicon atoms are held through co-valent bonds. Like germanium, silicon atoms are also arranged in an orderly manner. Therefore silicon has crystalline structure.

<u>Classification of semi Conductor materials</u> :-

Semi Conductor materials are classified in to two types
1. Intrinsic Semi Conductors
2. Extrinsic Semi Conductors.

1) <u>Intrinsic Semi Conductor</u> :- A pure form of semi-conductor material is known as intrinsic semi conductor material.

when there are four electrons in the outermost orbit, the semi Conductor material is refered to as pure or intrinsic Semi Conductor.

In pure Semi Conductor, the number of holes is equal to the number of free electrons.

Even at room temperature, some of valence electrons may acquire sufficient energy to enter the conduction band to form free electrons under the influence of electric field, these electrons constitutes the electric current.

The current due to the movement of free electrons in the conduction band is an electron current.

A missing electron in the valance band leaves a vacant space there, which is known as a hole.

under the influence of electric field, the current due to the movement of holes in the valance band is a hole current.

Therefore the electron as well as hole current together constitutes the total current in an intrinsic Semi Conductor.

<u>Extrinsic Semi Conductor</u> :- The intrinsic semi conductor has little current conduction capability at room temperature. To be useful in

electronic devices, the pure semi conductor must be altered so as to significantly increase its conducting properties. This is achieved by adding a small amount of suitable impurity to a semi conductor. It is then called impurity or Extrinsic semiconductor. so

Doped semiconductor material is called Extrinsic (impure) Semi Conductor.

The process of adding small amount of impurities to the pure form of semi Conductor in order to increase the conductivity of semi Conductor is Known as doping.

Depending upon type of impurities, there are two types of extrinsic semi Conductors

(1) N- type (2) P- type.

(1) N - type Semi Conductor :-

When a small amount of pentavalent impurity such as Arsenic (As), Antimony (Sb), Phosphorous, Bismuth etc is added to pure form of Semi Conductor, it is Known as n-type semi Conductor. These pentavalent impurities are also called 'donar imprity atoms', because they donate or provide free electrons to the semi Conductor crystal.

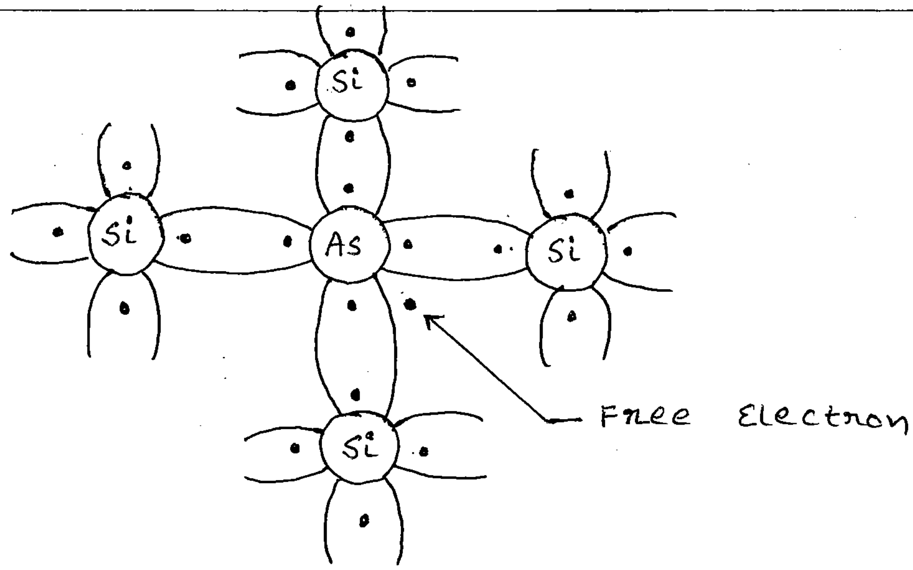


fig: Formation of covalent bonds in N-type semiconductor.

one donar impurity atom donates one free electron in N-type material. therefore free electrons are majority charge carriers in N-type semi conductors.

the following points may be noted carefully

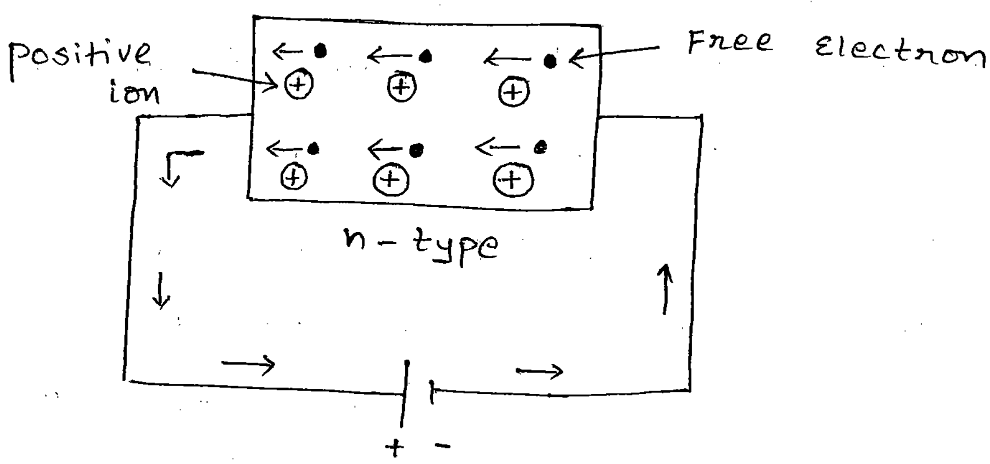
1) Many new free electrons are produced by the addition of pentavalent impurity.

2) Thermal energy at room temperature still generates a few electron-hole pairs. However the number of free electrons provided by the pentavalent impurity far exceeds the number of holes. It is due to this predominance of electrons over holes that it is called n-type semiconductor (n stands for negative). Here holes are the minority carriers.

n-type Conductivity :- The current conduction in an n-type semi conductor is predominantly by free electrons. when potential difference is applied across n-type semi Conductor, the free electrons (donated by impurity) in the crystal will be directed towards the positive terminal, constituting electric current. so this type of conductivity is called n-type conductivity.

** The donor impurity atom donates one electron to the crystal and becomes "positive ion"

therefore n-type semi Conductor cosists of free electrons and 'positive ion'



P - type semi Conductor :-

when a small amount of trivalent impurity such as Boron, Aluminium, Indium, Gallium is added to a pure semi Conductor, It is called P-type semi Conductor. These trivalent impurities are also called "Acceptor impurities".

one Acceptor impurity creates one hole in a P-type material, therefore the holes are majority charge carriers.

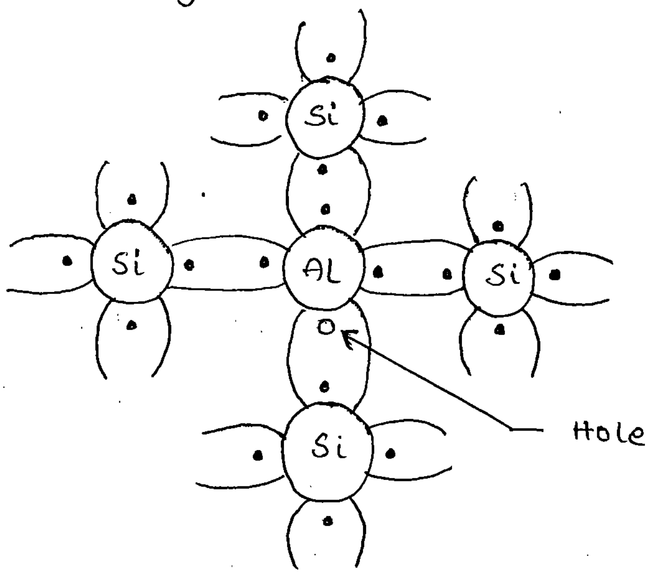
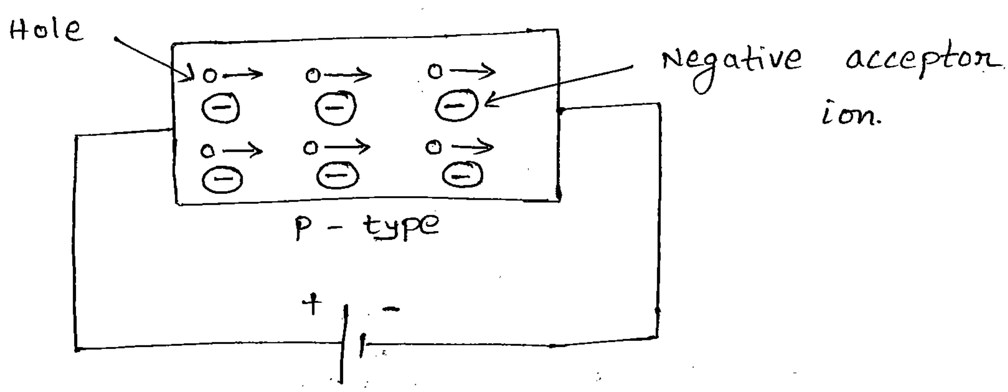


Fig: Formation of covalent bonds in P-type semi Conductors.

Here fourth bond is incomplete, being short of one electron. This missing electron is called a hole. Therefore for each ~~gallium~~ AL atom added, one hole is created. A small amount of gallium provides millions of holes.

However, there are a few conduction band electrons due to thermal energy associated with room temperature. but the holes are far exceeds the number of electrons. because of this predominance of holes over free electrons, this type of semiconductor is called P-type semi conductor. (P stands for positive)

<u>P-type conductivity</u> :-



The current conduction in P-type Semi Conductor is predominantly by holes. when potential difference is applied to the P-type Semi Conductor, the holes are shifted from one covalent bond to another. As the holes are positively charged, they are directed towards the negative terminal, constituting hole current. so this type of conductivity is called P-type conductivity.

** The acceptor impurity atom is short of one electron, and becomes a negative ion.

Therefore P-type semi Conductor consists of <u>holes</u> and <u>negative</u> <u>ions</u>.

Majority and minority carriers :-

In N-type Semi Conductor the majority Carriers are Electrons and the Minority carriers are the holes.

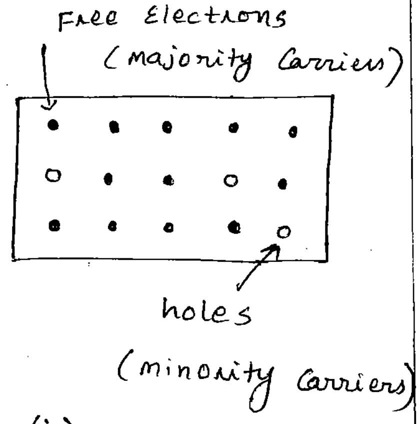
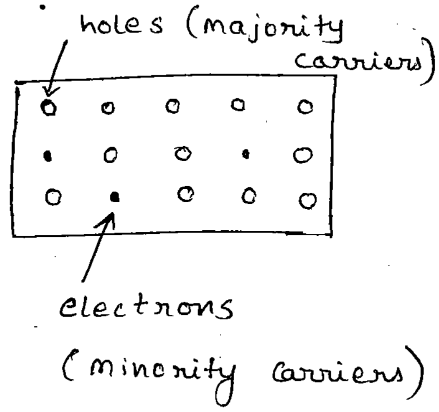


fig (i) N-type

In P-type Semi Conductor the majority carriers are holes and the minority Carriers are the electrons.

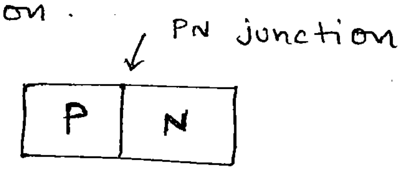


fig(ii) P-type

Qualitative theory of PN Junction (Formation of PN junction)

→ In a piece of semi conductor material, 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.



→ P-type semi conductor consists of both holes and Negative acceptor ions (the acceptor impurity atom is short of one electron and becomes a negative ion).

→ The N-type semiconductor consists of both electrons and positive donor ion (the donor impurity atom donates one electron and becomes a positive ion)

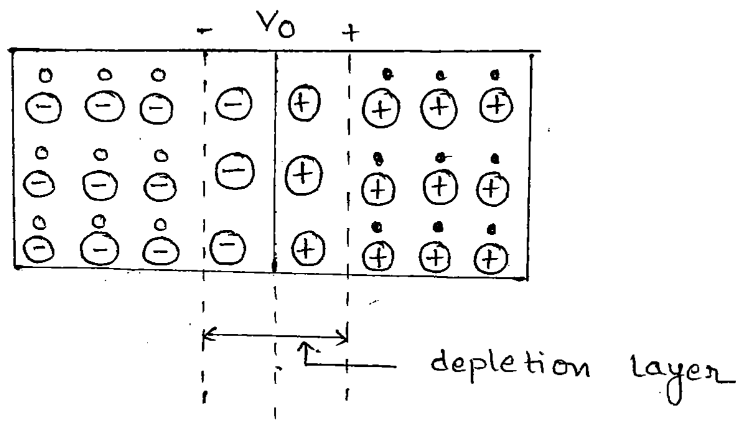
→ Here n-type material has a high concentration of free electrons while P-type material has high concentration of holes.

→ Therefore at the junction, there is a tendency for the free electrons to diffuse over to the P-side and holes to the N-side. This process is called diffusion.

→ As the free electrons move across the junction from n-type to P-type, Positive donor ions are uncovered. Hence a positive charge is built on the n-side of the junction.

→ At the same time, the free electrons cross the junction and uncover the negative acceptor ions by filling in the holes. Hence a net negative charge is established on P-side of the junction

→ Now positive charge on N-side repels holes to cross from P-type to n-type, and negative charge on P-side repels free electrons to enter from n-type to P-type. Thus barrier is set up against further movement of charge carriers. This is called potential barrier or barrier potential or junction barrier (V_0).



→ Barrier potential indicates the amount of voltage to be applied across the PN junction to restart the flow of electrons and holes across the junction

→ the barrior potential is expressed in volts. Its value is called the height of the barrior.

→ the Magnitude of the barrior potential varies with doping levels and temperature.

→ The potential barrior can be increased or decreased by applying an external voltage.

→ The potential barrior is approximately 0.7V for Si and 0.3 V for Ge at 25°C.

→ Inside the potential barrior, there is a positive charge on n-side and negative charge on P-side. This region is called <u>depletion</u> region or <u>space</u> <u>charge</u> <u>region</u>.

→ The thickness of this region is of the order of 10^{-4} cm (10^{-6} m = 1 micron)

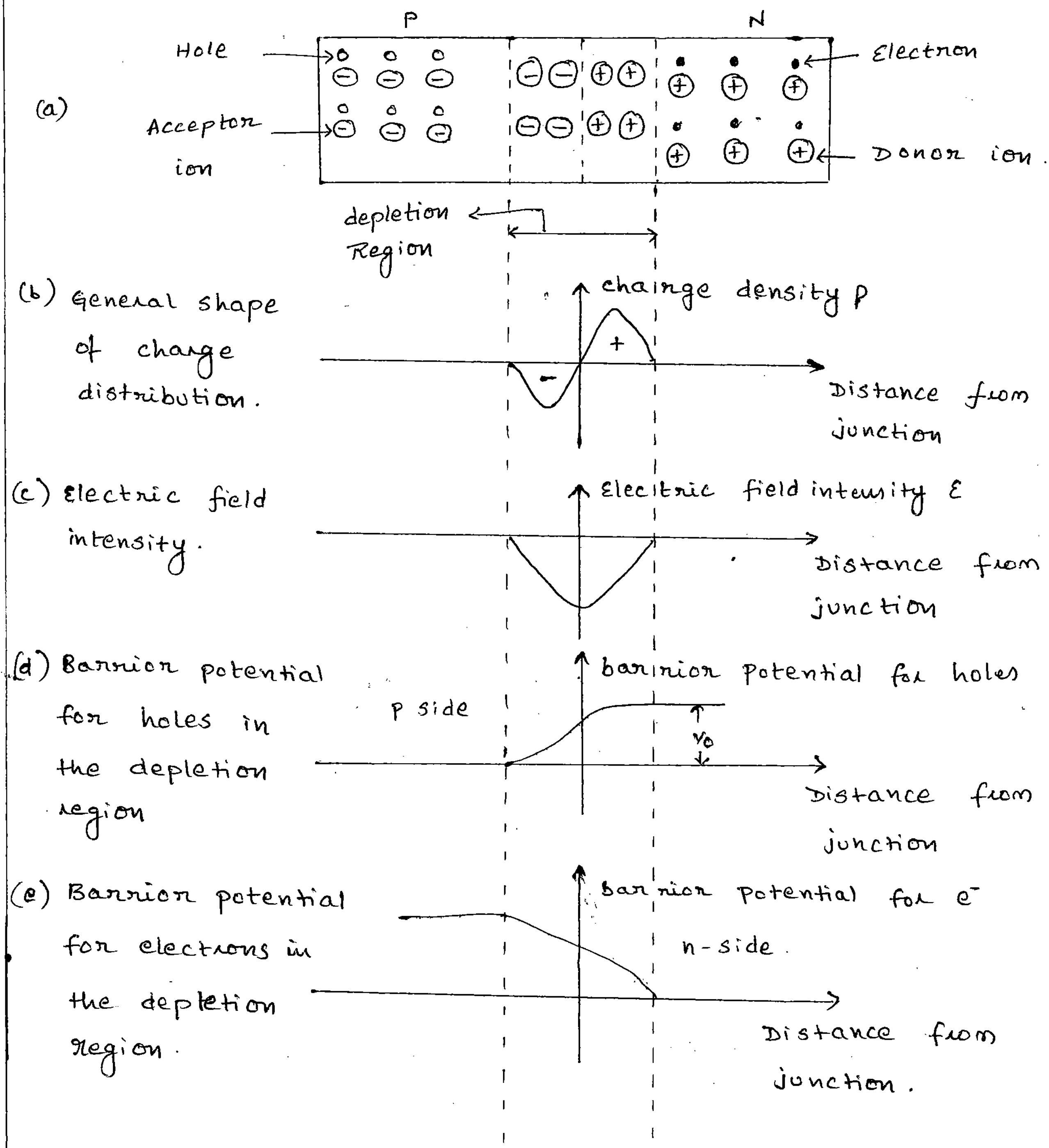
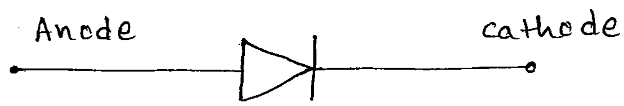


Figure: Formation of PN junction.

