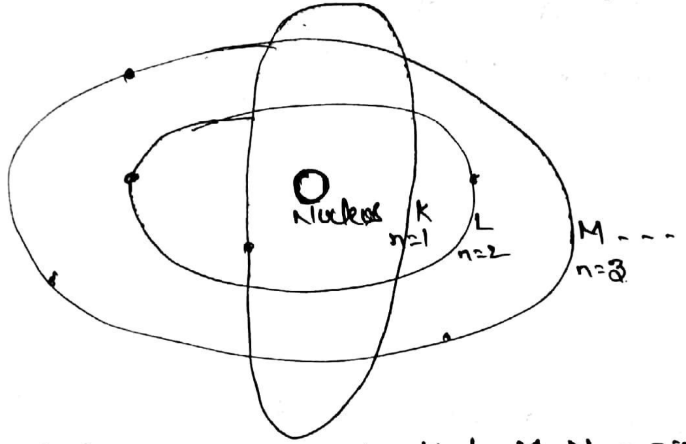
ATOM:- The most fundamental part of an element is called
atom.

The atomic number is the number of electrons or protons.

As per Bohr's theory, Electrons moves in orbitals around
the nucelus which contains protons and Neutrons.
i.e it follows the planetory structure.



The orbitals are named K, L, M, N, ...

The number of electrons in each orbit $= 2n^2$

For $n=1$ (K), No.of electrons $= 2.(1^2) = 2$
For $n=2$, (L) No.of " $= 2(2^2) = 8$

Every orbit has specific energy level.
The energy level increases as the distance of the orbit
increases from the nucleus because of less attraction.

In practice, we will consider only the two outermost
orbitals (Energy Bands) for electronic circuits.

The number of electrons or the orbitals vary from
atom to atom.

The outermost orbit is called the conduction Band, and the orbit internal to the conduction band is called Valance Band.

Sufficient energy is to be supplied to the electron to jump from valance band to conduction band.

$$\boxed{1\,e.V = 1.6 \times 10^{-19}\,\text{Jooles}}$$

Energy Gap is measured in Electron-volts, defined as the amount of energy required for the electron to jump 1volt

Energy Gap.

Based on the Energy Gap between valance band and Conduction band, the materials are classified

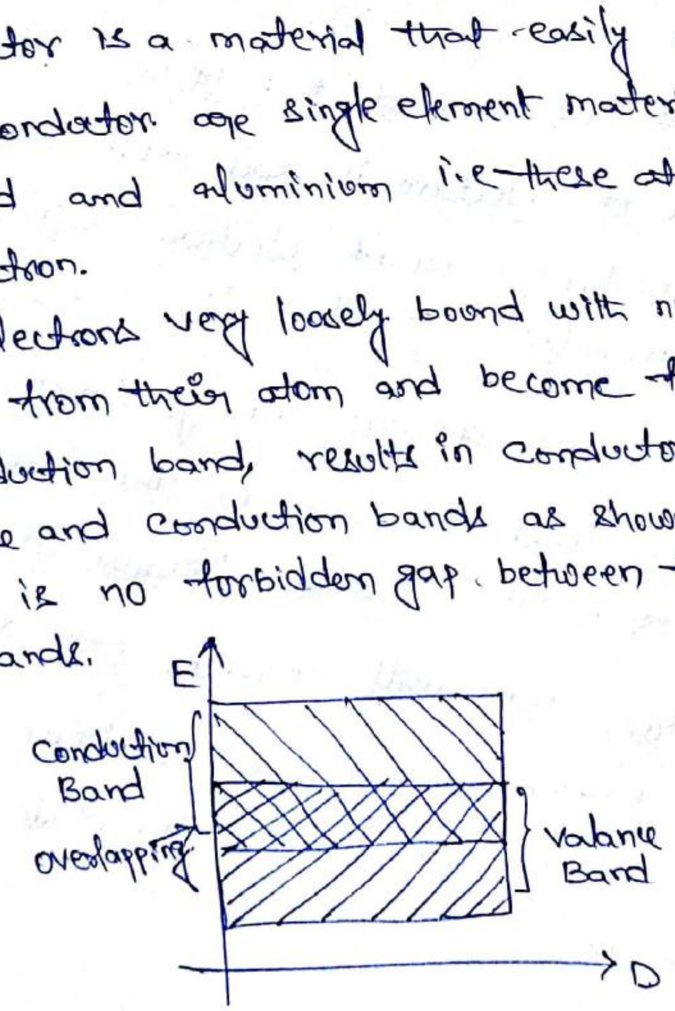
1. Conductor
2. Semi Conductor
3. Insulator.

Conductors:-

Conductor is a material that easily conduct the current. The best conductor are single element material such as copper, silver, gold and aluminium i.e these atoms have only one valance electron.

These electrons very loosely bound with nucli, so it can easily break away from their atom and become free electron and forms Conduction band, results in conductors have overlapping the valance and conduction bands as shown bellow.

i.e, there is no forbidden gap between the conduction and valance bands.



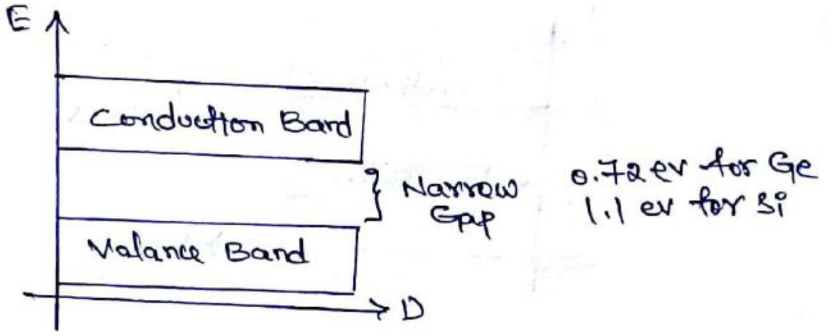
The resistance of conductor is very small compared with semiconductors and insulators.

Ex:- Copper, Aluminium, Iron etc.,

Semi Conductors

A semi conductor material is an element with 4 Valance electrons and whose electrical properties lie in between that of Insulators and conductors.

In terms of energy band, semiconductors can be defined as those materials which have partially filled conduction band and valance band with narrow energy gap separating the two as shown bellow.



At 0°K there are no electrons in conduction band and valance band is completely filled, hence it behaves as insulator.