PN Junction as a Diode :-

The essential electrical characteristic of a PN junction is that it constitutes a diode which permits the easy flow of current in one direction and restricts the flow of current in opposite direction.

Diode Symbol : Diode symbol is shown in figure below.



The P-type and n-type regions are referred to as Anode and Cathode respectively.

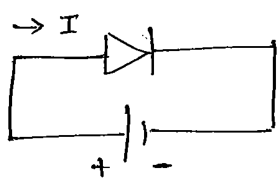
The Arrow in the symbol indicates the direction of easier conventional current flow.

Operation of PN junction Diode :

(1) **Forward Bias :**

→ When the positive terminal of the battery is connected to the P-type and the negative terminal of the battery is connected to n-type of PN junction diode, then the bias is said to be Forward bias.

→ A PN junction with forward bias is shown in figure below.



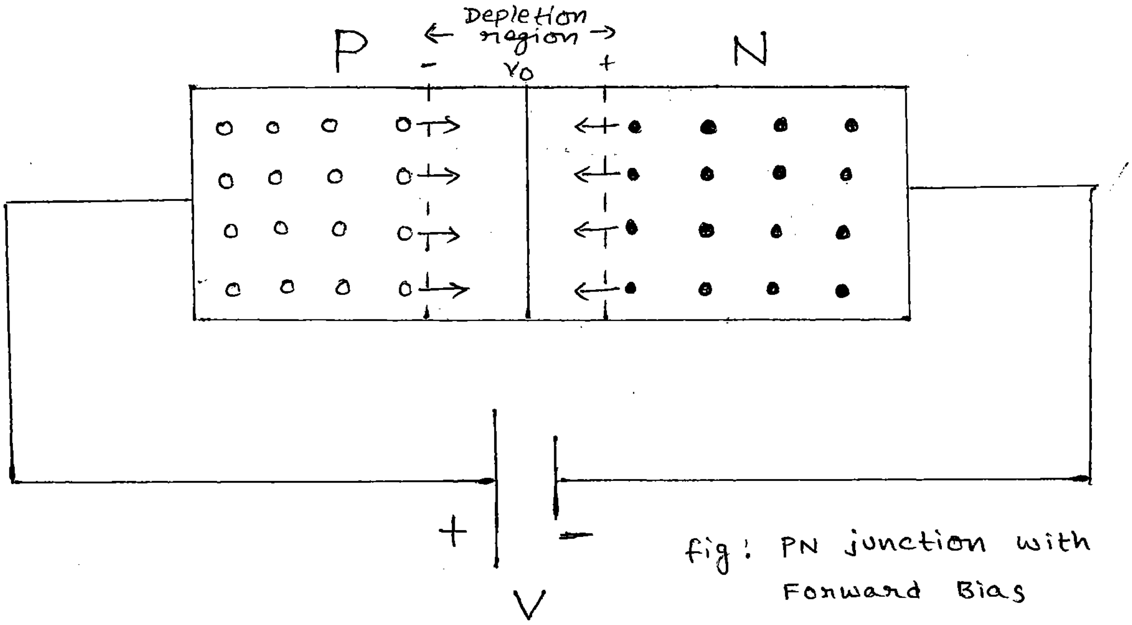


fig: PN junction with Forward Bias

→ when the PN junction is forward biased, as long as the applied voltage is less than the barrior potential there cannot be any conduction.

→ when the applied voltage becomes more than the barrior potential, the negative terminal of battery pushes the free electrons against barrior potential from n to p region. similarly positive terminal pushes the holes from p to n region. Thus holes get repelled by the positive terminal and cross the junction against the barrior potential, Electrons gets repelled by the negative terminal and cross the junction against the barrior potential. Thus the applied voltage overcomes the barrior potential. This reduces the width of the depletion region.

→ As forward voltage is increased, at a particular value the depletion region becomes very much narrow such that large number of majority charge carriers can cross the junction and these majority carriers can travel around the closed circuit and constitute a current called forward current.

→ The forward potential at which the potential barrior across the junction is completely eliminated and allows the current to flow through the junction is called cut-in voltage (or) threshold voltage of PN junction diode.

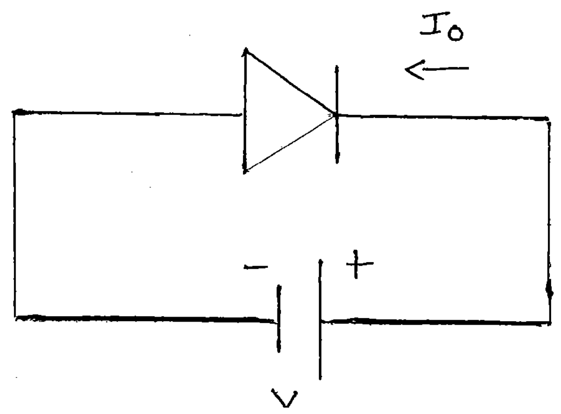
→ the cutin voltage for Ge is 0.3 V

→ the cut in voltage for Si is 0.7 V

(2) Reverse Bias :-

when the positive terminal of the battery is connected to the N type and the negative terminal of the battery is connected to the P type of the PN junction Diode, then bias is said to be 'Reverse Bias'.

A PN junction with reverse Bias is shown in figure below.



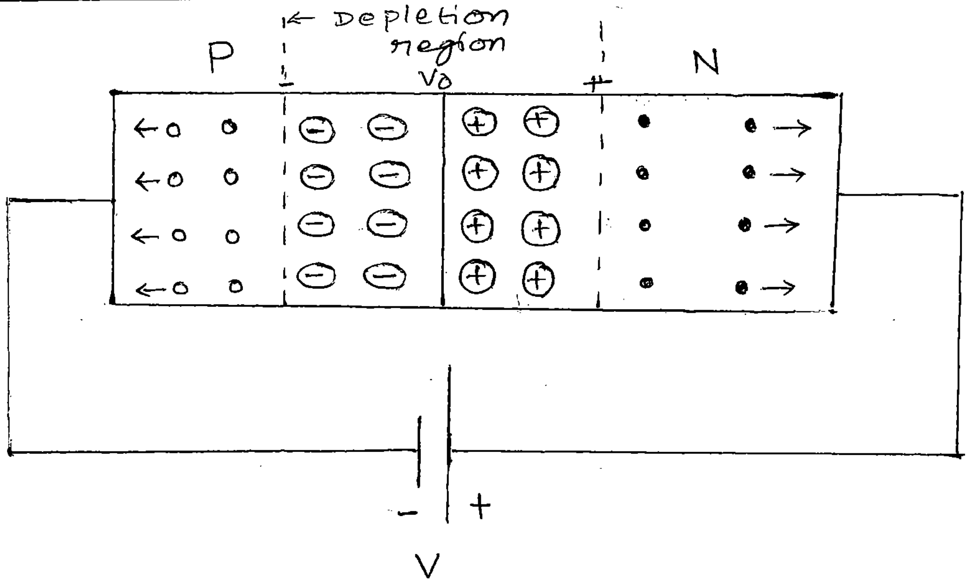


Fig: PN junction with Reverse Bias.

→ When the PN junction is reverse biased the negative terminal attracts the holes in the P-region, away from the junction, the positive terminal attracts the free electrons in the n-region away from the junction.

→ No charge carrier is able to cross the junction.

→ As electrons and holes both move away from the junction, the depletion region widens. Hence the resultant potential barrior is increased which prevents the flow of majority carriers in both directions.

→ therefore, theoretically no current should flow in the external circuit. But in practice, a very small current of the order of a few micro Amperes flows under reverse biased condition.

→ Electrons forming covalent bonds of the semiconductor atoms in the P and N type regions may absorb sufficient energy from heat and light to cause breaking of some covalent bonds. Hence electron-hole pairs are continually produced in both the regions.

→ under the reverse bias condition, the thermally generated holes in the P-region are attracted towards the negative terminal of the battery and the electrons in the N-region are attracted towards the positive terminal of the battery

→ consequently the minority carriers ie. electrons in the P-region, and holes in the n-region, wander over to the junction and flow towards their majority carrier side, giving rise to a small reverse current. this current is known as reverse saturation current I_0.

→ the Magnitude of reverse saturation current mainly depends upon junction temperature. because the Major source of minority carriers is thermally broken co-valent bonds.

→ As Already majority free Electrons from N-side are flowing towards ~~negative~~ positive terminal of battery, the newly Liberated electrons will also join with these majority electrons. thus a large number of free electrons are formed which is commonly called as an avalanche of free electrons. This leads to the breakdown of the junction leading to very large reverse current. The reverse voltage at which the junction break down occurs is known as Avalanche break down.

current components in a PN Diode :-

→ The minority carrier current due to electrons in P-side is denoted as I_{np}

→ similarly the minority carrier current due to holes in n-side is denoted as I_{pn}

→ If distance measured from the

Law of Junction :

→ If the hole concentrations at the edges of the depletion region are P_p and P_n in the P and N materials respectively, and if the barrior potential across this depletion layer is V_B then

$$P_p = P_n e^{V_B/V_T} \longrightarrow (1)$$

This is boltzman relation of kinetic gas theory.

→ For an open circuited pn junction

$P_p = P_{po}$, $P_n = P_{no}$, $V_B = V_0$ (V_0 is contact potential)

substituting the above values in eq (1) we get

$$P_{po} = P_{no}\, e^{V_0/V_T} \longrightarrow (2)$$

→ consider a forward biased junction with an applied Voltage V, then the barrior voltage V_B is decreased from its equilibrium value V_0 by the amount V (or) $V_B = V_0 - V$.

The hole concentration through out the P-region is constant and equal to thermal equilibrium value or $P_p = P_{p0}$.

the hole concentration varies with distance in to the n-side. At the edge of depletion layer, the distance from the junction $x = 0$

$$\therefore \quad P_n = P_n(0)$$

For this case boltzman relation is

$$P_{p0} = P_n(0)\, e^{(V_0 - V)/V_T} \longrightarrow (3)$$

combining eq (2) and eq (3) we get

$$P_{n0}\, e^{V_0/V_T} = P_n(0)\, e^{V_0 - V/V_T}$$

V_T = Volt equivalent of temperature

$$\Rightarrow \boxed{P_n(0) = P_{n0}\, e^{V/V_T}} \longrightarrow (4)$$

This boundary condition is called the Law of junction.

Similarly for electrons concentration on P-side

$$\boxed{n_p(0) = n_{p0}\, e^{V/V_T}} \longrightarrow (5)$$

The above equation (4) indicates that the hole concentration $P_n(0)$ at the junction under forward biased condition is greater than its thermal equilibrium value P_{n0}.

Diode current Equation :-

From the law of junction, we have

$$P_n(0) = P_{no}\, e^{V/V_T} \longrightarrow (1)$$

where

$P_n(0)$ = hole concentration at the edge of the depletion region in n-type material under forward biased condition

P_{no} = hole concentration at the edge of the depletion region in n-type material under open circuited condition.

V = applied voltage

V_T = volt equivalent of temperature.

The difference between two concentrations at the junction under biased and unbiased condition is called injected or excess concentration denoted as $P_n(0)$

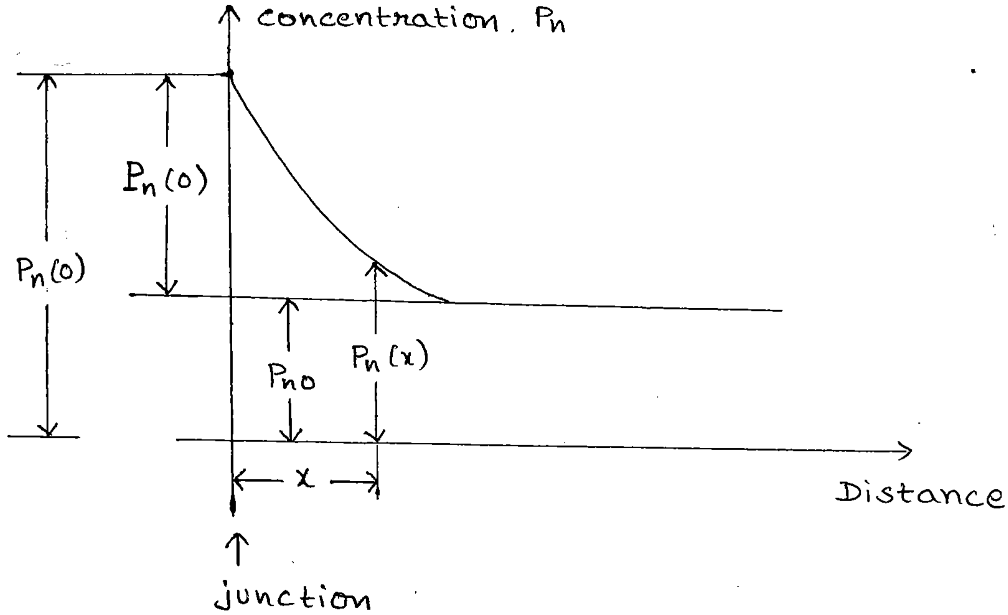
$$\therefore\ P_n(0') = P_n(0) - P_{no} \longrightarrow (2)$$

using eq (1) in eq (2)

$$P_n(0) = P_{no}\, e^{V/V_T} - P_{no}$$

$$\therefore\ P_n(0) = P_{no}\left(e^{V/V_T} - 1\right) \longrightarrow (3)$$

similarly $$N_p(0) = n_{po}\left(e^{V/V_T} - 1\right) \longrightarrow (4)$$



The hole current crossing the junction from p-side to n-side is given by

$$I_{pn}(0) = \frac{A q D_p P_n(0)}{L_p} \longrightarrow (5)$$

Similarly the electron current crossing the junction from n-side to p-side is given by

$$I_{np}(0) = \frac{A q D_n N_p(0)}{L_n} \longrightarrow (6)$$

where A = area of cross section of junction

D_p = Diffusion constant for holes

D_n = Diffusion constant for electrons

L_p = Diffusion Length for holes

L_n = Diffusion Length for electrons.

using (3) and (4) equations in eq's (5) and (6) the total current I at the junction is given by

$$I = I_{pn}(0) + I_{np}(0) = \left(\frac{A q D_p P_n(0)}{L_p} + \frac{A q D_n N_p(0)}{L_n} \right)$$

$$I = \left[\frac{A q D_p P_{no}}{L_p} + \frac{A q D_n n_{po}}{L_n} \right] \left(e^{V/V_T} - 1 \right)$$

$$\Rightarrow \quad I = I_o \left(e^{V/V_T} - 1 \right) \longrightarrow (7)$$

where $I_o = \left(\frac{A q D_p P_{no}}{L_p} + \frac{A q D_n n_{po}}{L_n} \right)$ = Reverse Saturation Current.

the equation (7) is the required expression for diode current. this equation is derived without considering the carrier generation and recombination in the depletion region.

If we consider the generation and recombination of carriers in the depletion region, the general equation of the diode current is approximately given by

$$I = I_o \left[e^{V/\eta V_T} - 1 \right] \longrightarrow (8)$$

where I = diode current

I_o = diode reverse saturation current at room temp

V = External voltage applied to the diode.

η = a constant [1 for Ge and 2 for Si]

$V_T = \frac{KT}{q} = \frac{T}{11600}$, volt equivalent of temp ie thermal voltage

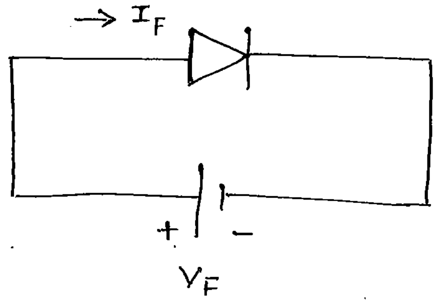
where K = Boltzman's constant (1.38×10^{-23} J/K) q = charge of the electron = 1.602×10^{-19} C

T = temperature of the diode junction (°K)

Volt - Ampere characteristics of a diode :-

(V-I characteristics)

(1) V-I characteristics in Forward bias condition:



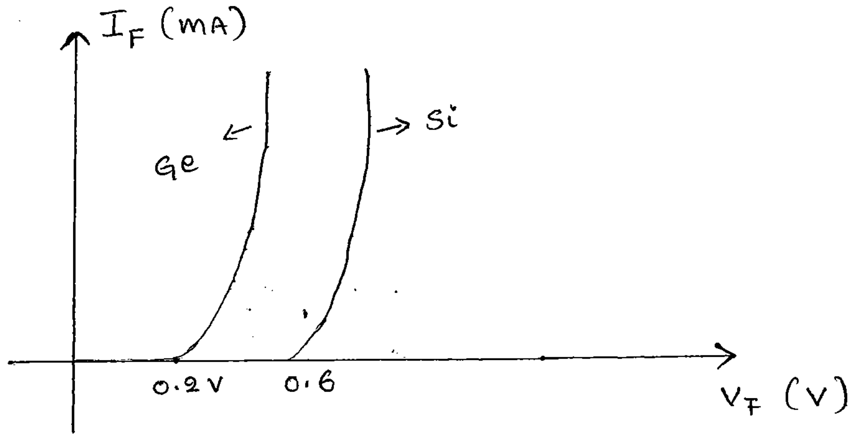
→ when a forward bias voltage V_F is applied to a PN junction diode, below the cut-in voltage V_γ, the diode will not conduct and the current flowing is very small. practically this current is assumed to be zero

→ The diodes will have a cut-in voltage or threshold voltage V_γ, below which current is very small, Beyond V_γ, the current rises very rapidly

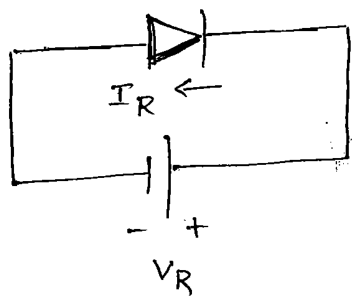
→ V_γ is approximately 0.2 V for Ge and 0.6 V for Si

→ As the forward biased voltage V_F is greater than the cut-in voltage V_γ, the potential barrior across the junction is completely eliminated and the current rises very rapidly.

→ The V-I characteristics under forward biased condition is shown in figure below.



(2) <u>V-I characteristics in Reverse biased condition:-</u>



When a PN junction diode is reverse biased, the negative terminal attracts the holes in the P-region away from the junction. The positive terminal attracts the free electrons in n-region away from the junction. No charge carrier is able to cross the junction.

As electrons and holes both move away from the junction, the depletion region widens.

As depletion region widens, barrior potential across the junction also increases. The polarities of barrier potential are same as that of the applied voltage.

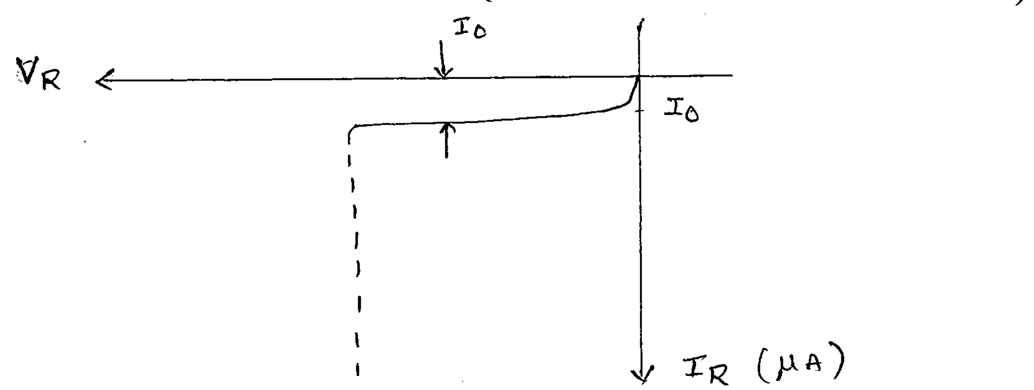
However a small reverse current called reverse saturation current I_0 flows across the junction due to the movement of minority charge carriers across the junction.

Reverse saturation current is very small of the order of few microamperes for Ge and few nanoamperes for Si Pn junction diode.

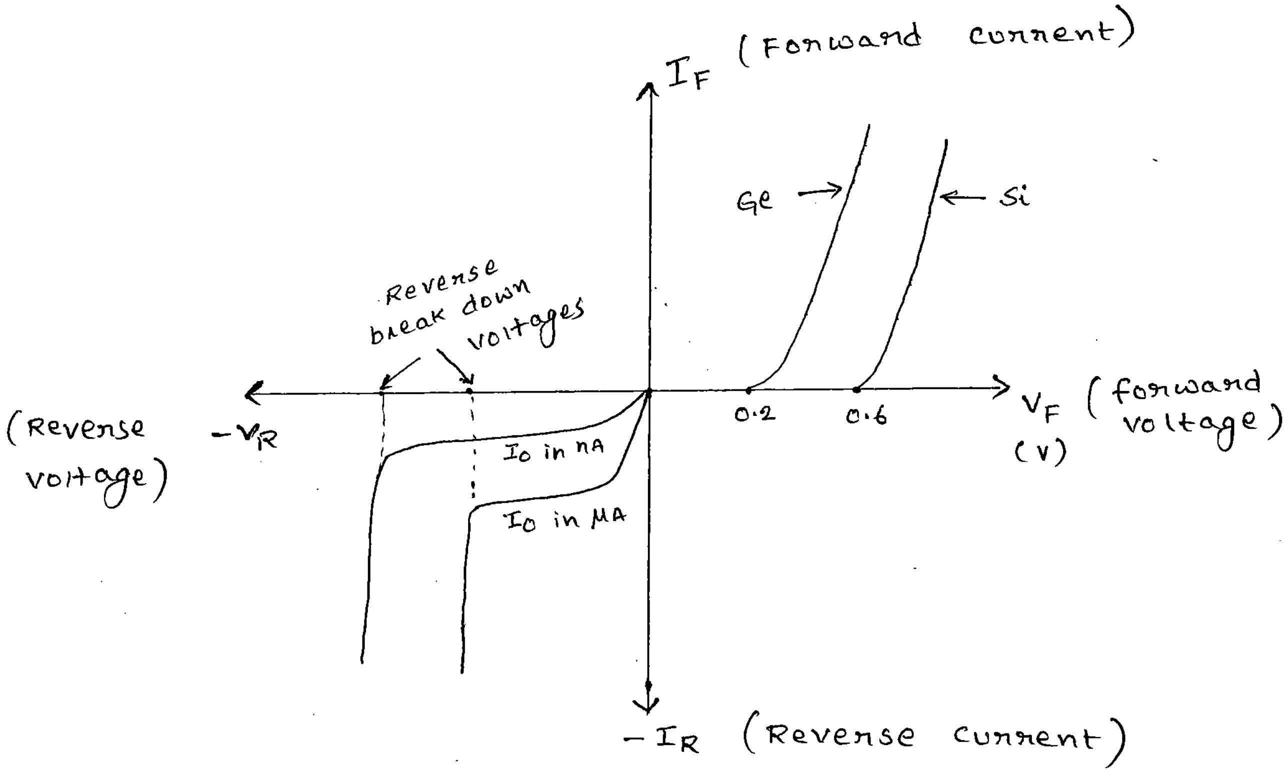
The generation of minority charge carriers depends on the temperature and not on the applied reverse bias voltage.

If the reverse bias voltage is increased beyond certain limit the junction breaks down and a very large reverse current flows.

The V-I characteristics under reverse biased condition for a Pn junction diode is shown in figure below.



The complete VI characteristics of a PN diode (Forward bias and Reverse bias) for both Ge and Si are shown in figure below.



Temperature dependence of V-I characteristics :-

The rise in temperature increases the generation of electron-hole pairs in semiconductors and increases their conductivity. As a result the current through the PN junction diode increases with temperature as given by the diode current equation.

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

The reverse saturation current I_0 of diode increases approximately 7 percent / °C for both Ge and Si.

Reverse saturation current approximately doubles for every 10°c rise in temperature. Hence if the temperature is increased at fixed voltage, the current I increases.

To bring the current I to its original value, the voltage V has to be reduced. It is found that at room temperature for either Germanium or silicon $\frac{dV}{dT} \approx -2.5\, mV/^\circ c$ in order to maintain the current I to a constant value.

At room temperature ie at 300°K, the value of barrior voltage or cut in voltage is about 0.3 V for Ge and 0.7V for Si. The barrior voltage is temperature dependent and it decreases by 2 mV/°c for both Ge and Si.

This fact may be expressed in mathematical form which is given by

$$I_{02} = I_{01} \times 2^{(T_2 - T_1)/10}$$

where I_{01} = Saturation current of the diode at temperature T_1

I_{02} = Saturation current of the diode at temperature T_2

Figure shows the effect of increased temperature on the characteristic curve of a a PN junction diode.

A Ge diode can be used upto a maximum of 75°c and a Si diode to a maximum of 175°c

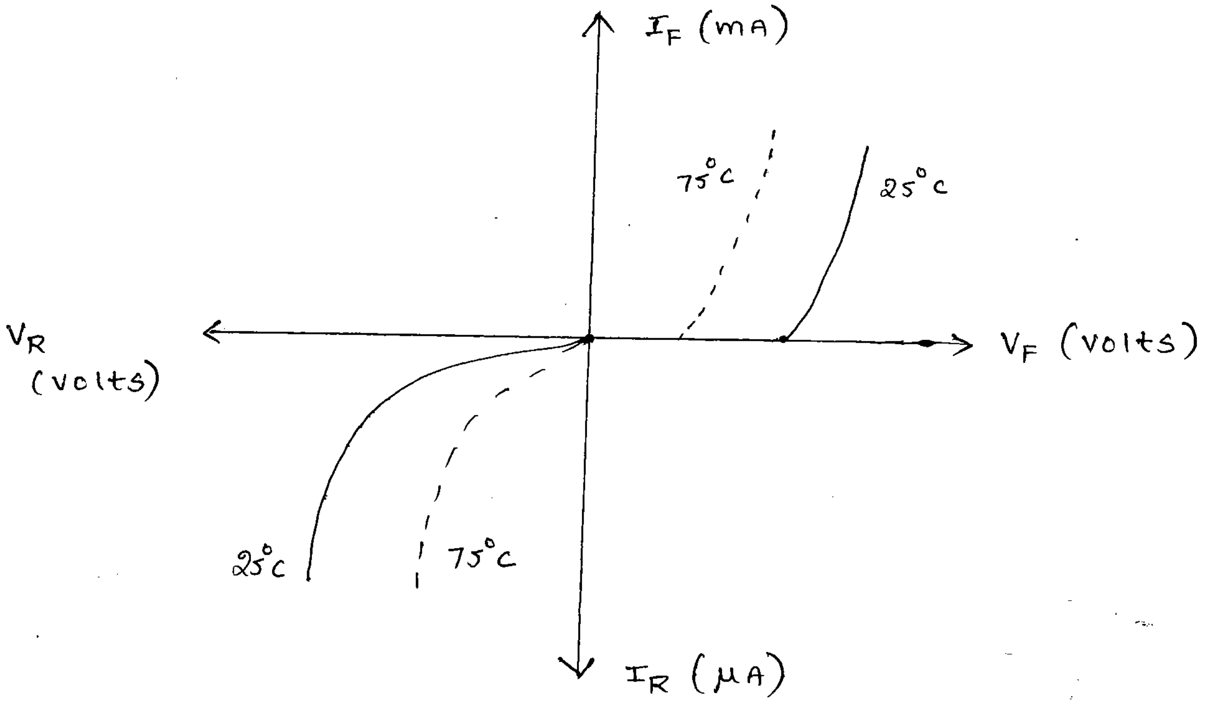


fig: Effect of temperature on the diode characteristics

Problem:

A silicon diode has a saturation current of 7.5 μA at temperature 300°K. calculate the saturation current at 400°K.

Solution: Given $I_{01} = 7.5 \times 10^{-6}$ A at $T_1 = 300°K$.

so $T_1 = 27°c$ $(300°K - 273°K)$

$T_2 = 400°K = 127°c$

Therefore the saturation current at 400°K is

$$I_{02} = I_{01} \times 2^{(T_2 - T_1)/10}$$

$$I_{02} = 7.5 \times 10^{-6} \times 2^{(127 - 27)/10}$$

$$I_{02} = 7.68 \text{ mA}$$

Problem :

A Silicon diode has a reverse saturation current of 7.12 nA at room temperature of 27°c. calculate its forward current if it is forward biased with a voltage of 0.7 V

Solution : Given data

$I_0 = 7.12 \times 10^{-9}$ A , $V = 0.7$ V

$T = 27^\circ c = 300^\circ K$, $\eta = 2$ for Si

$$V_T = \frac{KT}{q} = \frac{T}{11600} = \frac{300}{11600} \simeq 26 \text{ mV}$$

According to diode current equation

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

$$I = 7.12 \times 10^{-9} \left(e^{0.7/(2 \times 0.026)} - 1 \right)$$

$$I \simeq 5 \text{ mA}.$$

PROBLEM :

A Ge diode has a saturation current of 1 nA at 20°c. Find its current when it is forward biased by 0.4 V. Find the current in the same diode when the temperature rises to 110°c.

Solution : Given data

For Ge diode $\eta = 1$

$I_{01} = 1$ nA $= 10^{-9}$ A

$T_1 = 20^\circ C = 20 + 273 = 293^\circ K$

$$V_T = \frac{T_1}{11600} = \frac{293}{11600} = 0.0252 \text{ V}$$

$V = 0.4\,V \quad , \quad I = ?$

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

$$I = 10^{-9} \left(e^{0.4/(1 \times 0.0252)} - 1 \right)$$

$$I = 4.8\ mA.$$

If $T_2 = 110^\circ c$ then $I = ?$

$$I_{02} = \left[2^{(T_2 - T_1)/10} \right] I_{01}$$

$$I_{02} = 2^9 \times 10^{-9} = 512 \times 10^{-9}\ A.$$

At $T_2 = 110^\circ c = 110 + 273 = 383^\circ K$

$$V_T = \frac{383}{11600} = 0.033\,V$$

$$I = I_{02} \left(e^{V/\eta V_T} - 1 \right)$$

$$I = 512 \times 10^{-9} \left(e^{0.4/(1 \times 0.033)} - 1 \right)$$

$$I =$$

<u>Problem:</u>

The diode current is 0.6 mA, when the applied voltage is 400 mv and 20 mA when the applied voltage is 500 mv. Determine η. Assume $\frac{KT}{q} = 25\,mV$

<u>Solution:</u> The diode current $I = I_0 \left(e^{V/\eta V_T} - 1 \right)$

$$0.6 \times 10^{-3} = I_0 \left(e^{\frac{400}{25\eta}} \right)$$

($\because$ neglecting 1)

Similarly $20 \times 10^{-3} = I_o \left(e^{\frac{500}{25\eta}} \right)$

After simplifying $\eta = 1.14$.

Diode Resistance :-

(1) **Forward resistance of a diode :**

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

(i) Static or DC forward resistance (R_F)

(ii) Dynamic or AC forward resistance (r_f)

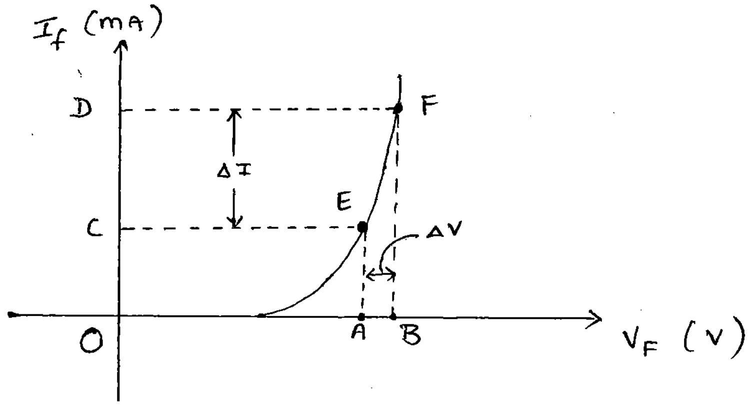


Fig : Forward characteristics of a diode.

(i) **Static or DC forward resistance :-**

The static or DC forward resistance R_F is defined as the ratio of the DC voltage applied across the PN junction to the DC current flowing through the PN junction.

$$R_F = \frac{\text{Forward dc voltage}}{\text{Forward dc current}} = \frac{OA}{OC} \text{ at point E}$$

ii) Dynamic or AC forward resistance :-

The resistance offered by the Pn junction under AC conditions is called dynamic or ac forward resistance and is denoted by r_f

→ The dynamic resistance is defined as the reciprocal of the slope of the V-I characteristics.

$$\text{ie} \quad r_f = \frac{dV}{dI}$$

The dynamic resistance is not a constant but depends upon the operating voltage.

From the diode current equation, we have

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

Differentiating the above equation w.r.t V, we get

$$\Rightarrow \frac{dI}{dV} = I_0 \left(e^{V/\eta V_T} \cdot \frac{1}{\eta V_T} - 0 \right)$$

$$\Rightarrow \frac{dI}{dV} = \frac{I_0 \, e^{V/\eta V_T}}{\eta V_T}$$

$$\Rightarrow \frac{dI}{dV} = \frac{I_0 + I}{\eta V_T}$$

For a forward bias, $I >> I_0$ and r_f is given approximately by

$$r_f = \frac{dV}{dI} \simeq \frac{\eta V_T}{I}$$

$$\therefore \boxed{r_f = \frac{\eta V_T}{I}}$$

→ The dynamic resistance varies inversely with current.

→ At room temperature and for $\eta = 1$

$$r_f = \frac{1 \times 26 mV}{I}$$, where I is in mA. then

r_f will be in ohms (Ω)

For a forward current of 26 mA, the dynamic resistance is 1Ω.

From the above figure

$$r_f = \frac{\Delta V}{\Delta I} = \frac{1}{\Delta I/\Delta V} = \frac{1}{\text{slope of forward characteristics}}$$

→ Generally the value of r_f is very small of the order of few ohms in the operating region.