When increase in temperature, width of forbidden energy band is decreased. so that some of the electrons are liberated into conduction band thus it behaves as conductor.

The resistance of semi conductors is high when compared to that of conductors, low when compared to that of insulators.

Ex:- Si, Ge, Gallium Arsenide etc.,

Insulators:

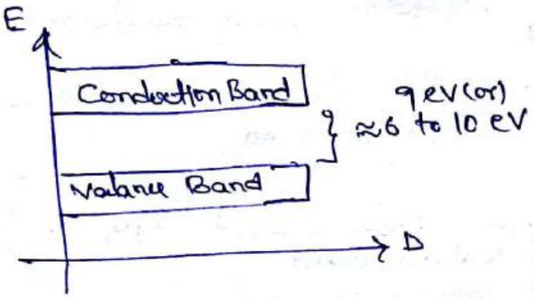
Insulators are those materials in which eight valance electrons and are bound very tightly to parent atoms, thus requiring very large electric field to remove them from attraction of their nucleus.

In other words, Insulators have no free charge carrier available with them under normal condition.

- The forbidden energy gap is very large.

Insulators have very high resistance.

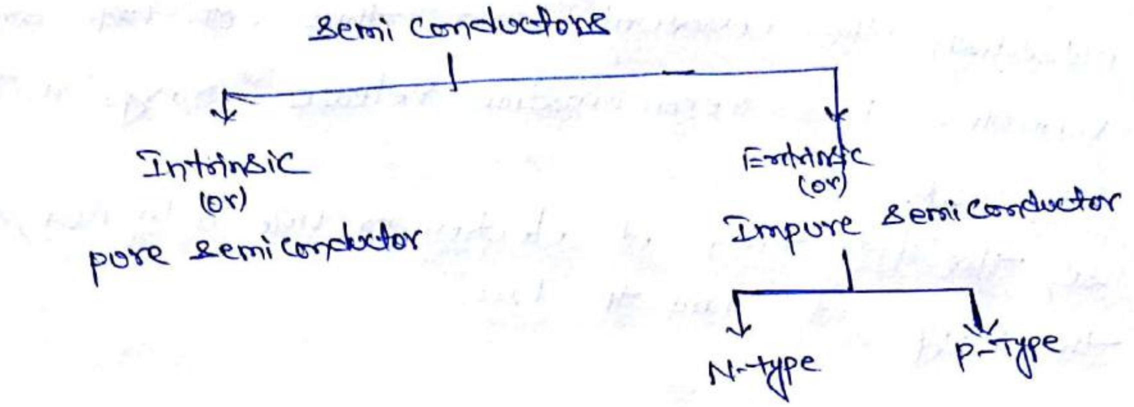
Ex:- paper, Mica, Nacl. etc.,



Comparison:-

Conductors	Semi Conductors	Insulators
1. Easily conducts the electrical current	Conducts electrical current less than conductor and greater than insulator.	Doesn't Conduct any current
2. one valance electron in its outermost orbit	4 valance electrons in its outermost orbit	8 valance electrons in its outermost orbit
3. Formed by metallic bonding	Formed due to Covalent bonding	Formed due to ionic bonding
4. Valance and Conduction bands are overlapped	Valance and Conduction bands are separated by energy gap of 1.1 eV	Valance and Conduction bands are separated by forbidden energy gap of 6 to 10 eV.
5. Resistance is very small	Resistance is High	Resistance is very High
6. It has positive temperature Coefficient	It has negative temperature Coefficient	It has negative temperature coefficient.
7. Ex:- Copper, Aluminium, silver etc.	Ex:- Si, Ge etc.	Ex:- paper, Mica etc.,

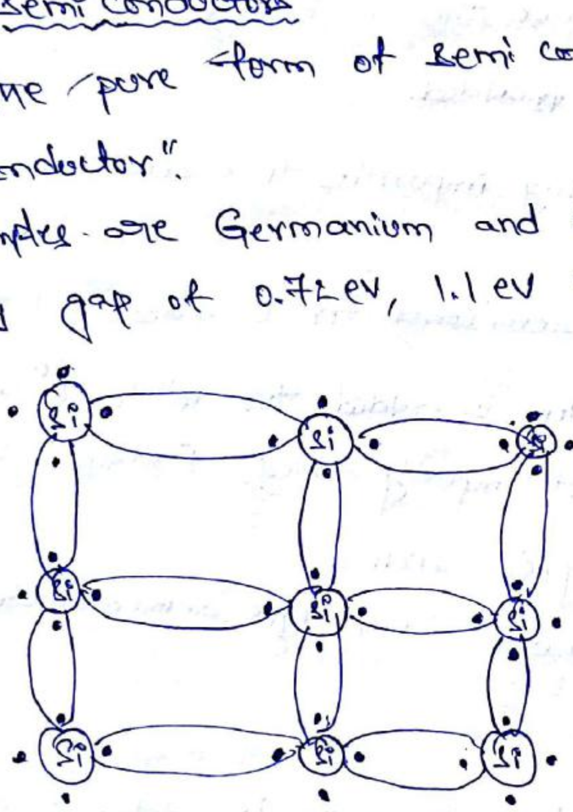
Semi conductors are classified into two types.

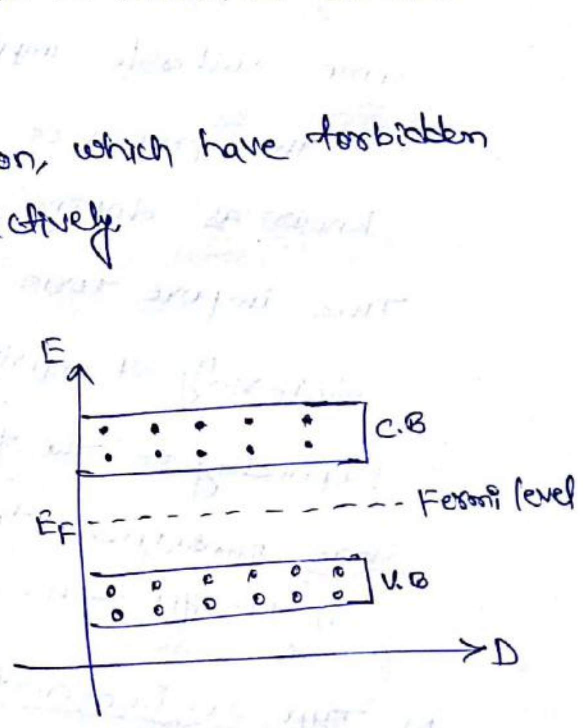


Intrinsic Semi conductors

The pure form of semi conductor is known as "Intrinsic semi conductor".