(2) <u>Reverse Resistance of a diode</u> :-

→ The resistance offered by the diode in reverse biased condition is called "<u>Reverse resistance</u>"

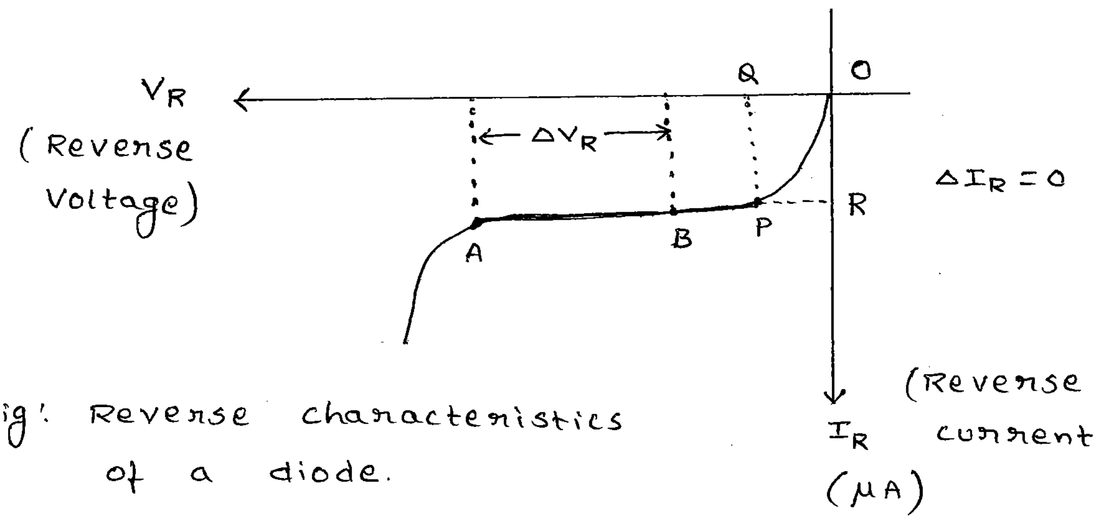


fig: Reverse characteristics of a diode.

The reverse resistance is defined in two ways

(i) static or DC reverse resistance (R_R)

(ii) dynamic or AC reverse resistance (r_r)

(i) Static reverse resistance (R_R) :-

The static reverse resistance R_R is defined as the ratio of applied reverse DC voltage to the reverse saturation current (I_o) flowing through the PN junction.

$$R_R = \frac{\text{Applied Reverse DC voltage}}{\text{Reverse Saturation current}} = \frac{OQ}{OR}$$

(at point P)

(ii) Dynamic reverse resistance (r_r) :

The reverse dynamic resistance r_r is defined as the ratio of incremental change in the reverse voltage applied to the corresponding change in the reverse current.

$$r_r = \frac{\Delta V_R}{\Delta I_R} = \frac{\text{change in reverse voltage}}{\text{change in reverse Current}}$$

Problem :

A PN junction diode has a reverse saturation current of 30 μA at a temperature of 125°c. At the same temperature find the dynamic resistance for 0.2 V bias in forward and reverse direction.

Solution : Given data

$$I_0 = 30\,\mu A = 30 \times 10^{-6} A$$

$$T = 125^\circ c = 125 + 273 = 398^\circ K$$

$$V = 0.2\ V$$

For Ge, $\eta = 1$, $V_T = \frac{T}{11600} = \frac{398}{11600} = 0.0343\,V$

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

neglecting '1' we get

$$I = I_0 \, e^{V/\eta V_T}$$

differentiating w.r.t voltage (V)

$$\frac{dI}{dV} = \frac{I_0 \, e^{V/\eta V_T}}{\eta V_T}$$

$$\frac{dI}{dV} = \frac{I_0}{V_T} e^{V/V_T} \quad [\because \eta = 1]$$

$$\frac{1}{r_f} = \frac{dI}{dV} = \frac{I_0}{V_T} e^{V/V_T} \quad [\text{sub all the values}]$$

we get $\therefore r_f = 3.36 \, \Omega$

lly $\frac{1}{r_r} = \frac{dI}{dV} = \frac{I_0}{V_T} e^{-V/V_T}$

$\therefore r_r =$

Problem:

calculate the dynamic forward and reverse resistance of PN junction silicon diode when the applied voltage is 0.25 V at $T = 300^\circ K$ with given $I_0 = 2 \mu A$.

Solution: Given data

$I_0 = 2 \mu A$

$V = 0.25 \, V$

For Si, $\eta = 2$

At $T = 300^\circ K$

$V_T = 26 \, mV$

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

Neglecting '1' we get $I = I_0 \, e^{V/\eta V_T}$

$$\frac{dI}{dV} = \frac{I_0}{\eta V_T} e^{V/\eta V_T}$$

Forward resistance $r_f = \frac{dV}{dI} = \frac{\eta V_T}{I_0} e^{V/\eta V_T}$

$$r_f = \frac{2 \times 26 \times 10^{-3}}{2 \times 10^{-6}} e^{0.25/(2 \times 26 \times 10^{-3})}$$

$$r_f = 212.3 \, \Omega$$

For reverse resistance r_r use $V = -0.25 V$

$$r_r = \frac{\eta V_T}{I_0} e^{-V/\eta V_T}$$ (After substituting all values)

$$r_r = 3.18 \, M\Omega$$

Problem:

The voltage across a silicon diode at room temp of $300^\circ K$ is 0.7V, when 2mA current flows through it. If the voltage increases to 0.75V, calculate the diode current assuming $V_T = 26 \, mV$.

Solution: Given data $V = 0.7 V$, $\eta = 2$ for Si,

$V_T = 26 \, mV$, $I = 2 mA$.

Now $I = I_0 \left(e^{V/\eta V_T} - 1 \right)$ After substituting all values

we get $I_0 = 2.84 \times 10^{-9}$ A.

Now New voltage $V' = 0.75 V$

$\therefore I' = I_0 \left(e^{V'/\eta V_T} - 1 \right) \Rightarrow I' = 5.23 \, mA$ [After substituting all values]

Ideal versus practical diode :

Ideal diode :

1) The cut-in voltage is zero. Since for an ideal diode there is no barrior potential, thus any small forward bias voltage causes conduction through the device

2) The forward resistance is zero

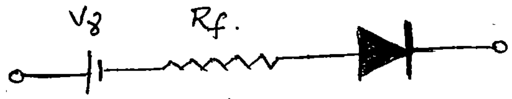
3) The reverse resistance is infinite

4) The diode readily conducts when forward biased and it blocks conduction when reverse biased.

5) The reverse saturation current I_0 is zero

6) The ideal diode acts as a fast acting electronic switch.

Practical Diode :-



1) There is a potential barrior across the junction, and this must be overcome before the diode can conduct.

2) The cut-in voltage or threshold voltage is approximately 0.2 V for Ge and 0.6 V for Si.

3) The forward resistance is in the range of few tens of ohms.

4) The reverse resistance is in the range of Mega ohms.

5) In forward bias condition, when the bias voltage is more than the cut-in voltage, the diode conducts.

6) The diode doesn't conduct when reverse biased. However a small reverse saturation current flows across the junction in the range of nano Amps for Si diode and micro Amps for Ge diode.

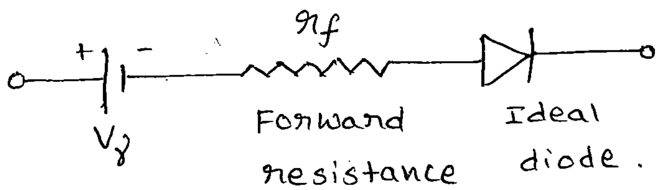
7) The diode also acts as a fast acting Electronic Switch.

<u>Diode Equivalent circuits</u> :-

An equivalent circuit is a combination of elements properly chosen to best represent the actual terminal characteristics of a device in a particular operating region.

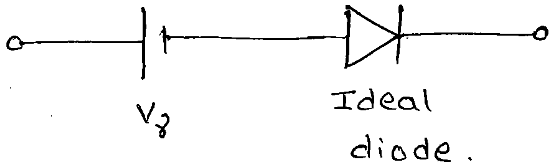
→ A diode is replaced by a model with a battery equivalent to cut-in voltage of a diode, the forward resistance of a diode in series with an ideal diode.

→ the piece wise Linear equivalent circuit of a diode is shown in figure below.



Assuming $r_f = 0$, since for most applications, it is small to be ignored compared with resistance of other elements of the network.

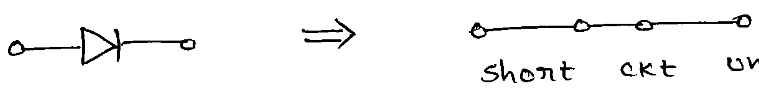
→ Therefore the simplified equivalent circuit is as shown in figure below.



→ Asuming $V_\gamma = 0$ and $r_f = 0$, the equivalent circuit becomes the circuit model for an ideal diode.

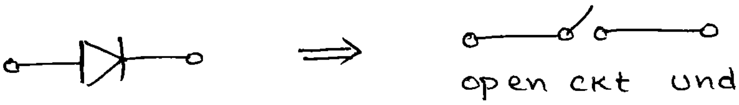
Ideal diode

→ In forward biased condition the ideal diode acts as short circuit



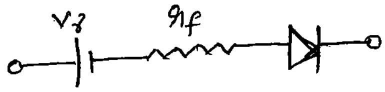
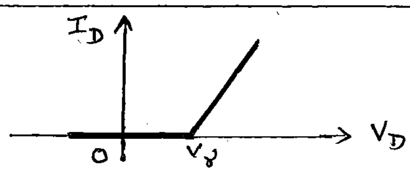
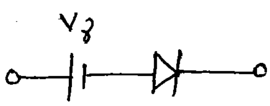
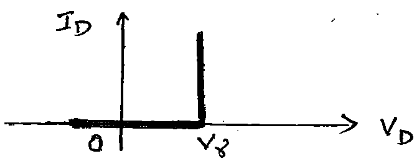
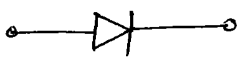
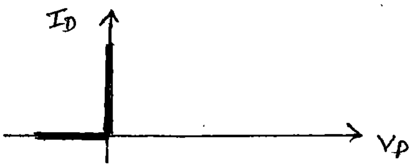
short ckt under forward bias

→ In Reverse bias condition the ideal diode acts as open ckt.



open ckt under Reverse bias.

Diode Equivalent circuits / models / V-I characteristics :-

S.NO	Type	Model	characteristics
1.	Piece wise Linear model	 $V_\gamma \neq 0$, $r_f \neq 0$, $r_r = \infty$	
2.	Simplified Model	 $V_\gamma \neq 0$, $r_f = 0$, $r_r = \infty$	
3.	Ideal Model	 $V_\gamma = 0$, $r_f = 0$, $r_r = \infty$	

Breakdown Mechanisms in a Diode :-

→ When the diode is reverse biased, for a small reverse voltage, then the diode current is small and almost constant at I_0

→ But when reverse voltage increases beyond certain value, large diode current flows, this is called breakdown of diode and corresponding voltage is called reverse breakdown voltage of diode.

→ There are two distinct mechanisms due to which the breakdown may occur in the diode, these are

1. Avalanche break down
2. Zener breakdown.

1) Avalanche break down :-

→ The avalanche break down occurs in Lightly doped diodes

→ As the applied reverse biased voltage is increased, the velocity and hence the kinematic energy ($K.E = \frac{1}{2} mv^2$) of thermally generated charge carriers increases.

→ If such charge carriers colloide against an electron involved in covalent bond and creates new charge carriers.

→ These secondary particles are also accelerated and participate in collisions that generates new electron - hole pairs. This phenomenon is known as Avalanche multiplication.

→ The multiplication factor due to avalanche effect is given by

$$M = \frac{1}{1 - \left(\frac{V}{V_{BD}}\right)^n}$$

where M = carrier multiplication factor

n = empirical constant, which depends on the lattice material and carrier type

for n-type silicon $n = 4$

for p-type silicon $n = 2$

V = applied reverse voltage

V_{BD} = Reverse break down voltage.

→ Due to this avalanche effect, the junction is said to be in break down and the current starts increasing rapidly.

→ The diodes having reverse break down voltage greater than 6V shows the avalanche Mechanism of break down.

(2) <u>Zener break down</u> :-

→ The Zener break down occurs in heavily doped diodes

→ For heavily doped diodes, the depletion region width is small.

→ under reverse bias conditions, the electric field across the depletion layer is very intense. Breaking of covalent bonds due to intense electric field across the narrow depletion region and generating large number of electrons is called 'Zener Effect'.

→ These generated electrons constitute a very large current and the mechanism is called zener breakdown.

→ The diodes having reverse break down voltage less than 5V shows the zener mechanism of breakdown.

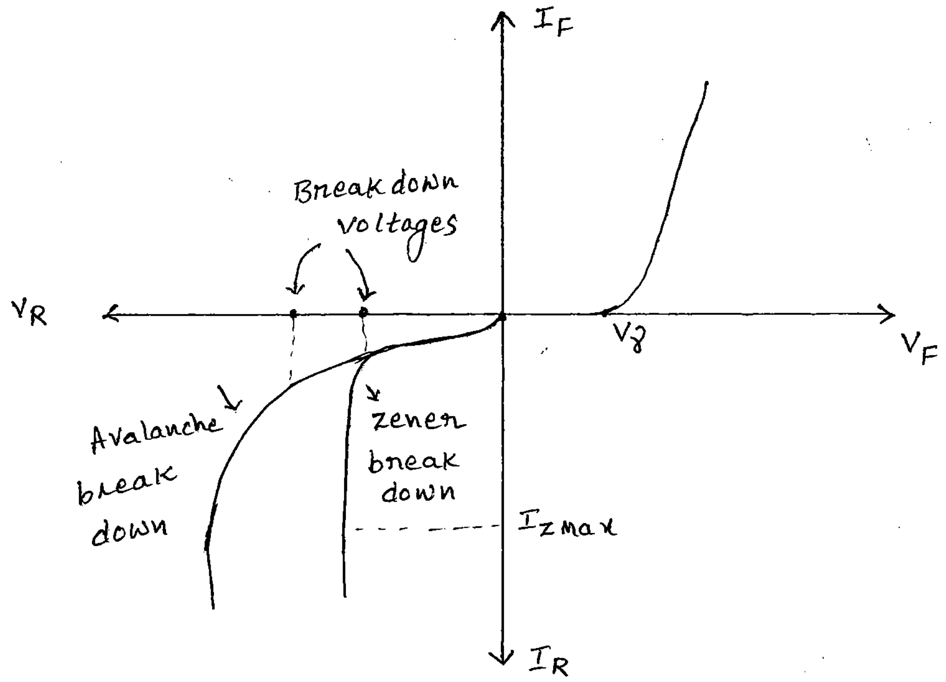


Figure : Showing zener and Avalanche breakdowns

Temperature dependence of Break down Voltages :

In heavily doped diodes, the depletion region width is very small. The applied voltage produces an electric field which is very intense. In such a case, if temperature increases, valence electrons acquire high energy levels and it is easy for the applied voltage to pull such electrons from covalent bonds to make them free. Thus for small voltage, at higher temperature break down occurs.

→ Thus the break down voltage decreases as the temperature increases for zener break down. The zener breakdown has "negative temperature co-efficient"

→ In lightly doped diodes, the width of the depletion layer is large and field intensity is low. The breakdown possibility is because of avalanche effect.

→ In such a case, if temperature increases, the vibrations of atoms in the crystal increases. The intrinsic holes and electrons have less opportunity to impart sufficient energy between the collisions due to vibrations, to start the carrier multiplication. Thus voltage must be increased to cause the breakdown. So at higher temperature, higher break-down voltage is necessary.

→ Thus the break down voltage increases as the temperature increases for avalanche breakdown the avalanche break down has "positive temperature coefficient.

PN diode Applications :-

An ideal PN junction diode is a two terminal Polarity sensitive device that has zero resistance when it is forward biased and infinite resistance when reverse biased. Due to this characteristic the diode finds a number of applications as follows.

1) Rectifiers in dc power supplies
2) Switch in digital logic circuits used in Computers.
3) clamping networks used as dc restorer in TV receivers and voltage multipliers.
4) clipping circuits used as wave shaping circuits used in computers, radars, radio and TV receivers
5) Demodulation (detector) circuits.

→ The same PN junction with different doping Concentration finds special applications as follows

1) Detectors (PIN photo diode) in optical communication circuits.
2) Zener diodes in Voltage Regulators
3) Varactor diodes in tuning sections of radio and TV receivers
4) LED's in digital displays
5) LASER diodes in optical Communication.
6) Tunnel diodes as a relaxation oscillator at Microwave frequencies.

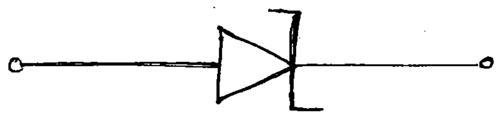
ZENER DIODE :

When the reverse voltage reaches breakdown voltage in normal PN junction diode, the current through the junction and the power dissipated at the junction will be high. Such an operation is destructive and the diode gets damaged.

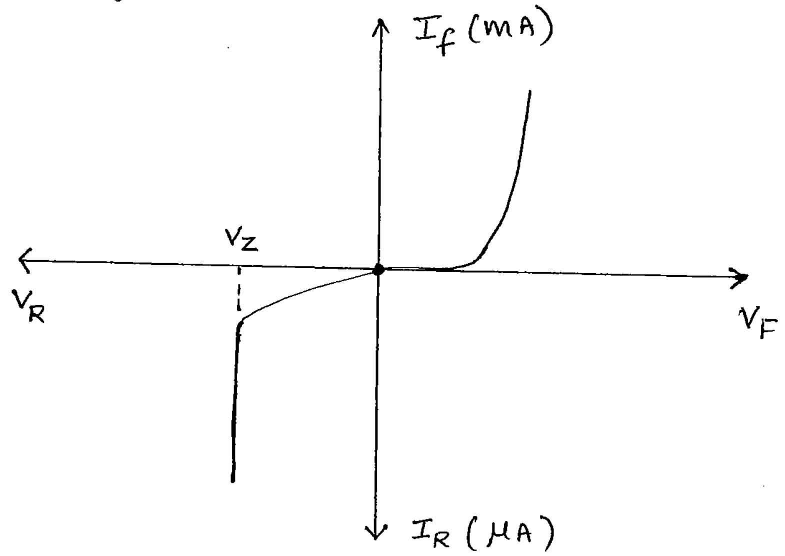
→ Where as diode can be designed with adequate power dissipation capabilities to operate in the breakdown region. One such a diode is known as zener diode.

→ Zener diode is heavily doped than the ordinary diode.

→ Symbol of zener diode is as shown in figure below.