Examples are Germanium and silicon, which have forbidden energy gap of 0.72 ev, 1.1 ev respectively.





At room temperature, because of thermal energy supplied, many valance electrons broken covalent bond and jump into conduction band. A vacancy is created at the place of vacance electron, it is known as hole.

In intrinsic semi conductors, the no. of holes and electrons are equal because thermal energy produces free electrons and holes in pairs.

The total current inside the semi conductor is equal to the sum of hole current and electron current.

When one free electron meets a hole they recombine to establish the covalent bond, thus both hole and electron vanish. This recombination releases energy in the form of heat.

So, the life time of electron or hole is limited, lying in the range of 1 ms to 1 µs.

Extrinsic semi Conductor:-

To significantly increase the conductivity of the semiconductor, some suitable impurity is added.

"The process of adding impurities to a semiconductor is known as doping".

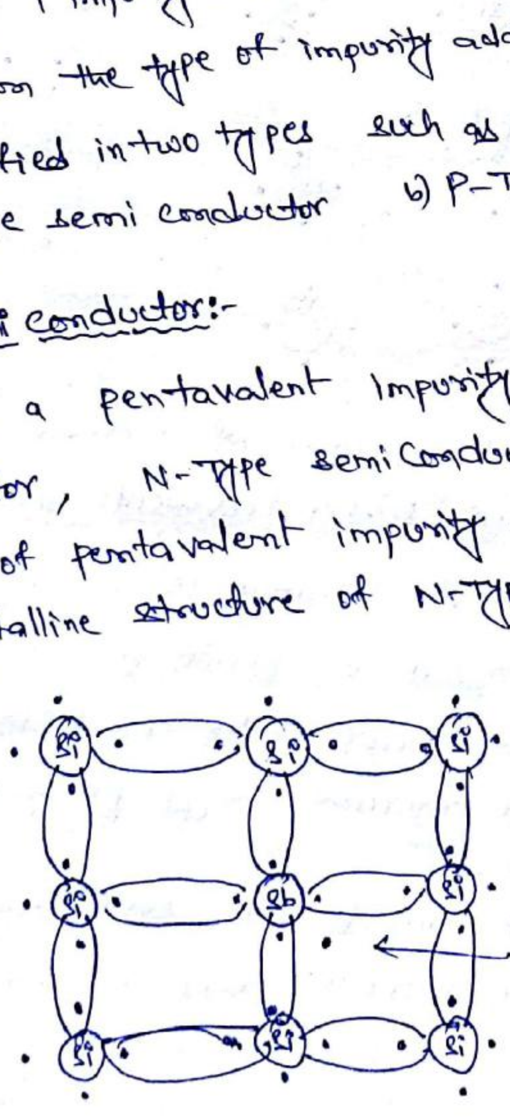
This impure form of semi conductor is called as Extrinsic Semiconductor. Generally 1 impurity atom is added for 10^6 to 10^{10} atoms.

Depending on the type of impurity added, Extrinsic semiconductors are classified in two types such as

a) N-Type semi conductor b) P-Type semiconductor.

N-Type semi conductor:-

When a pentavalent impurity is added to a intrinsic semiconductor, N-Type semi conductor is obtained. Examples of pentavalent impurity are Arsenic, Antimony etc. The crystalline structure of N-Type semiconductor is shown bellow.



Si has 4 valance electrons and Antimony has 5 valance electrons. Each Antimony atom forms a covalent bond with surrounding four Si atoms. Thus 5th valance electrons of Antimony is left free which is loosely bound to the Antimony atom.

It can be easily excited from the valance band to the conduction band by the application of electric field or thermal energy.

Thus every Antimony atom contributes one conduction electron without creating a hole. Such pentavalent impurities are called donor impurities.

Thus addition of pentavalent impurity increases the number of electrons in the conduction band thereby increasing the conductivity of N-Type semi conductor.

As a result of doping, the number of free electrons far exceeds the number of holes in an N-Type semi conductor.

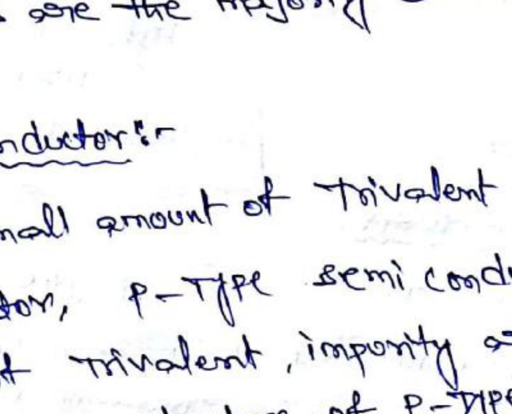
So, Electrons are the majority carriers and holes are the minority carriers.

P-Type Semi Conductor:-

When a small amount of Trivalent impurity is added to a pure semi conductor, P-Type semi conductor is formed.

Examples of Trivalent impurity are Al, Boron, gallium, Indium etc.

The crystalline structure of P-Type semiconductor is as shown below.



Free Hole
(Vacancy of Electron)

The three electrons of Boron forms covalent Bond with four surrounding Si Atoms. one bond is incomplete, leads to a formation of Hole. Thus trivalent impurity when added to Intrinsic semiconductor, introduces a large number of holes in the valance band.

These positively charged holes increases the conductivity of P-type semiconductor.

As the number of holes is very much greater than the number of free electrons in a p-type material, holes are termed as majority carriers and electrons as minority carriers.

* Intrinsic Vs Extrinsic Semiconductor:-

Intrinsic semiconductor	Extrinsic semiconductor
1. It is pure form of Semi Conductor	1. It is impure form of semiconductor
2. Number of electrons and holes are equal. $n = p$	2. Number of electrons and holes are not equal $n \neq p$
3. Conductivity is poor	3. Conductivity is improved.