→ The V-I characteristics of a zener diode is shown in figure below



From the VI characteristics of the zener diode shown in above figure, it is found that the operation of Zener diode is same as that of the ordinary PN diode under forward biased condition

→ where as under reverse biased condition, breakdown of the junction occurs. The break down voltage depends upon the amount of doping. If the diode is heavily doped depletion layer will be thin and consequently break-down occurs at lower reverse voltage and ~~further~~ the break down voltage is sharp.

Equivalent circuit of zener diode:

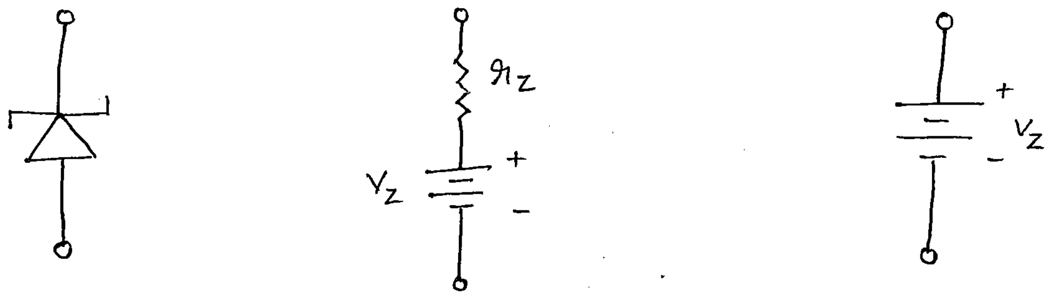


fig (a): zener diode

fig(b): practical Equivalent circuit

fig(c): Ideal Equivalent circuit.

Applications of zener diode :-

The various applications of zener diode are

1) As a voltage regulating element in voltage regulators.

2) In various protecting circuits

3) In Zener limiters ie: clipping circuits which are used to clip off the unwanted portion of the voltage waveform.

Tunnel Diode :

→ The tunnel diode is a thin junction diode, under forward bias condition it exhibits negative resistance. This makes the tunnel diode useful for oscillations or Amplification

→ In conventional, PN Diode is doped to have impurity atoms in the concentration of 1 part in 10^8. Then the width of the depletion layer is of the order of 5micron.

→ But in tunnel diode the impurity concentration is greatly increased to 1 part in 10^3. Then the depletion layer width reduces to 10^{-8} m. Thus device characteristics get completely changed.

→ this diode utilizes the phenomenon called tunnelling and hence the diode is referred as Tunnel diode

→ Tunnel diode is also called 'ESAKI diode'

Tunnelling phenomenon :-

→ The width of the junction barrior varies inversely as the square root of the impurity concentration. That is if the concentration of impurity atom is greatly increased, the barrior width 'W' reduces.

→ A particle must have an energy atleast equal to the height of the potential barrior in order to cross over the junction.

→ However if the barrior is extremely thin, then electron instead of crossing over the junction barrior the electron may penetrate through the barrior. This behaviour exhibited by the electron to the applied potential is called 'tunnelling' and hence the diode is called as 'tunnel diode.'

VI characteristics :-

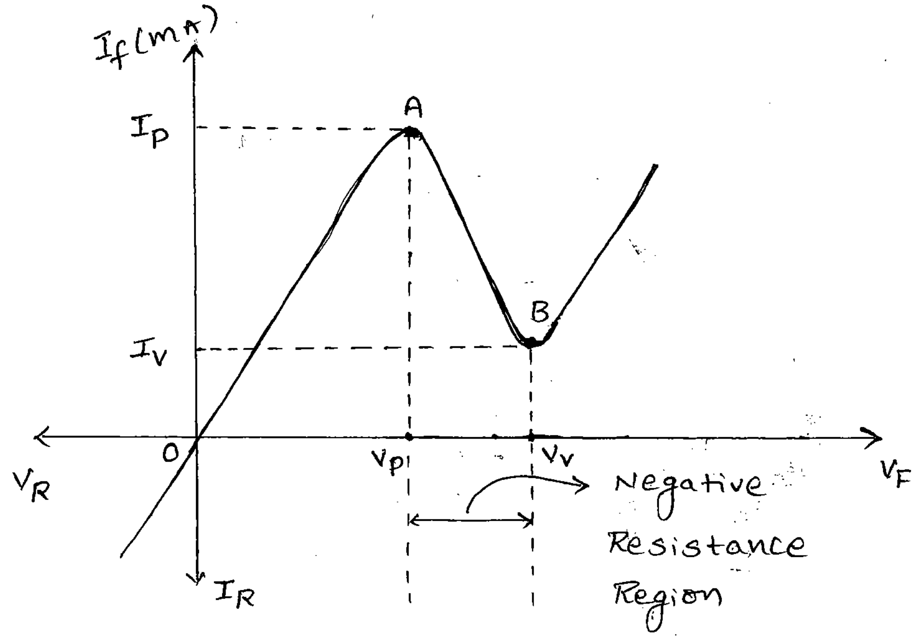


figure :- VI characteristics of Tunnel diode

→ The heavily doped tunnel diode results in a thin depletion layer so as to permit tunnelling to occur.

→ The VI characteristics of a typical germanium tunnel diode is shown in above figure

→ It is seen from the figure, if a small forward bias voltage is applied the current rises

Sharply and reaches the peak current I_p point (A)

→ As the forward bias is increased above this point (A), the forward current drops and continues to drop until a point B is reached. This point is the valley voltage or valley current (I_v)

→ The tunnel diode exhibits negative resistance characteristics seen between the peak current I_p and minimum value I_v (valley current).

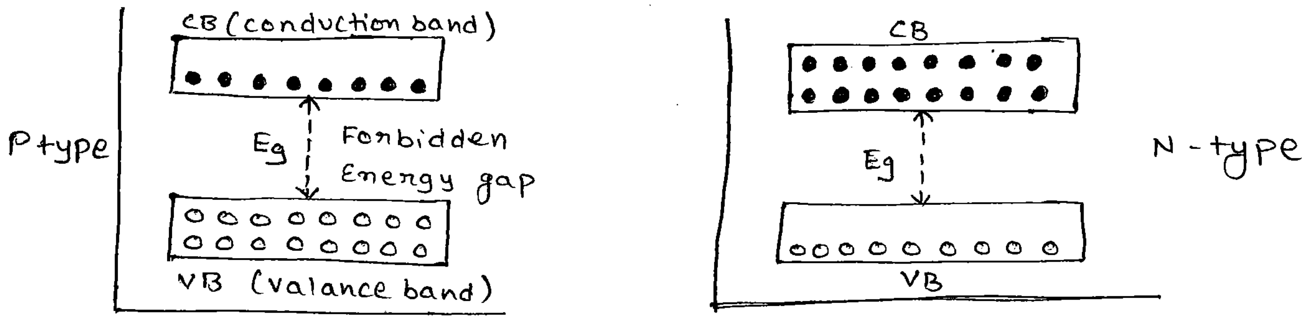
→ The peak current I_p depends on the impurity.

→ After the valley point is reached further increase in input voltage increases the current very rapidly as PN junction diode.

Explanation of VI characteristics on the basis of tunnelling theory or Energy band diagram of Tunnel diode:-

The tunnelling phenomenon is explained in terms of the energy band diagram of the material used.

In P-type material, due to heavy doping there is increased concentration of holes in the valance band



fig(a): Energy band diagram of two types of silicon.

similarly in n-type the concentration of electron is more in conduction band. when P and n type materials are joined together then the energy level diagram is as shown in figure (a).

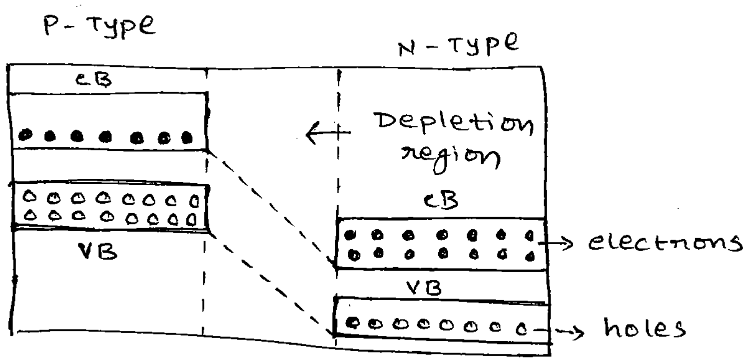


fig (b)

Till no forward bias is applied (shown in figure (b)) there is rough alignment of their respective valance and conduction bands. The energy levels of holes in P region are slightly out of alignment (ie. above) with the energy levels of conduction electrons in N region of the junction. thus no current flows across the junction.

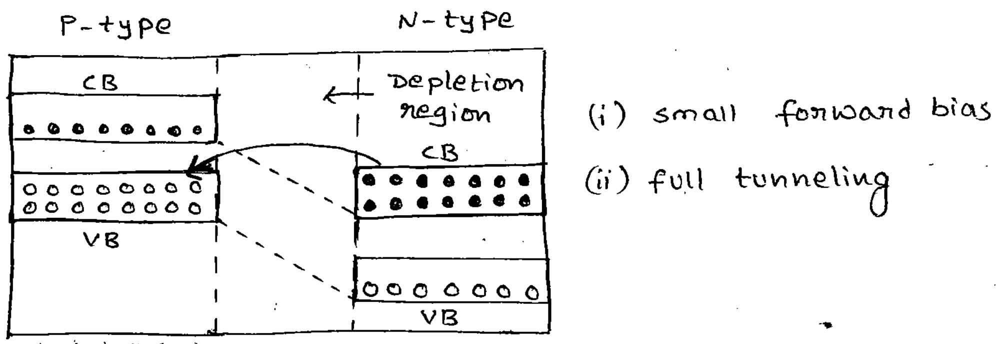
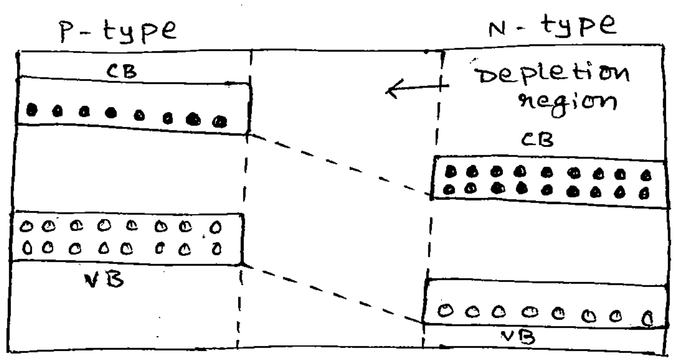


fig (c)

when a small forward voltage (0.1 V) is applied, the energy bands move upward. Due to this motion of energy levels of n-region relative to those of P-region, the electrons in the conduction band on 'n' side just cross the barrior in the valence band of 'P' side because the two are in exact alignment. At this stage electrons tunnels through the depletion region with the velocity of light and gives rise to large current. this tunnelling current reaches a maximum value I_P at a forward bias V_P.



i) bias increased
(ii) tunnelling stopped

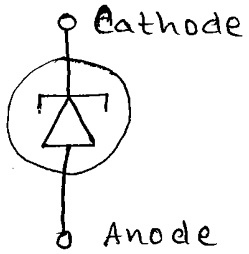
fig(d)

After the peak point if the applied voltage is increased, the current starts decreasing because the energy levels of N region are raised so high thus two bands are out of alignment. In this case tunnelling is stopped as shown in figure(d). The current reaches the minimum value (called valley current) when the two bonds are totally out of alignment at a forward bias V_V (called valley voltage). At a bias voltage V_V, the tunnelling is completely stopped.

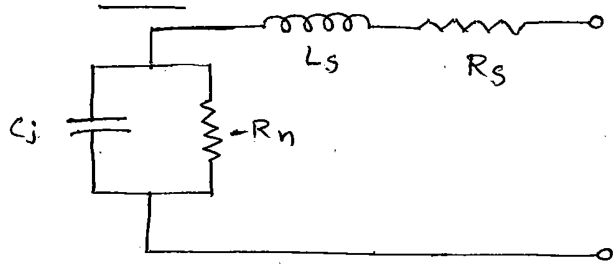
For voltages greater than V_V, the current rises again because of injection currents in an ordinary PN junction diode.

Tunnelling is much faster than a normal crossing. This enables a tunnel diode to switch ON and OFF much faster than an ordinary diode.

Tunnel diode symbol.



Equivalent circuit of tunnel diode



Applications :

1. Tunnel diode is used as an ultra high speed switch with switching speed of the order of ns or ps
2. As logic Memory storage device.
3. As microwave oscillator
4. In relaxation oscillator circuit.
5. As an amplifier.

Advantages :

1. Low noise
2. Ease of operation
3. High speed
4. Low power

Disadvantages :

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

RECTIFIERS AND FILTERS

PN junction as a rectifier

Halfwave Rectifier

Fullwave Rectifier

Bridge Rectifier

Harmonic components in a Rectifier circuits

Inductor filter

Capacitor filter

Zener diode as a Voltage Regulator.

Half wave rectifier converts an a.c voltage in to a pulsating d.c voltage using only one half of the applied a.c voltage. The rectifying diode conducts during one half of the a.c cycle only. fig(a) and fig(b) shows the basic circuit and wave forms of a half wave rectifier

Operation :

Let V_i be the voltage to the primary of the transformer and given by the equation

$$V_i = V_m \sin\omega t \quad ; \quad V_m >> V_\gamma$$

where V_γ is the cut-in voltage of the diode.

→ During the positive half cycle of the input signal, the anode of the diode becomes more positive with respect to the cathode and hence diode D conducts (Forward bias)
For an ideal diode the forward voltage drop is zero. So the whole input voltage will appear across the load resistance (R_L).

→ During negative half cycle of the input signal, the anode of the diode becomes negative with respect to the cathode and hence diode D doesn't conduct. (Reverse bias)
For an ideal diode, the impedance offered by the diode is infinity. Hence the diode conducts no current Hence the voltage drop across R_L is zero.

Harmonic components of a Half wave Rectifier.

The input sinusoidal voltage ~~of~~ applied at the input of the transformer is given by

$$V_i = V_m \sin wt \longrightarrow (1)$$

The diode current or load current is given by

$$i(t) = \begin{cases} I_m \sin wt & \text{for } 0 < wt < \pi \\ 0 & \text{for } \pi < wt < 2\pi \end{cases} \longrightarrow (2)$$

Maximum or peak current through the circuit

$$I_m = \frac{V_m}{R_f + R_L} \longrightarrow (3)$$

where R_f = Forward resistance of the diode

R_L = Load resistance.

i) Average current (or) DC current :-

$$I_{avg} = I_{d.c} = \frac{1}{T} \int_0^T i(t)\, dt$$

$$= \frac{1}{2\pi} \int_0^{2\pi} i(t)\, dt \qquad [\because T = 2\pi]$$

$$\Rightarrow I_{dc} = \frac{1}{2\pi} \left\{ \int_0^{\pi} I_m \sin wt\, d(wt) + \int_{\pi}^{2\pi} 0 \cdot d(wt) \right\}$$

$$I_{dc} = \frac{I_m}{2\pi} \left[-\cos wt \right]_0^{\pi}$$

$$I_{dc} = \frac{I_m}{2\pi} \left\{ -\left[(-1) - 1\right] \right\} = \frac{I_m}{\pi} = \frac{V_m}{\pi (R_f + R_L)}$$

Similarly the DC output voltage or Average voltage is given by

$$V_{d.c} = I_{d.c} \cdot R_L = \frac{I_m}{\pi} R_L = \frac{V_m}{\pi (R_f + R_L)} \cdot R_L$$

$$\therefore \boxed{V_{dc} = \frac{V_m}{\pi\left(1 + \frac{R_f}{R_L}\right)}}$$

② <u>RMS</u> <u>Current</u> :

$$I_{rms} = \sqrt{\frac{1}{T} \int_0^T i^2(t)\, d(\omega t)}$$

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

$$I_{rms} = \sqrt{\frac{1}{2\pi} \int_0^{\pi} I_m^2 \sin^2 \omega t\, d(\omega t) + \int_{\pi}^{2\pi} 0 \cdot d(\omega t)}$$

$$I_{rms} = \sqrt{\frac{I_m^2}{2\pi} \int_0^{\pi} \left(\frac{1 - \cos 2\omega t}{2} \right) d\omega t}$$

$$I_{rms} = \sqrt{\frac{I_m^2}{4\pi} \int_0^{\pi} d(\omega t) - \frac{I_m^2}{4\pi} \int_0^{\pi} \frac{\cancel{\cos 2\omega t}}{2\omega} d(\omega t)} \quad (\to 0)$$

$$I_{rms} = \sqrt{\frac{I_m^2}{4\pi} \times \pi} = \frac{I_m}{2} = \frac{V_m}{2(R_f + R_L)}$$

Similarly RMS voltage across the load is given by

$$V_{rms} = I_{rms} \cdot R_L = \frac{I_m}{2} R_L = \frac{V_m}{2(R_f + R_L)} \cdot R_L$$

$$\boxed{V_{rms} = \frac{V_m}{2\left(1 + \frac{R_f}{R_L}\right)}} \Rightarrow \text{If } R_f << R_L \text{ then } \boxed{V_{rms} = \frac{V_m}{2}}$$

(3) Rectifier efficiency (η)

Rectifier efficiency is defined as ratio of dc output power (P_{dc}) to A.c input power (P_{ac}).

Here $P_{dc} = I_{d.c}^2 R_L = \frac{I_m^2 R_L}{\pi^2}$

$$P_{ac} = P_d + P_L$$

P_d = Power dissipated across diode

P_L = power dissipated across load

$$P_d = I_{rms}^2 R_f = \frac{I_m^2}{4} R_f$$

$$P_L = I_{rms}^2 R_L = \frac{I_m^2}{4} R_L$$

$$\therefore \quad P_{ac} = \frac{I_m^2}{4}(R_f + R_L)$$

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

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

$$\% \eta = \frac{0.406}{1 + \frac{R_f}{R_L}} \times 100 = \frac{40.6}{1 + \frac{R_f}{R_L}}$$

If $R_f << R_L$ then $\% \eta = 40.6 \%$

The maximum efficiency of a half wave rectifier is 40.6 %

4) Ripple factor (Γ) :-

The ratio of rms value of a.c component to the dc component in the output is known as ripple factor (Γ).

$$\text{Ripple factor} = \frac{\text{rms value of a.c component}}{\text{d.c value of component}}$$

$$\Gamma = \frac{V_{r,rms}}{V_{dc}}$$

$$V_{r,rms} = \sqrt{V_{rms}^2 - V_{dc}^2}$$

$$\therefore \Gamma = \frac{\sqrt{V_{rms}^2 - V_{dc}^2}}{V_{dc}} = \sqrt{\frac{V_{rms}^2 - V_{dc}^2}{V_{dc}^2}}$$

$$\Gamma = \sqrt{\left(\frac{V_{rms}}{V_{dc}}\right)^2 - 1}$$

$$\Gamma = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$$

$$\Gamma = \sqrt{\frac{\left(\frac{I_m}{2}\right)^2}{\left(\frac{I_m}{\pi}\right)^2} - 1} = \sqrt{\left(\frac{\pi}{2}\right)^2 - 1} = 1.21$$

5) Transformer utilisation factor :-

In the design of any power supply, the rating of the transformer should be determined. This can be done with a knowledge of the d.c power delivered to the load and the type of rectifying circuit used

$$TUF = \frac{\text{dc power delivered to the load}}{\text{ac rating of the transformer secondary}}$$

$$TUF = \frac{P_{dc}}{P_{ac\ rated}}$$

$$P_{dc} = I_{dc}^2 R_L \Rightarrow \left(\frac{I_m}{\pi}\right)^2 \times R_L .$$

$$P_{ac\ rated} = \text{rated voltage of transformer secondary} \times I_{rms}$$

$$P_{ac\ rated} = \frac{V_m}{\sqrt{2}} \times \frac{I_m}{2} = \frac{I_m^2 (R_f + R_L)}{2\sqrt{2}}$$

$$\therefore \quad TUF = \frac{\frac{I_m^2}{\pi^2} \times R_L}{\frac{I_m^2}{2\sqrt{2}} (R_f + R_L)} = \frac{0.287\ R_L}{(R_f + R_L)}$$

$$\therefore \quad TUF = \frac{0.287}{\left(1 + \frac{R_f}{R_L}\right)}$$

As $R_f << R_L$, $TUF = 0.287$.

⑥ **Regulation :-**

It is defined as the variation in dc voltage with change in dc load current.

It is also defined as

$$\text{Percentage Regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100$$

Here V_{NL} = No load voltage

V_{FL} = Full load Voltage.

Ideally Full load voltage is equal to No load voltage and hence the percentage regulation of an ideal device is zero.

(7) ~~It is defined as the~~ Peak inverse voltage (PIV):-

It is defined as a maximum reverse voltage that a diode can withstand without destroying the junction.

The peak inverse voltage across a diode is the peak of the Negative half cycle

For half wave rectifier PIV is V_m.

Form factor :-

$$\text{Form Factor} = \frac{\text{Rms value}}{\text{Average value}} = \frac{\frac{I_m}{2}}{\frac{I_m}{\pi}} = \frac{\pi}{2} = 1.57$$

Peak Factor :-

$$\text{Peak Factor} = \frac{\text{Peak Value}}{\text{rms Value}} = \frac{I_m}{\frac{I_m}{2}} = 2$$

Problem :

A Half wave rectifier, having a resistive load of 1000Ω, rectifies an alternating voltage of 325 V peak value and the diode has forward resistance of 100Ω. Calculate

a) peak, average and rms value of current

b) d.c Power output

c) a.c input power and

d) Efficiency of the rectifier

Solution : Given data

$R_L = 1000\Omega$, $V_m = 325$ V , $r_f = 100\Omega$

a) Peak value of current $= I_m = \dfrac{V_m}{r_f + R_L}$

$$\therefore I_m = \frac{325}{100 + 1000} = 295.45 \text{ mA}$$

Average current $I_{d.c} = \dfrac{I_m}{\pi} = \dfrac{295.45 \text{ mA}}{3.14}$

$$\therefore I_{dc} = 94.046 \text{ mA}$$

RMS value of current $I_{rms} = \dfrac{I_m}{2} = \dfrac{295.45 \text{ m}}{2}$

$$\therefore I_{r.m.s} = 147.725 \text{ mA}$$

b) d.c power output, $P_{d.c} = I^2_{d.c} \times R_L$

$$P_{d.c} = (94.046)^2 \times 1000 = 8.845 \text{ W}$$

c) A.c input power $P_{a.c} = (I_{r.m.s})^2 \times (r_f + R_L) = 24 \text{ W}$

d) Efficiency of rectification $\eta = \dfrac{P_{d.c}}{P_{a.c}} = \dfrac{8.845}{24} = 36.85\%$

Problem : A half wave rectifier is used to supply 24V dc to a resistive load of 500 Ω and a diode has forward resistance of 50 Ω. Calculate the maximum value of the a.c voltage required at the input.

Solution : Given data

$V_{d.c} = 24\ V$, $R_L = 50\ \Omega$.

Average value of load current

$$I_{d.c} = \frac{V_{d.c}}{R_L} = \frac{24}{500} = 48\ mA$$

$$I_{d.c} = \frac{I_m}{\pi} \Rightarrow I_m = I_{d.c} \times \pi$$

Maximum value of load current $I_m = I_{d.c} \times \pi$

$$I_m = 48 \times 10^{-3} \times 3.14 = 150.8\ mA$$

Therefore maximum a.c voltage required at the input $V_m = I_m (r_f + R_L) = 82.94\ V$

Problem :- An a.c supply of 230 V is applied to a half wave rectifier circuit through transformer of turns ratio 5:1. Assume the diode is an ideal one. The load resistance is 300 Ω. Find

a) d.c output voltage b) PIV c) maximum and d) average values of power delivered to the load.

Solution : Given data

$V_1 = 230\ V$, $N_1 : N_2 = 5 : 1$, $R_L = 300\ \Omega$

a) Transformer secondary voltage

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

$$V_2 = V_1 \times \frac{N_2}{N_1} = \frac{230 \times 1}{5} = 46\ V$$

$$V_2 = V_{r.m.s} = 46\ V$$

maximum value of secondary voltage is V_m

$$V_{r.ms} = \frac{V_m}{\sqrt{2}} \Rightarrow V_m = 46 \times \sqrt{2} = 65\ V$$

$\therefore$ d.c output voltage $V_{d.c} = \frac{V_m}{\pi} = 20.7\ V$

b) PIV of a diode is $V_m \Rightarrow V_m = 65\ V$

c) maximum value of load current

$$I_m = \frac{V_m}{R_L} = \frac{65}{300} = 0.217\ A$$

maximum value of power delivered to the load

$$P_m = I_m^2 \times R_L = (0.217)^2 \times 300 = 14.1\ W$$

d) The average value of load current

$$I_{d.c} = \frac{V_{d.c}}{R_L} = \frac{20.7}{300} = 0.069\ A$$

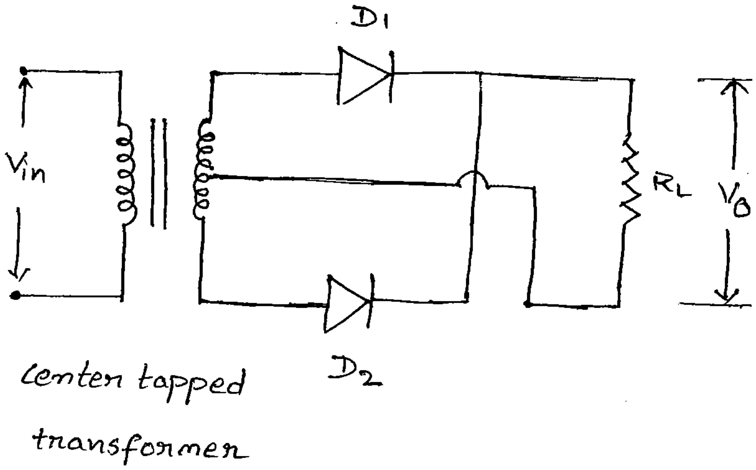
average value of power delivered to the Load

$$P_{d.c} = I_{d.c}^2 \times R_L = (0.069)^2 \times 300$$

$$P_{d.c} = 1.43\ W.$$

Full wave rectifier :

It converts an a.c voltage into a pulsating d.c voltage using both half cycles of the applied a.c voltage. It uses two diodes of which one conducts during one half cycle while the other diode conducts during the other half cycle of the applied a.c voltage. Figure shows the basic circuit and waveforms of full-wave rectifier.



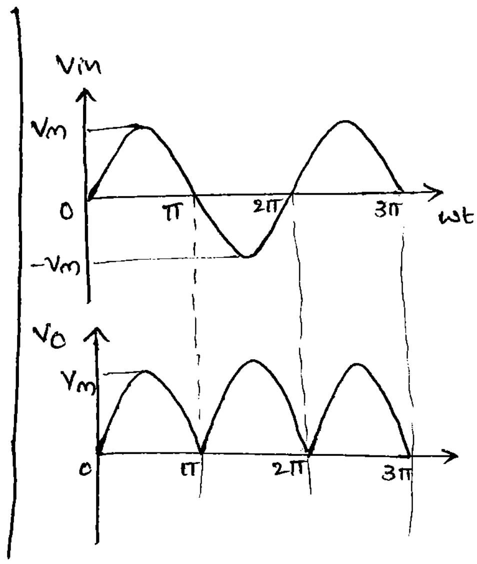
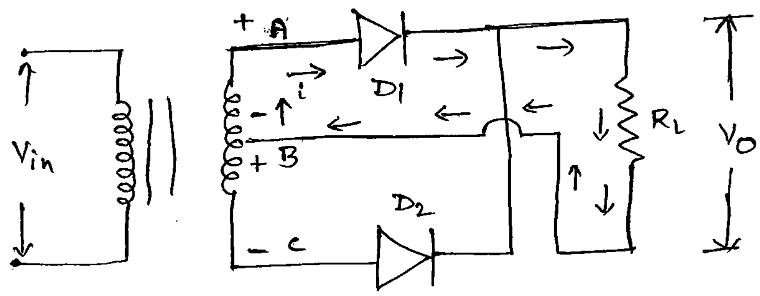


fig: Full wave rectifier

operation :

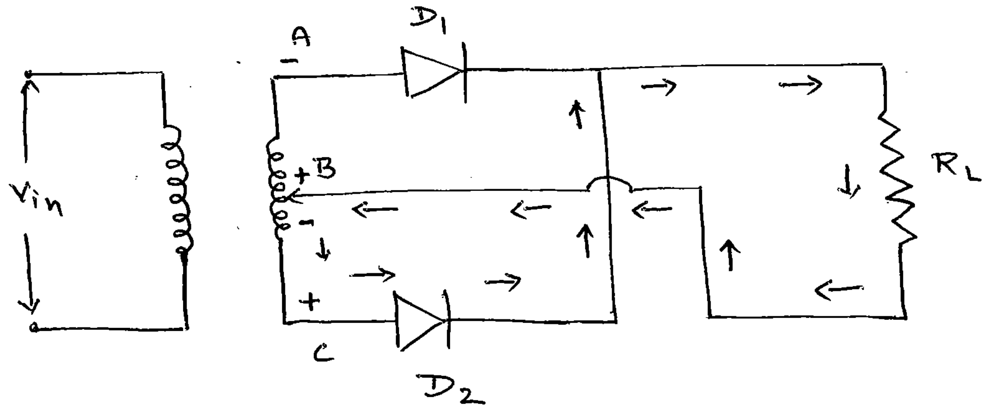
During positive half cycle



During the positive half cycle of ac input the terminal A is more positive than terminal C so diode D_1 becomes forward biased and D_2 becomes reverse biased. Therefore diode D_1 conducts while diode D_2 doesn't conduct. The conventional current flow is shown by the path below.

$A \rightarrow D_1 \rightarrow R_L \rightarrow B \rightarrow A.$

During Negative Half cycle :-



During the Negative half cycle, ~~of~~ the input terminal C is more positive than A. So diode D_1 becomes reverse biased and D_2 becomes forward biased. Therefore diode D_2 conducts while D_1 doesn't conduct. The path shown below gives the conventional current flow during Negative half cycle.

$C \rightarrow D_2 \rightarrow R_L \rightarrow B \rightarrow C$

Harmonic components in a fullwave rectifier circuit :

1) Average current (or) dc current :-

$$I_{dc} = \frac{1}{T} \int_0^T i(t)\, dt$$

$$I_{dc} = \frac{1}{\pi} \int_0^{\pi} I_m \sin\omega t \; d(\omega t)$$

$$I_{dc} = \frac{I_m}{\pi} \Big[-\cos\omega t \Big]_0^{\pi} = -\frac{I_m}{\pi} \left[-1-1\right]$$

$$I_{dc} = \frac{2 I_m}{\pi} = \frac{2 V_m}{\pi (R_f + R_L)} \quad \left[\because I_m = \frac{V_m}{R_f + R_L} \right]$$

Similarly $V_{dc} = I_{dc} \times R_L = \dfrac{2 V_m}{\pi (R_f + R_L)} \cdot R_L$

$$\therefore V_{dc} = \frac{2 V_m}{\pi \left(1 + \frac{R_f}{R_L}\right)}$$

As $R_f << R_L \Rightarrow V_{dc} = \dfrac{2 V_m}{\pi}$.

2) RMS current :

$$I_{rms} = \sqrt{\frac{1}{T} \int_0^T i^2(t)\, dt}$$

$$I_{rms} = \sqrt{\frac{1}{\pi} \int_0^{\pi} I_m^2 \sin^2\omega t \; d(\omega t)}$$

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

$$I_{rms} = \sqrt{\frac{I_m^2}{2\pi} \times \pi} = \frac{I_m}{\sqrt{2}} = \frac{V_m}{\sqrt{2}\,(R_f + R_L)}$$

Similarly ~~Average~~ voltage

$$V_{rms} = I_{rms} \times R_L$$

$$V_{rms} = \frac{I_m}{\sqrt{2}} R_L = \frac{V_m R_L}{\sqrt{2}(R_f + R_L)}$$

$$V_{rms} = \frac{V_m}{\sqrt{2}\left(1 + \frac{R_f}{R_L}\right)}$$

As $R_f << R_L \Rightarrow V_{rms} = \frac{V_m}{\sqrt{2}}$

3) <u>Rectifier</u> <u>Efficiency</u> (η) :-

$$\eta = \frac{\text{dc output power}}{\text{AC input power}} = \frac{P_{dc}}{P_{ac}}$$

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

$$P_{ac} = I_{rms}^2 (R_f + R_L)$$

$$P_{dc} = I_{dc}^2 \cdot R_L$$

$$P_{dc} = \left(\frac{2 I_m}{\pi}\right)^2 \times R_L = \frac{4 I_m^2}{\pi^2} \times R_L$$

$$P_{ac} = I_{rms}^2 (R_f + R_L) = \left(\frac{I_m}{\sqrt{2}}\right)^2 (R_f + R_L)$$

$$\therefore \eta = \frac{P_{dc}}{P_{ac}} = \frac{\frac{4 I_m^2}{\pi^2} \times R_L}{\frac{I_m^2}{2} \times (R_f + R_L)}$$

$$\eta = \frac{8}{\pi^2} \times \frac{R_L}{R_f + R_L} = \frac{0.812}{\left(1 + \frac{R_f}{R_L}\right)}$$

As $R_f << R_L$, $\eta = 0.812$

% Efficiency = % η = 81.2 %

$$81.2\% = 2 \times (40.6\%)$$

Full wave rectifier Efficiency = 2×(Half wave rectifier Efficiency)

∴ The maximum efficiency of a full wave rectifier is twice the maximum efficiency of a Half wave rectifier.

4) Ripple factor (Γ) :-

$$\Gamma = \frac{\text{rms value of a.c component}}{\text{dc value of component}}$$

$$\Gamma = \frac{V_{r,rms}}{V_{dc}}$$

$$\Gamma = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$$

$$\Gamma = \sqrt{\frac{\left(\frac{I_m}{\sqrt{2}}\right)^2}{\left(\frac{2 I_m}{\pi}\right)^2} - 1}$$

$$\Gamma = 0.48.$$

5) Transformer utilisation factor (TUF) :-

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

$$\therefore \text{TUF} = \frac{(\text{TUF})_{\text{primary}} + (\text{TUF})_{\text{secondary}}}{2}$$

$(\text{TUF})_{\text{primary}}$:-

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.

$$(\text{TUF})_{\text{primary}} = 2 \times \text{TUF of HWR} = 2 \times 0.287$$

$$\therefore (\text{TUF})_{\text{primary}} = 0.574$$

$(\text{TUF})_{\text{secondary}}$:-

$$(\text{TUF})_{\text{secondary}} = \frac{\text{dc power delivered to the load}}{\text{a.c rating of Transformer secondary}}$$

$$(\text{TUF})_{\text{secondary}} = \frac{P_{dc}}{P_{ac\,rated}}$$

$$P_{dc} = I_{dc}^2 \times R_L = \left(\frac{2 I_m}{\pi}\right)^2 \times R_L = \frac{4 I_m^2}{\pi^2} R_L$$

$$P_{ac\,rated} = \text{rated voltage of transformer secondary} \times I_{rms}$$

$$P_{ac\,rated} = \frac{V_m}{\sqrt{2}} \times \frac{I_m}{\sqrt{2}} = \frac{I_m (R_f + R_L)}{\sqrt{2}\,(\cancel{R_f + R_L})} \times \frac{I_m}{\sqrt{2}}$$

$$P_{ac\,rated} = \frac{I_m^2}{2(\cancel{R_f + R_L})} \times (R_f + R_L)$$

$$(\text{TUF})_{\text{secondary}} = \frac{\frac{4 I_m^2}{\pi^2} \times R_L}{\frac{I_m^2}{2(\cancel{R_f + R_L})} (R_f + R_L)} = \frac{8}{\pi^2 \left(1 + \frac{R_f}{R_L}\right)}$$

As $R_f << R_L$, $(TUF)_{secondary} = 0.812$

$$\therefore \quad TUF = \frac{(TUF)_p + (TUF)_s}{2} = \frac{0.574 + 0.812}{2}$$

$$\boxed{TUF = 0.693}$$

6) Peak inverse voltage (PIV) :-

Peak inverse voltage can be defined as the maximum voltage that a diode can withstand under reverse biased condition.