* N-Type Vs P-Type Semiconductor:-

N-Type semi conductor	P-Type Semiconductor
1. It is obtained by adding pentavalent impurities to pure Si (or) Ge	1. It is obtained by adding Trivalent impurities to pure Si(or)Ge
2. Electron concentration is greater than hole concentration $n >> p$	2. Hole concentration is greater than electron concentration $p >> n$
3. Electrons are the majority carriers	3. Holes are the majority carriers
4. Holes are the minority carriers	4. Electrons are the minority carriers
5. Doping agents are As, Antimony(Sb), phosporus(P) etc.	5. Doping agents are B, Al, Ga etc.
6. pentavalent Impurities are Donor impurities	6. Trivalent impurities are called Acceptor impurities

*conductivity:-

In a pure semi conductor, the number of electrons and holes are equal. By thermal energy, electron - Hole pairs are created and disappears after recombination.

With each Electron-Hole pair created, two types of charge particles are formed. one is negative, which is the free electron with mobility μ_n and the other is the positive i.e hole with mobility μ_p.

The electrons and holes will move in opposite directions in an applied electric field 'E'.

The total current density 'J' with in the semi conductor is given by,

$$J = Q.V$$

$$J = Q.\mu E \quad \left[\because \mu = \frac{V}{E} = \frac{\text{velocity}}{\text{Electric Field}}\right]$$

$$J = \left[qn\mu_n + qP\mu_p\right].E \quad — ①$$

where n, P are the charge concentrations of electron, holes.

The point form of ohm's law states $J = \sigma E$ — ②

From Eq. ①, ②. $\boxed{\sigma = q\left(n\mu_n + P\mu_p\right)}$

σ is the conductivity of the material.

Resistivity is the reciprocal of conductivity.

$$\rho = \frac{1}{\sigma}.$$

For an intrinsic semi conductor, $n = P = n_i$

$$\text{so,} \quad \sigma = n_i q\left(\mu_n + \mu_p\right)$$

For an N-Type semi conductor, $n >> P$.

$$\sigma = qn\mu_n.$$

For a P-Type semi conductor, $P >> n$

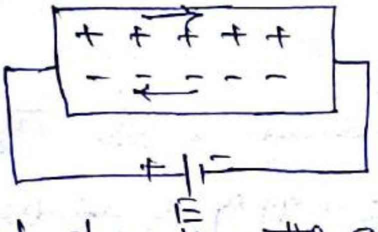
$$\sigma = qP\mu_p$$

* Drift and Diffusion currents

The flow of charge i.e current through a semi conductor material is of two types namely Drift and Diffusion currents.

Drift current:-

When an electric field is applied across the semi conductor, the electric field established in the material causes free electrons to drift in one direction and holes in opposite direction. The total current is due to hole current and electron current. The current produced in this way is known as Drift current.



The drift current depends on the ability of charge carriers to move through the semi conductor. The measure of this ability is called Mobility denoted by μ.

$$\mu = \frac{\text{Velocity (V)}}{\text{Electric Field (E)}} = \frac{V}{E}$$

$$I_{drift} = I_{\text{Drift Electron}} + I_{\text{Drift Holes}}$$

$$I_{drift} = (qn\mu_n + qp\mu_p)E \cdot A \qquad [\because J = \frac{I}{A}]$$

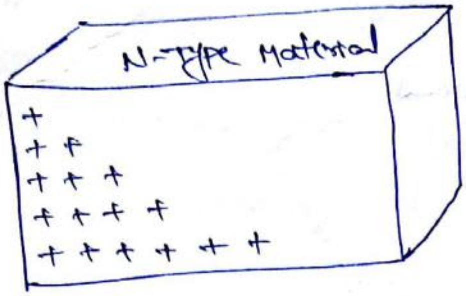
$$I_{drift} = qE(n\mu_n + p\mu_p) A$$

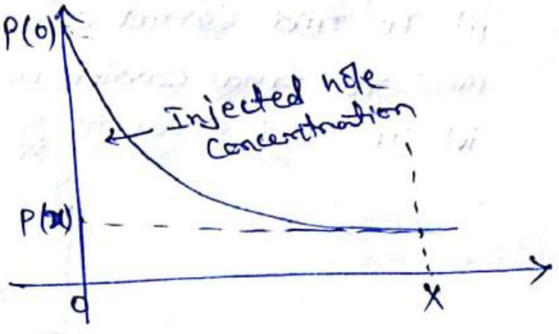
Diffusion Current:-

Even in the absence of Applied electric voltage, there is possibility of an electric current to flow in a semi conductor. The concentration gradient exist if the number of electrons or holes is greater in one region of a semi conductor as compared to the rest of the region as shown below.

The charge carriers have the tendency to move from higher concentration region to lower concentration region.

Thus movement of charge carriers takes place resulting in a current called Diffusion Current.





In the above diagram, the hole concentration p(x) in the semiconductor bar varies from high value to low value.

The diffusion current density due to holes is given by

$$J_p = -q D_p \cdot \frac{dp}{dx}$$

where D_p = Diffusion Constant of holes.

The negative sign indicates that the degradation of gradient is in the direction of current.

Diffusion current density due to Electrons is

$$J_n = q D_n \cdot \frac{dn}{dx}$$

where D_n is the Diffusion Constant of Electron

The positive sign indicates that current is in the increasing direction of the gradiant.

1. Determine the conductivity and resistivity of an intrinsic Sample solution at normal room temperature 300° K.

Electron Mobility $\mu_e = 1350\ cm^2/volt\text{-}sec$

Hole " $\mu_h = 480\ cm^2/volt\text{-}sec$

Intrinsic Density $n_i = 1.52\times10^{10}/cm^3$

Sol Given that $\mu_e = 1350\ cm^2/volt\text{-}sec$

$\mu_h = 480\ cm^2/volt\text{-}sec$

$n_i = 1.52\times10^{10}/cm^3$

Conductivity $\sigma = n_i q(\mu_n+\mu_p)$

$= (1.52\times10^{10})(1.6\times10^{-19})(1350+480)$

$= 4.45\times10^{-6}\ ℧/cm$

Resistivity $\rho = \frac{1}{\sigma} = \frac{1}{4.45\times10^{-6}} = 2.25\times10^{5}\ \Omega\ cm$

2. A semi-conductor wafer is 0.5mm thick, a potential of 100mV is applied across it

a) what is the electron drift velocity if $\mu_e = 0.2\ m^2/V\text{-}sec$?

b) what is the time required for an electron to move across this thickness?

Sol a) Mobility of electron $\mu_e = \frac{V}{E} = \frac{\text{Drift velocity}}{\text{Electric Field applied}}$

$$V = \mu_e E = \mu_e \cdot \frac{V}{d}$$

$$V = 0.2\ \frac{100\times10^{-3}}{0.5\times10^{-3}} = 40\ m/sec$$

b) Time Required $T = \frac{\text{Distance}}{\text{velocity}} = \frac{0.5\times10^{-3}}{40} = 12.5\ \mu sec$

3. The intrinsic resistivity of Ge at 300°K is 47 Ω cm. what is the intrinsic carrier concentration? If $E = 100\, V/cm$; $\mu_n = 0.39\, m^2/V\text{-sec}$, $\mu_p = 0.19\, m^2/V\text{-sec}$. what is the drift velocity of holes and electrons.

Sol Given that $E = 100\, V/cm$

$\mu_n = 0.39\, m^2/V\text{-sec}$

$\mu_p = 0.19\, m^2/V\text{-sec}$

$\rho = 47\, \Omega\, cm$

Conductivity $\sigma = n_i q(\mu_n + \mu_p)$

$$n_i = \frac{\sigma}{q(\mu_n+\mu_p)} = \frac{1}{\rho q(\mu_n+\mu_p)}$$

$$n_i = 2292 \times 10^{10} / cm^3$$

Drift velocity of holes $V_d = \mu_p E = 19 \times 10^4\, cm/sec$

Drift velocity of Electron $V_n = \mu_n E = 39 \times 10^4\, cm/sec$

* Fermi - Dirac Function:-

The Fermi - Dirac probability function specifies the fraction of all states at energy E (in ev) occupied under conditions of thermal equilibrium.

From quantum physics,

$$f(E) = \frac{1}{1+e^{(E-E_F)/KT}}$$

where 'K' is the Boltzman's Constant in eV/K

'T' is the temperature in K

Carrier Concentrations are given by,

$$p = N_V \cdot e^{-(E_F-E_V)/KT}$$

$$n = N_C \cdot e^{-(E_C-E_F)/KT}$$

* Fermi level in Intrinsic semi conductor

In case of intrinsic semiconductor,

$$n_i = p_i$$

$$N_c \cdot e^{-(E_c-E_F)/KT} = N_v \cdot e^{-(E_F-E_v)/KT}$$

$$\frac{N_c}{N_v} = e^{\frac{-(E_F-E_v)+(E_c-E_F)}{KT}}$$

$$\ln\left(\frac{N_c}{N_v}\right) = \frac{E_c+E_v-2E_F}{KT}$$

If the effective masses of electrons and holes are same

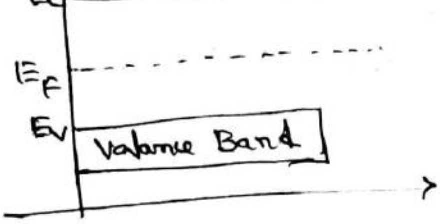
$$N_c = N_v.$$

Then $$0 = \frac{E_c+E_v-2E_F}{KT}$$

$$2E_F = E_c+E_v$$

$$\boxed{E_F = \frac{E_c+E_v}{2}}$$

From the above equation, Fermi level is present at the center of the forbidden energy band.



* Fermi levels in Extrinsic Semi conductor:-

The Fermi level in an N-Type material is,

For an n-Type material $n \simeq N_D$

$$n = N_c \cdot e^{-(E_c - E_F)/KT}$$

$$N_D = N_c \cdot e^{-(E_c - E_F)/KT}$$

$$E_F = E_c - KT \ln\left(\frac{N_c}{N_D}\right) \quad \text{— (1)}$$

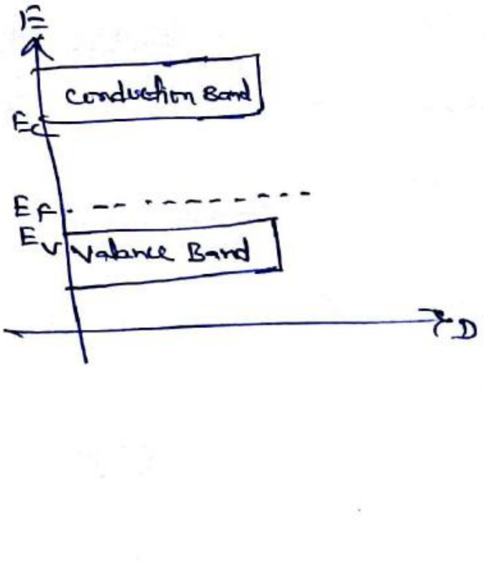
For a p-Type material, $p \simeq N_A$

$$p = N_v \cdot e^{-(E_F - E_v)/KT}$$

$$N_A = N_v \cdot e^{-(E_F - E_v)/KT}$$

$$E_F = E_v + KT \ln\left(\frac{N_v}{N_A}\right) \quad \text{— (2)}$$

From the above equations, Fermi level is present just below conduction band for N-Type Semi conductor and just above valance band for p-Type semi conductor.



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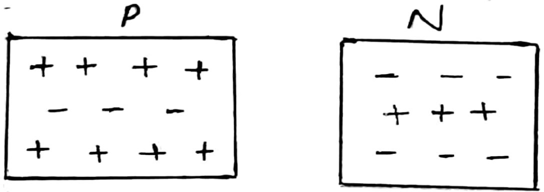
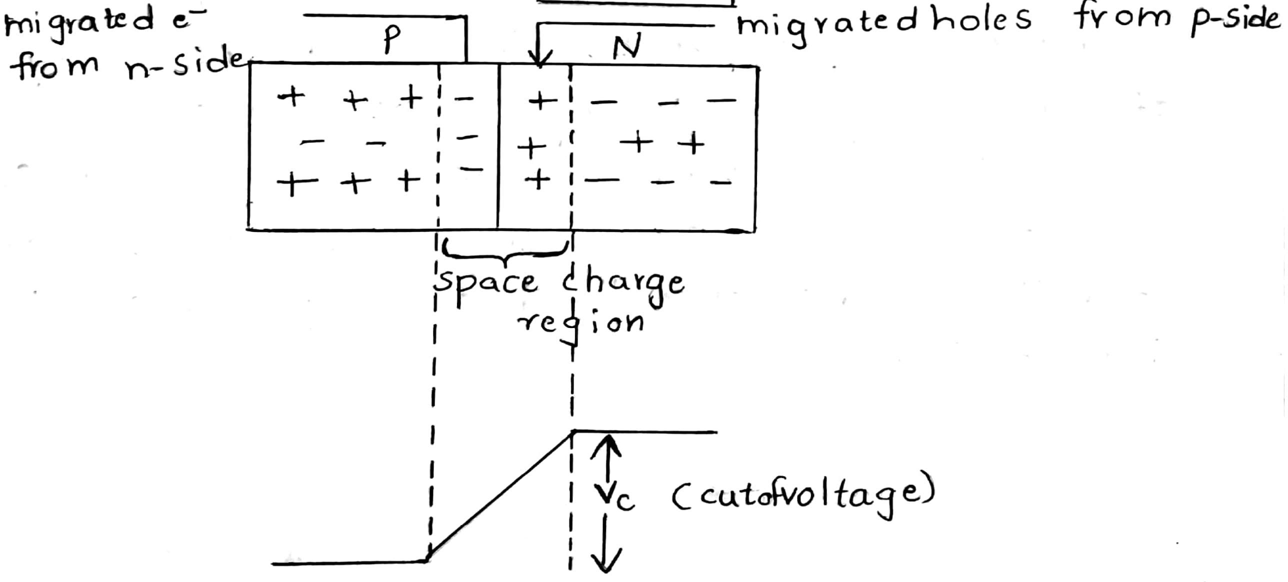
* <u>open circuit p-n junction</u>:- A junction is formed between p-type semiconductor and n-type semiconductor are joined together. This device is called p-n junction diode because there it has 2 electrodes. One for p-region (anode) and the other for n-region (cathode).