In this case peak inverse voltage is calculated as follows. during positive half cycle, D_1 is conducting and D_2 is off. The maximum voltage at the lower part of the transformer is V_m and the voltage drop across the R_L due to diode D_1 conducting is V_m. Hence the total voltage across diode D_2 is ~~($V_m + V_m$)~~ $2V_m$ ($V_m + V_m$)

Therefore $PIV = 2V_m$

7) Voltage Regulation :- It is defined as variation in dc voltage with change in dc load current.

$$\text{Percentage Regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100.$$

where V_{NL} = No load voltage

V_{FL} = Full load voltage.

8) $$\text{Form factor} = \frac{\text{Rms value}}{\text{Average value}} = \frac{I_{rms}}{I_{dc}} = \frac{\frac{I_m}{\sqrt{2}}}{\frac{2I_m}{\pi}} = 1.11$$

9) $$\text{Peak factor} = \frac{\text{Peak value}}{\text{Rms value}} = \frac{I_m}{I_{rms}} = \frac{I_m}{I_m/\sqrt{2}} = \sqrt{2}$$

Problem:

A 230 V, 60 Hz voltage is applied to the primary of a 5:1 step down, center tap transformer used in a full wave rectifier having a load of 900Ω. If the diode resistance and the secondary coil resistance together has a resistance of 100Ω. determine

a) dc voltage across the load b) dc current flowing through the load c) dc power delivered to the load d) PIV across each diode and e) ripple voltage and its frequency.

Solution: Given data

Primary voltage $V_1 = 230V$, $N_1 : N_2 = 5:1$

$R_L = 900\Omega$, $r_s + r_f = 100\Omega$.

secondary voltage V_2

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \Rightarrow \frac{230}{V_2} = \frac{5}{1} \Rightarrow V_2 = 46\ V$$

Voltage from Center tapping to one end = 23 V

$V_m = \sqrt{2} \times 23\ V$.

$V_m = 23\sqrt{2}\ V$

a) d.c voltage across the load $V_{d.c} = \frac{2V_m}{\pi}$

$$V_{d.c} = \frac{2 \times 23 \times \sqrt{2}}{\pi} = 20.7\ V$$

b) dc current flowing through the load

$$I_{dc} = \frac{V_{d.c}}{r_s + r_f + R_L}$$

$$I_{d.c} = \frac{20.7}{100+900} = 20.7\ mA.$$

c) d.c power delivered to the load

$$P_{d.c} = (I_{d.c})^2 \times R_L = (20.7 \times 10^{-3})^2 \times 900 = 0.386\ W$$

d) PIV across each diode $= 2V_m = 2 \times 23 \times \sqrt{2} = 65\ V$

e) ripple voltage $V_{r,rms} = \sqrt{(V_{rms})^2 - (V_{d.c})^2}$

$$V_{r.m.s} = \frac{V_m}{\sqrt{2}} = \frac{23\sqrt{2}}{\sqrt{2}} = 23$$

$$\text{Ripple voltage} = \sqrt{(23)^2 - (20.7)^2} = 10.05\ V$$

frequency of ripple voltage $2f_m = 2 \times 60 = 120\ Hz.$

Problem:

A full wave rectifier delivers 50W to a load of 200Ω. If the ripple factor is 1%. calculate the a.c ripple voltage across the load.

Solution: Given data $P_{d.c} = 50\ W$, $R_L = 200\ \Omega$

Ripple factor $(\Gamma) = 1\% = \frac{1}{100} = 0.01$

we know that $P_{d.c} = \frac{V_{d.c}^2}{R_L} \Rightarrow V_{d.c}^2 = P_{d.c} \times R_L$

therefore $V_{dc} = \sqrt{P_{d.c} \times R_L} = \sqrt{50 \times 200} = 100V$

$$\text{Ripple factor } \Gamma = \frac{V_{r,rms}}{V_{d.c}} = \frac{V_{ac}}{V_{d.c}}$$

$$\Rightarrow 0.01 = \frac{V_{a.c}}{100} \Rightarrow V_{ac} = 1V$$

a.c ripple voltage across the load $= 1V.$

Full wave Bridge Rectifier :-

The need for a center tapped power transformer is eliminated in the bridge rectifier. It contains four diodes D_1, D_2, D_3 and D_4 connected to form bridge as shown in figure below.

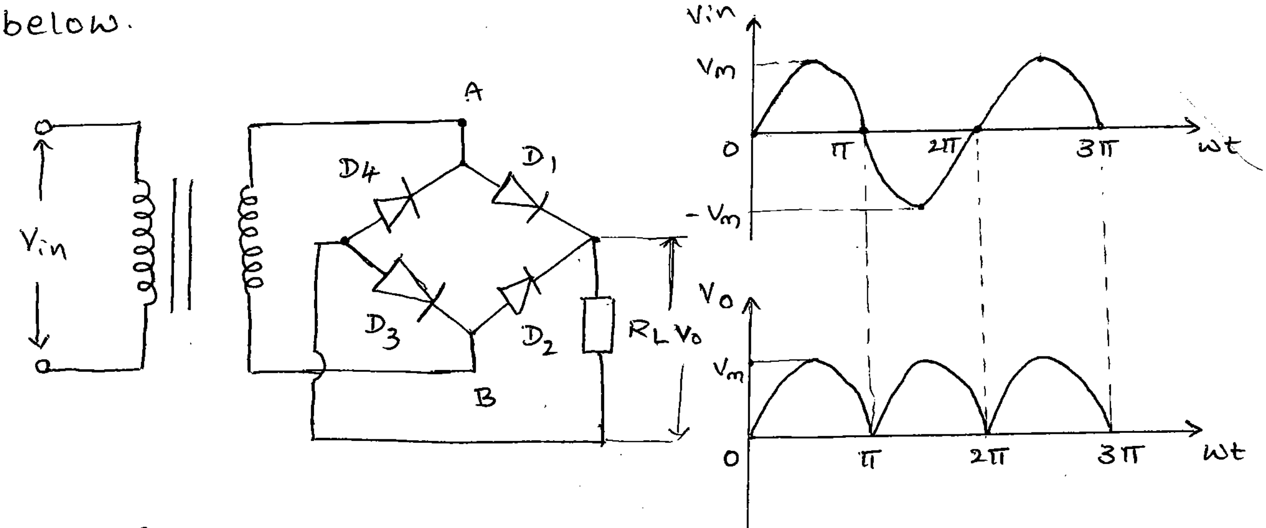


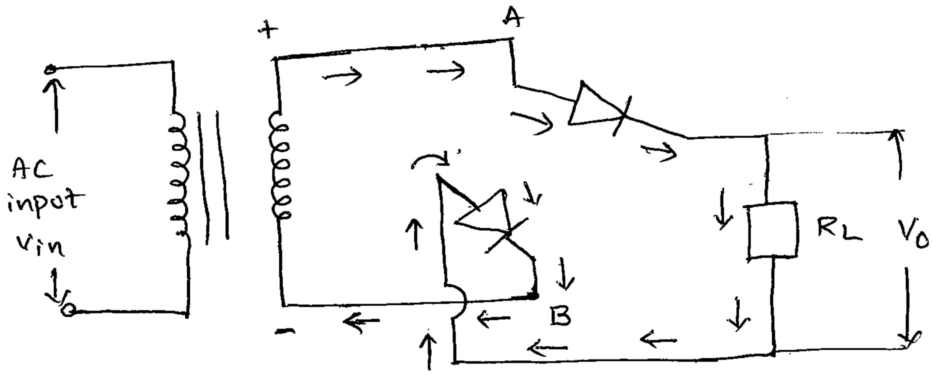
fig: Full wave bridge rectifier and wave forms

Operation :-

During positive half cycle :

During positive half cycle the point A of the secondary winding becomes positive and point B becomes negative.

This makes diodes D_1 and D_3 forward biased while D_2 and D_4 are reverse biased.

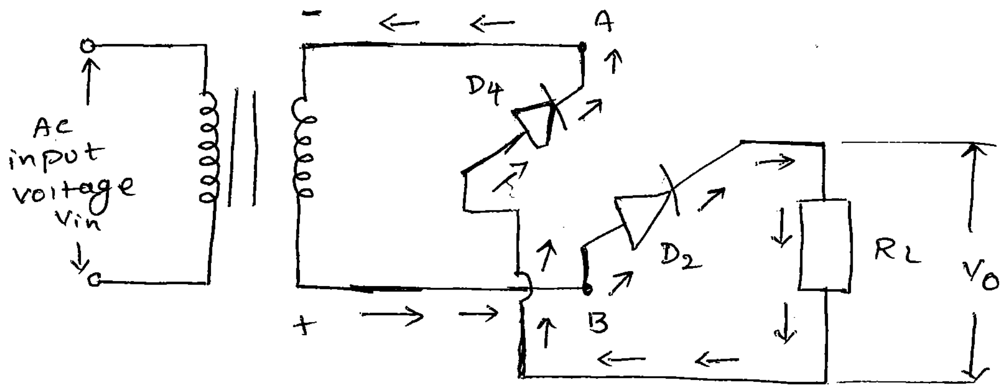


Therefore only diodes D_1 and D_3 conduct. These two diodes will be in series through the load R_L as shown in figure above.

The conventional current flow path ~~s~~ of full wave bridge rectifier is shown below

$A \rightarrow D_1 \rightarrow R_L \rightarrow D_3 \rightarrow B$

__During Negative half cycle :-__



During the Negative half cycle of Secondary voltage, the point A becomes Negative and point B becomes positive.

This makes diodes D_2 and D_4 becomes forward biased while diodes D_1 and D_3 becomes reverse biased. Therefore only diodes D_2 and D_4 conduct. These two diodes will be in series through the Load R_L as shown in figure above.

The conventional current flow of full wave bridge rectifier during Negative half cycle is shown below. $B \rightarrow D_2 \rightarrow R_L \rightarrow D_4 \rightarrow A$.

→ In both the case the current flowing through the resistor R_L is in same direction, thus it is called uni directional current.

→ The wave form of the load current is essentially the same as in the case of full wave rectifier. The ripple frequency of the output is twice that of the fundamental frequency.

Harmonic components of bridge rectifier :-

The average values of output voltage and load current for bridge rectifier are the same as for a center tapped full wave rectifier. Hence

$$V_{d.c} = \frac{2V_m}{\pi} \qquad V_{rms} = \frac{V_m}{\sqrt{2}}$$

$$I_{dc} = \frac{2I_m}{\pi} \qquad I_{rms} = \frac{I_m}{\sqrt{2}}$$

Ripple factor (Γ) = 0.48

Rectifier efficiency = 81.2 %

PIV across each diode = V_m

Ripple frequency = f_m

Note : The derivations for bridge rectifiers are same as that of centre tapped FWR, except transformer utilisation factor (TUF)

In this case centre tapped transformer is not required hence the secondary utilisation factor itself defines the TUF

$$TUF = \frac{P_{dc}}{P_{ac\ rated}}$$

$$P_{dc} = (I_{d.c})^2 \times R_L = \left(\frac{2I_m}{\pi}\right)^2 \times R_L$$

$$P_{ac\ rated} = \text{rated voltage of a transformer} \times I_{rms} = \frac{V_m}{\sqrt{2}} \times \frac{I_m}{\sqrt{2}}$$

$$P_{ac\ rated} = \frac{V_m I_m}{2} = \frac{I_m^2}{2R_L} \quad \left[\because V_m = \frac{I_m}{R_L}\right]$$

$$\therefore \boxed{TUF = 0.812}$$

→ Form factor and peak factor are same as that of Full wave rectifier.

Form factor = 1.11

Peak factor = $\sqrt{2}$

Problem : A 230V, 50 Hz voltage is applied to the primary of a 4:1 step down transformer used in a bridge rectifier having a load resistance of 600 Ω. Assuming the diodes to be ideal, determine (a) dc output voltage (b) dc power delivered to the load (c) PIV (d) output frequency.

Solution : Given data primary voltage $V_1 = 230V$

$N_1 : N_2 = 4:1$, $R_L = 600\Omega$

secondary voltage V_2 ?

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \Rightarrow V_2 = V_1 \times \frac{N_2}{N_1} = 230 \times \frac{1}{4}$$

Secondary Voltage $V_2 = 57.5\,V$

$$V_m = \sqrt{2} \times \text{secondary voltage} = 81.3\,V$$

a) $V_{d.c} = \frac{2V_m}{\pi} = 52\,V$

b) $P_{d.c} = \frac{V_{d.c}^2}{R_L} = \frac{52^2}{1000} = 2.704\,W$

c) PIV across each diode $V_m = 81.3\,V$

d) output frequency $= 2f_m = 2 \times 50 = 100\,Hz$

Comparison of Rectifiers :-

S.NO	Parameter	Half wave	Full wave	Bridge
1	NO of diodes	1	2	4
2.	Maximum efficiency	40.6 %	81.2 %	81.2 %
3.	$V_{d.c}$ (no load)	V_m/π	$2V_m/\pi$	$2V_m/\pi$
4.	Average current $I_{d.c}$	I_m/π	$2I_m/\pi$	$2I_m/\pi$
5.	Ripple factor	1.21	0.48	0.48
6.	Peak inverse voltage	V_m	$2V_m$	$2V_m$
7.	output frequency	f_m	$2f_m$	$2f_m$
8	TUF	0.287	0.693	0.812
9	Form factor	1.57	1.11	1.11
10	Peak factor	2	$\sqrt{2}$	$\sqrt{2}$

Introduction to Filters :

The output of the rectifier circuit is a pulsating dc, it contains both ac and dc components. The presence of ac components is undesirable feature, hence it has to be removed from the rectified output by using a suitable circuit. Such a circuit is known as a filter.

A filter may be defined as the circuit which removes the unwanted ac components of the rectifier output and allows only dc components to reach the load.

A filter circuit consists of a passive circuit elements, such as inductors, capacitors and their combinations.

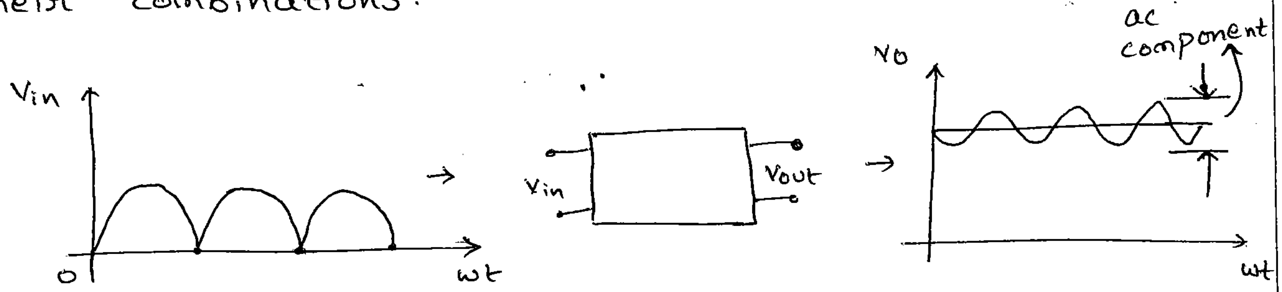


figure shows the concept of a filter, where the full wave rectified output voltage is applied at its input. The output of a filter is not exactly a constant d.c. level. But it also contains a small amount of a.c component. Some important filters are

1) Induction filter 2) capacitor filter
3) LC or L-section filter 4) CLC or π-type filter

Inductor Filter

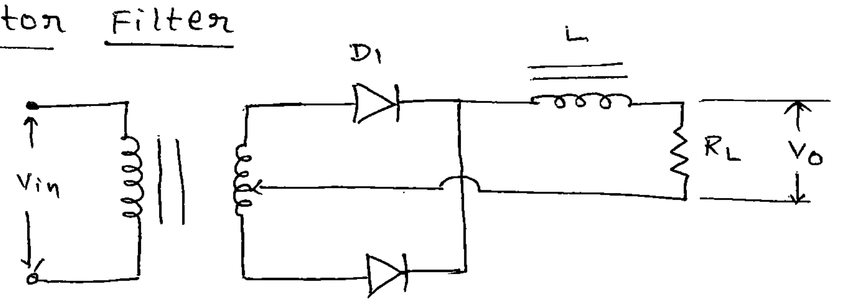


fig: Full wave rectifier with Inductor filter.

Figure shows the fullwave rectifier with inductor filter. when the output of the FWR passes through an inductor, it blocks the ac component and allows only the dc component to reach the load.

The ripple factor of the inductor filter is given by

$$\Gamma = \frac{R_L}{3\sqrt{2}\,\omega L}$$

It shows that the ripple factor will decrease when L is increased. and R_L is decreased. The inductor filter is more effective only when the load current is high (small R_L). The larger value of the inductor can reduce the ripple and at the same time the output d.c voltage will be lowered as a inductor has a higher d.c. resistance.

The operation of the inductor filter depends on its well known fundamental property to oppose any change of current passing through it.