The n-type semiconductor has high concentration of free electrons. while p-type semiconductor has high concentration of holes as shown in below figure. At the junction, there is a tendency for the free electrons to move towards to p-side and holes to the n-side. This process is known as "Diffusion"





when the free electrons diffusing from n-side to p-side, they recombine with the holes and leaves a negatively charge immobile ion near the junction of p-side.

When the holes diffusing from p-side to n-side they recombine with electrons and leaves a

Positively charged immobile ion near the junction n-side.

After certain extent the immobile positive and neg ve ions in n+p regions respectively prevents further charge carrier diffusion from p to n and n to p regio These immobile ions forms a region called depletio region. This region is also known as space charge region

This region develops the potential difference across the junction, this potential acts as a barri for further conduction. Thus, this potential is name as barrier potential (or, cut-in cutting voltage

The barrier voltage is 0.3V for Ge and 0.7V for 'Si'

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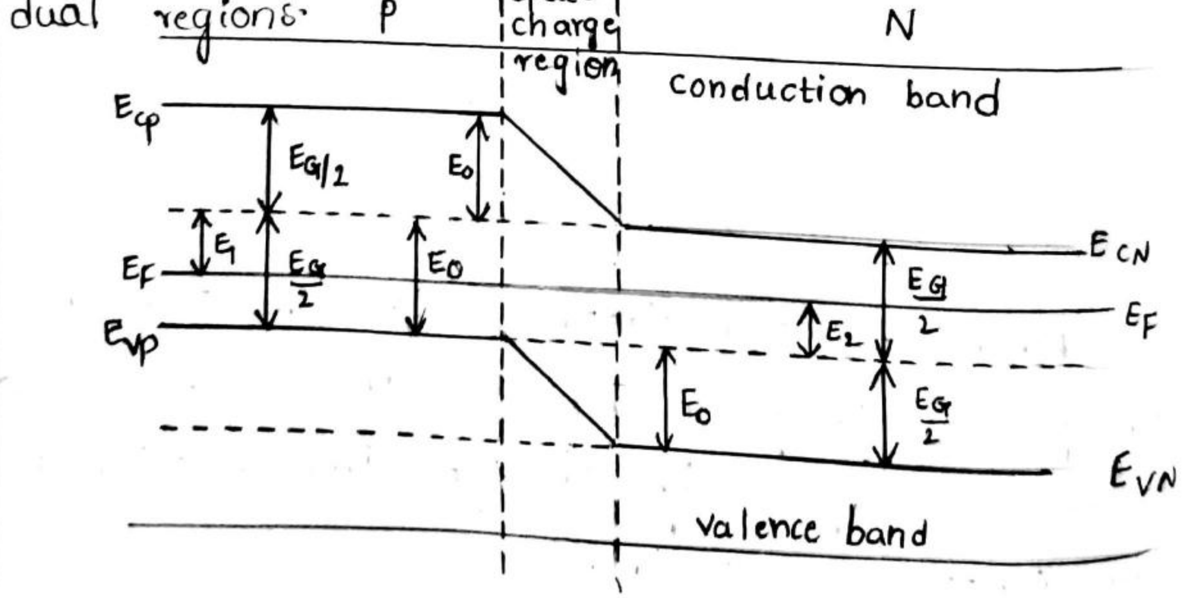
Energy band diagram of p-n junction diode:-

When a p-n junction is formed the energy le of these regions undergo relative shift to make the fermi level constant throughout the specimen Such a shift doesnot disturb the relative position of conduction band, valence band and fermi levels of indi dual regions.



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We know that Fermilevel (E_F) is closer to the conduction band at E_{CN} in N-type and closer to the valence band edge (E_{VP}) in p-type. But it is constant throughout the region when forming a p-n junction.

The total shift in the energy level 'E_0' is given by

$$E_0 = E_1 + E_2$$

$$E_0 = \left[\frac{E_G}{2} - (E_F - E_{VP})\right] + \left[\frac{E_G}{2} - (E_{CN} - E_F)\right]$$

$$E_0 = E_G - (E_F - E_{VP}) - (E_{CN} - E_F)$$

$$(E_0 = \gamma)$$

we know that $E_F - E_{VP} = KT \ln\left[\frac{N_V}{N_A}\right]$

$$E_{CN} - E_F = KT \ln\left[\frac{N_C}{N_D}\right]$$

$$E_0 = KT \ln\left[\frac{N_C N_V}{n_i^2}\right] - KT \ln\left[\frac{N_V}{N_A}\right] - KT \ln\left[\frac{N_C}{N_D}\right]$$

$$= KT \ln\left[\frac{N_C N_V}{n_i^2}\right] - KT \ln\left[\frac{N_V N_C}{N_A N_D}\right]$$

$$= KT \ln\left[\frac{N_C N_V}{n_i^2} \times \frac{N_A N_D}{N_V N_C}\right]$$

$$E_0 = KT \ln\left[\frac{N_A N_D}{n_i^2}\right]$$

but $E_0 = qV_0$

$$qV_0 = KT \ln\left[\frac{N_A N_D}{n_i^2}\right]$$

$$\boxed{V_0 = \frac{KT}{q} \ln\left[\frac{N_A N_D}{n_i^2}\right]}$$

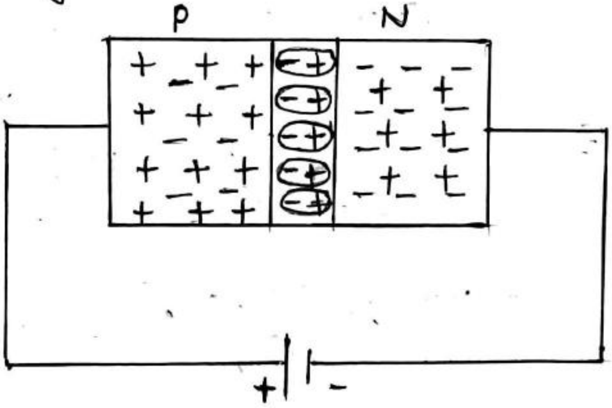
The above expression, gives the potential barrier across the p-n junction diode.

Operation of p-n junction:-

The working of p-n junction diode should be considered under the effect of foward bias and reverse bias across the junction.

1. **Forward bias operation:-** In an unbiased p-n junction there is no flow of current. A p-n junction connected to external voltage source is called a biased p-n junction. By this biasing, the width of depletion region is controlled.

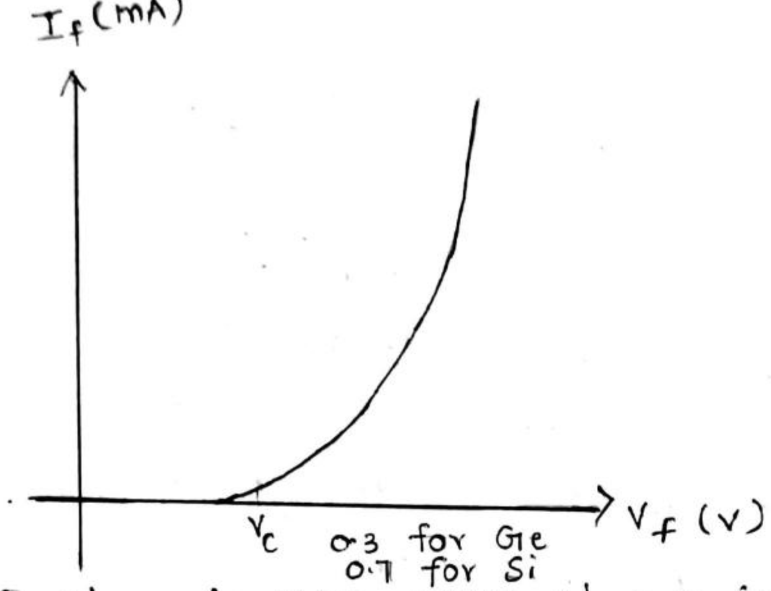
when the positive terminal of battery is connected to the p-type semiconductor and negative terminal to n-type semiconductor, it provides the forward bias to p-n junction as shown in below figure.



The applied forward potential establishes an electric field opposite to the potential barrier. Therfore, the potential barrier is reduced. As the potential barrier is very small (0.3 for Ge and 0.7 for Si), a small forward voltage is sufficient completely eleminate the barrier potential, thus the junction resistance becames zero.

In otherwords, the positive terminal of battery repels the holes in p-type region to move towards the junction and negative terminal of battery repels electrons in n-type to move towards the junction, which results in decreasing of the depletion region when the applied potential is more than the internal barrier potential then the depletion region completely dissapears.

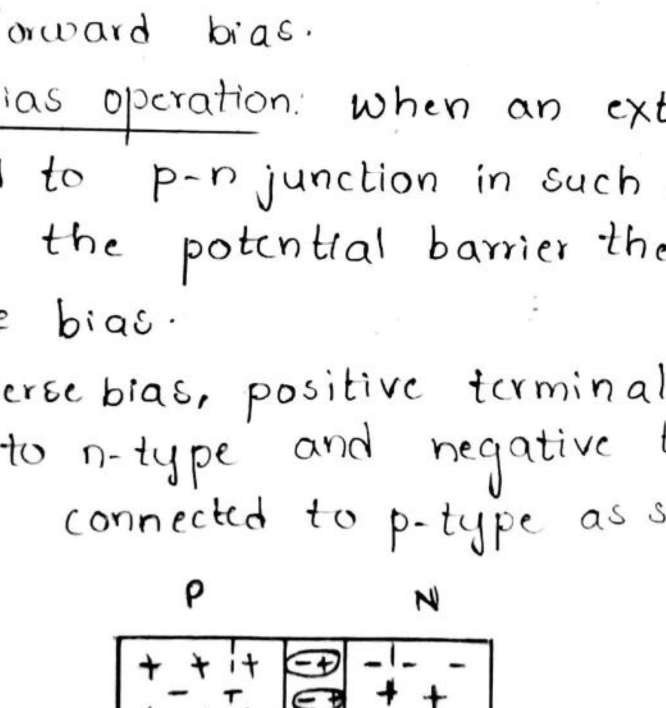
In forward bias, the low resistance path allows the current, which is called as forward bias current.



The VI characterstics curve of p-n junction diode in forward bias.

2 Reverse bias operation: when an external voltage is applied to p-n junction in such a way that it increases the potential barrier then it is called as Reverse bias.