Analysis of Inductor filter :

To analyse this filter for a full-wave, the fourier series can be written as

$$V_0 = \frac{2V_m}{\pi} - \frac{4V_m}{\pi}\left[\frac{1}{3}\cos 2\omega t + \frac{1}{15}\cos 4\omega t + \frac{1}{35}\cos 6\omega t + \cdots\right] \rightarrow ①$$

Assuming the third and higher terms contribute little output, the output voltage is

$$V_0 = \frac{2V_m}{\pi} - \frac{4V_m}{3\pi}\cos 2\omega t . \longrightarrow ②$$

The diode, choke (L) and transformer resistances can be neglected since they are very small as compared with R_L. Therefore

The d.c component of current $I_m = \frac{V_m}{R_L}$

The impedance of series combination of L and R_L at 2ω is (for second harmonic)

$$Z = \sqrt{R_L^2 + (2\omega L)^2} = \sqrt{R_L^2 + 4\omega^2 L^2} .$$

Therefore the a.c component of current

$$I_m = \frac{V_m}{\sqrt{R_L^2 + 4\omega^2 L^2}} \qquad \left(\because I_m = \frac{V_m}{Z}\right)$$

Therefore the resulting current is given by from Eq ②

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

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

where ϕ is the angle by which the load current lags behind the voltage, From eq (3)

$$I_{dc} = \frac{2V_m}{\pi R_L}, \quad I_{rms} = \frac{I_m}{\sqrt{2}}$$

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

The ripple factor which can be defined as the ratio of rms value of the ripple to the d.c value of the wave.

$$\text{Ripple factor } \Gamma = \frac{I_{rms}}{I_{dc}} = \frac{\dfrac{4V_m}{3\pi\sqrt{2}\sqrt{R_L^2 + 4\omega^2 L^2}}}{\dfrac{2V_m}{\pi R_L}}$$

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

If $\frac{4\omega^2 L^2}{R_L^2} >> 1$, then a simplified expression for Γ is

$$\Gamma = \frac{2}{3\sqrt{2}} \frac{1}{\sqrt{\frac{4\omega^2 L^2}{R_L^2}}} = \frac{2}{3\sqrt{2}} \times \frac{R_L}{2\omega L}$$

$$\boxed{\Gamma = \frac{R_L}{3\sqrt{2}\,\omega L}}$$

This expression clearly shows that reduced ripple will occur for larger values of L. But it also shows that the ripple will increase as the load increased to Infinite value

Hence this filter ~~is~~ ~~suitable~~ ~~for~~ ~~only~~ should only be used where R_L is consistently small.

Problem: Calculate the value of inductance to use in the inductor filter connected to a full-wave rectifier operating at 60Hz to provide a d.c output with 4% ripple for a 100Ω load.

Solution: Given data

$$f = 60\,Hz \quad , \quad R_L = 100\,\Omega$$

$$\text{Ripple factor } \Gamma = 4\% = 0.04$$

we know that ripple factor of inductor filter is

$$\Gamma = \frac{R_L}{3\sqrt{2}\,\omega L} \quad , \quad \omega = 2\pi f$$

$$0.04 = \frac{100}{3\sqrt{2} \times (2 \times \pi \times 60) \times L}$$

$$\Rightarrow \quad L = 1.5625\ Hz.$$

Capacitor filter :- An inexpensive filter for light loads is found in the capacitor filter which is connected directly across the load as shown in figure below.

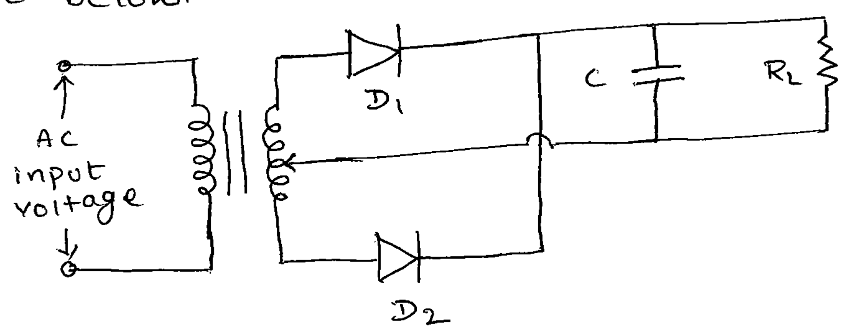
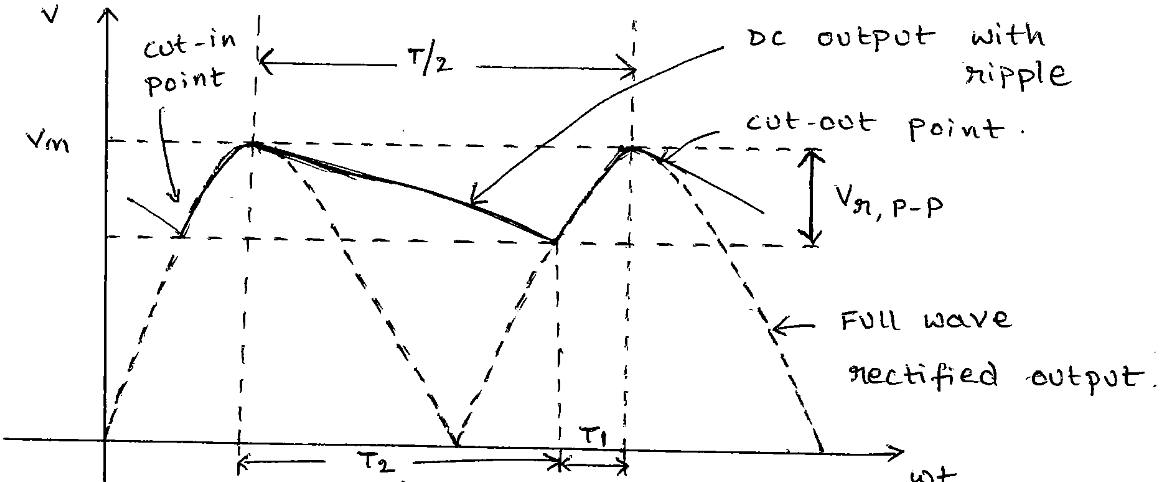


fig: Full wave rectifier with capacitor filter

The property of a capacitor is that it allows a·c component and blocks the dc component. The operation of a capacitor filter is to short the ripple to ground but leave the dc to appear at the output when it is connected across a pulsating d·c voltage.



fig(b) : Ripple voltage triangular waveform

During the positive half cycle, the capacitor charges upto the peak value of the transformer secondary voltage, V_m and will try to maintain this value as the full wave input drops to zero.

The capacitor will discharge through R_L slowly until the transformer secondary voltage again increases to a value greater than the capacitor voltage. The diode conducts for a period which depends on the capacitor voltage. The diode will conduct when the transformer secondary voltage becomes more than the diode voltage. This is called the cut-in voltage.

The diode stops conducting when the transformer voltage becomes less than the diode voltage. This is called cut-out voltage.

In figure (b) with slight approximation, the ripple voltage waveform can be assumed as triangular.

From the cut-in point to cut-out point, whatever ~~the~~ charge, the capacitor acquires, is equal to the charge, the capacitor has lost during the period of non-conduction. ie from cut out point to the next cut-in point.

The charge it has acquired $= V_{r,P-P} \times C \longrightarrow ①$

The charge it has lost $= I_{d.c} \times T_2 \longrightarrow ②$

Therefore $V_{r,P-P} \times C = I_{d.c} \times T_2 \longrightarrow ③$

With the assumption made above, the ripple waveform will be triangular in nature and the rms value of the ripple is given by

$$V_{r,rms} = \frac{V_{r,P-P}}{2\sqrt{3}} \longrightarrow ④$$

If the value of the capacitor is fairly large, or the value of the load resistance is very large, then it can be assumed that that the time T_2 is equal to the half the periodic time of the waveform

$$T_2 = \frac{T}{2} = \frac{1}{2f} \quad \text{then from eq ③}$$

$$V_{r,P-P} = \frac{I_{d.c}}{2fC} \longrightarrow ⑤$$

substituting eq ⑤ in eq ④

$$V_{r,rms} = \frac{I_{d.c}}{4\sqrt{3} f C}$$

$$V_{r,rms} = \frac{V_{d.c}}{4\sqrt{3} f C R_L} \quad \left[\because I_{d.c} = \frac{V_{d.c}}{R_L}\right]$$

Therefore ripple $\Gamma = \frac{V_{r,rms}}{V_{d.c}} = \frac{1}{4\sqrt{3} f C R_L}$

The ripple may be decreased by increasing C (or) R_L (or both) with a resulting increase in d.c output voltage.

Problem :

Calculate the value of capacitance to use in a capacitor filter connected to a full-wave rectifier operating at a standard air craft power frequency of 400 Hz, If the ripple factor is 10 % for a Load of 500Ω.

Solution : Given data

ripple factor $= \frac{10}{100} = 0.1$

$f = 400$ Hz, $R_L = 500\Omega$

$$\Gamma = \frac{1}{4\sqrt{3} f C R_L}$$

$$0.1 = \frac{1}{4 \times \sqrt{3} \times 400 \times C \times 500}$$

$C = 72.2\ \mu F$.

Zener diode as Voltage Regulator :-

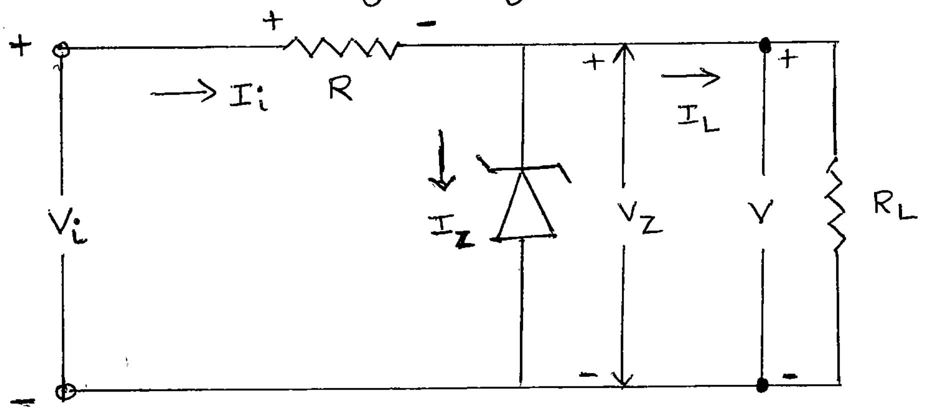


fig: Zener voltage regulator.

A zener diode, under reverse bias break down condition, can be used to regulate the voltage across a load, irrespective of the supply voltage or load current variations. A simple zener voltage regulator circuit is shown in figure above.

The zener diode is selected with V_Z equal to the voltage desired across the load. The zener diode has a characteristic that under reverse bias condition, the voltage across it practically remains constant, even if the current through it changes by a large extent.

Under normal conditions the input current $I_i = I_L + I_Z$ flows through resistor R. The input voltage V_i can be written as

$$V_i = I_i R + V_Z$$

$$V_i = (I_L + I_Z) R + V_Z$$

Operation:

a) Regulation with varying input voltage :-

When the input voltage V_i increases (say due to supply voltage variations), as the voltage across zener diode remains constant, the drop across resistor R will increase with a corresponding increase in $I_L + I_Z$. As V_Z is a constant, the voltage across the load will also remain constant and hence I_L will be a constant. Therefore an increase in $I_L + I_Z$ will result in an increase in I_Z which will not alter the voltage across the load.

b) Regulation with varying load current :-

Assume the input voltage as constant but load current is varied by varying the load resistance. The variation of load resistance changes the current through it. In this case the input current and voltage across R remain constant.

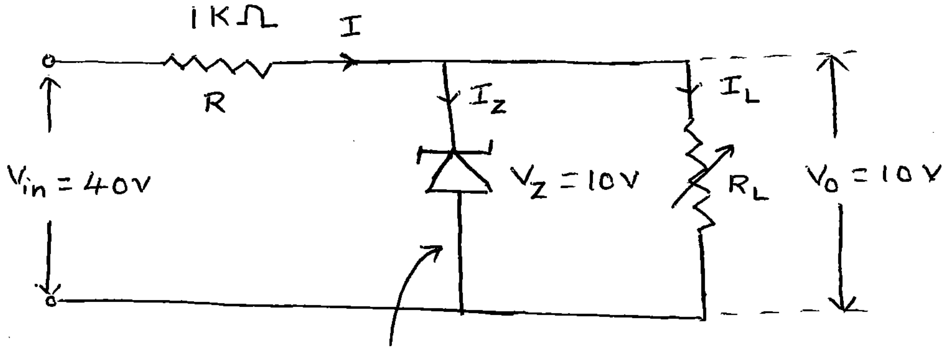
We know that input current is sum of zener current and load current. hence when a load resistance decreases, the load current increases, this causes the zener current to decrease. Thus the load voltage remains constant.

→ It must be ensured that the reverse voltage applied to the zener diode never exceeds PIV of the diode and at the same time, the applied input voltage must be greater than the break down voltage of the zener diode for its operation.

→ The zener diodes can be used as stand alone regulator circuits and also as reference voltage sources.

Problems :-

1) For the zener voltage regulator shown, determine the range of R_L and I_L that gives the stabilizer voltage of 10V.



Sol : Given data

$$V_Z = V_0 = 10 \text{ V},$$

$$V_{in} = 40 \text{ V}, \quad I_{Z max} = 24 \text{ mA},$$

Assume $I_{Z min} = 5 \text{ mA}$.

From the circuit

$$I = I_Z + I_L$$

$$I = \frac{V_{in} - V_Z}{R} = \frac{40 - 10}{1K} = 30 \text{ mA}$$

when I_Z is maximum, I_L is minimum and vice versa.

$$I = I_{Z max} + I_{L min}$$

$$I_{L min} = I - I_{Z max}$$

$$I_{L min} = 30 \text{ mA} - 24 \text{ mA} = 6 \text{ mA}$$

$$R_{L max} = \frac{V_0}{I_{L min}} = \frac{10}{6 \text{ mA}} = 1.667 \text{ K}\Omega$$

Ily $I = I_{Z\,min} + I_{L\,max}$

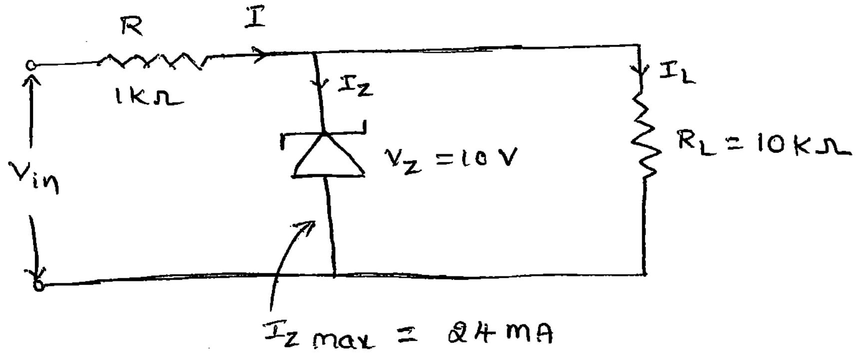
$$I_{L\,max} = I - I_{Z\,min}$$

$$I_{L\,max} = 30\text{ mA} - 5\text{ mA}$$

$$I_{L\,max} = 25\text{ mA}.$$

$$R_{L\,min} = \frac{V_0}{I_{L\,max}} = \frac{10}{25\text{ mA}} = 400\,\Omega.$$

2) Determine the range of input voltage that maintains the output voltage of 10V, for the Regulator circuit shown.



Solution : Given data $V_0 = V_Z = 10$ V

As $V_0 = 10$ V constant, $R_L = 10$ kΩ constant

$$I_L = \frac{V_0}{R_L} = \frac{10}{10\text{ k}} = 1\text{ mA} \quad (\text{constant})$$

when $V_{in} = V_{in(max)}$, $I_Z = I_{Z\,max}$

$$I = I_Z + I_L$$

$$I_{max} = I_{Z\,max} + I_L$$

$$\frac{V_{in\,max} - V_Z}{R} = I_{Z\,max} + I_L$$

$$\therefore V_{in(max)} = 35\text{ V}$$

when $V_{in} = V_{in(min)}$, $I_Z = I_{Z min} = 5\ mA$ (Assume)

$$I_{min} = I_{Z min} + I_L$$

$$\frac{V_{in(min)} - V_Z}{R} = (5 \times 10^{-3}) + (1 \times 10^{-3})$$

$$\Rightarrow V_{in(min)} = 16\ V$$

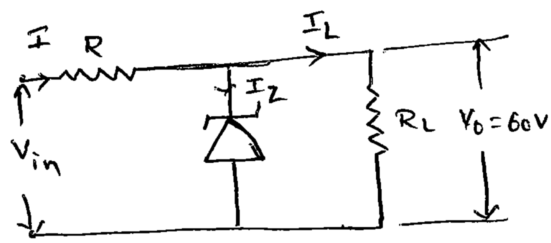
Thus range of input voltage is 16 V to 35 V for which output voltage will be of 10 V.

3) A zener voltage regulator circuit is to maintain constant voltage at 60V, over a current range from 5 to 50 mA. The input supply voltage is 200V. Determine the value of resistance R to be connected in the circuit for voltage regulation from load current $I_L = 0$ mA to $I_{L max}$, the maximum possible value of I_L. What is the value of $I_{L max}$.

Solution :- Given data

$V_0 = 60V$, $I_{Z max} = 50\ mA$, $I_{Z min} = 5\ mA$, $V_{in} = 200V$

$I_{L min} = 0\ mA$



$$I = I_{Z max} + I_{L min}$$

$$I = 50\ mA$$

and $I = \frac{V_{in} - V_Z}{R} = \frac{V_{in} - V_0}{R} \Rightarrow R = 2800\ \Omega$

$$I = I_{Z min} + I_{L max}$$

$$50 = 5 + I_{L max}$$

$$I_{L max} = 45\ mA$$