For Reverse bias, positive terminal of battery is connected to n-type and negative terminal of battery is connected to p-type as shown in below figure



When the reverse bias voltage is applied to the junction, all the majority carriers of p-region

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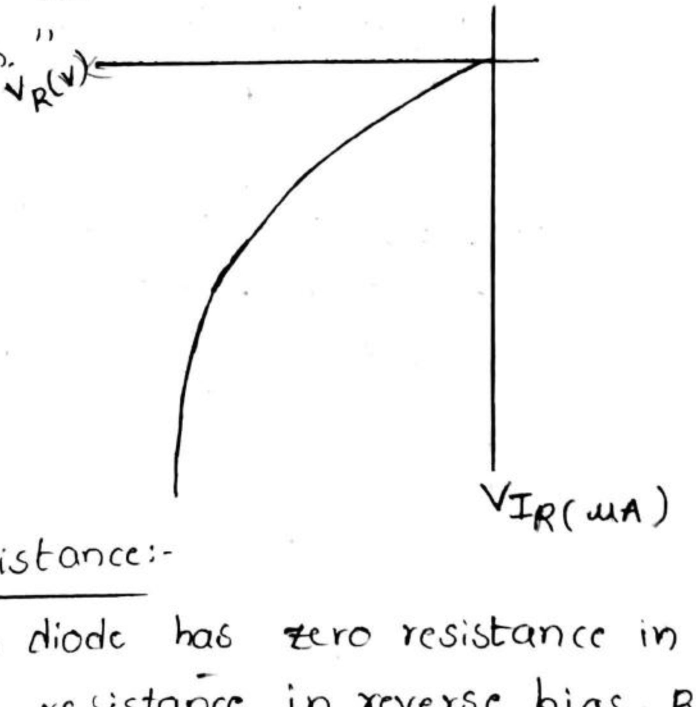
are attracted towards negative terminal of the battery. and electrons (majority carriers o n-type) are attracted towards the positive termi al of battery. Hence the depletion region increa So, the diode offers high resistance in reverse bia A small amount of current flows through the junction due to minority carriers which is known a "Reverse saturation current." (I_{so})

If the reverse voltage is further increased, the kinetic energy of minority carriers (electrons) becomes so high which breaks covalent bonds in the crystal. Thus releasing the free charge carriers. The newly released free charge carriers gain enough energy to disrupt other covalent bonds. This process is uncontrolled chain reaction which leads to "Avalanche (or) flood of cha carriers". Thus increase in the reverse current drastically. This breakdown is called as "Avalanche breakdown."



Diode Resistance:-

An ideal diode has zero resistance in forward bia and infinite resistance in reverse bias. But in practic no diode can act as ideal diode.

The ratio of V/I of V-I characteristics of diode gives static resistance of diode. (R)

It is the reciprocal of the slope of the line (V-I

AC or dynamic resistance is defined as

$$r = \frac{\Delta V}{\Delta I} = \frac{\text{change in voltage}}{\text{change in current}}$$

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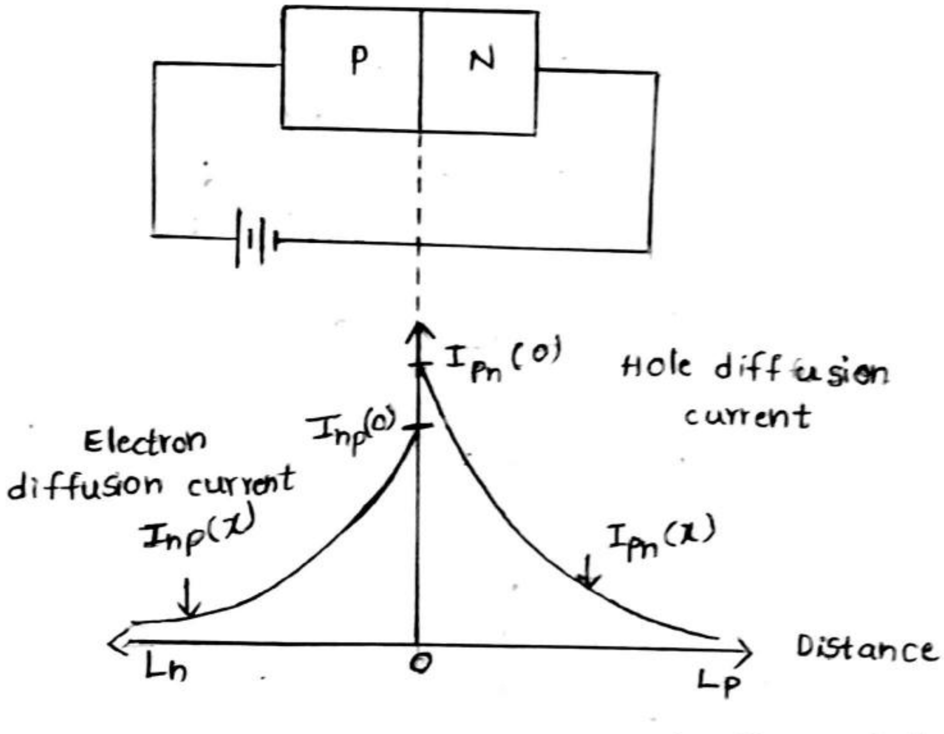
Diode current equation: (current components)

When a p-n diode is in forward bias, holes are injected from p-side to n-side and electrons are injected from n-side to p-side. The below figure shows several components of hole concentration in n-side of a forward bias diode.

Assume the doping of two regions is unequal i.e $N_A > N_D$.



The hole diffusion current $I_{pn}(x)$ in n-region is greater than electron diffusion current $I_{np}(x)$ in p-region. The total current at the junction is given by $I = I_{np}(0) + I_{pn}(0)$

We know that the diffusion current

$$I_{pn} = -qAD_p \frac{dP_n}{dx}$$

$$I_{pn}(x) = \frac{qAD_p}{L_p} P_n'(x) \; e^{-x/L_p}.$$

where L_p is diffusion length of holes in n-regi

At $x = 0$

$$I_{pn}(0) = \frac{qAD_p\, p_n'(0)}{L_p}$$

$$I_{pn}(0) = \frac{qAD_p}{L_p}\left[p_n(0) - p_{no}\right] \quad -①$$

As the diode is in forward bias, the total curren density due to holes.

$$J_p = qp\mu_p E + \left(-qD_p\frac{dp}{dx}\right)$$

$$J_p = qp\mu_p E - qD_p\frac{dp}{dx}$$

When the bias voltage is increase 'J' becom zero. At higher supply, drift current = diffusion current

so, $qp\mu_p E = qD_p\frac{dp}{dx}$

$$E = \frac{D_p}{\mu_p}\times\frac{1}{p}\frac{dp}{dx}$$

We know that

From Einstein relation $\frac{D_p}{\mu_p} = V_T = \frac{KT}{q}$

where V_T = volt equivalent temperat-ure

$$E = \frac{V_T}{p}\frac{dp}{dx}$$

we know that $E = -\frac{dV}{dx}$

$$-\frac{dV}{dx} = \frac{V_T}{p}\frac{dp}{dx}$$

$$-\frac{dV}{V_T} = \frac{dp}{p}$$

Integrate on both sides.

$$\int_{p_{po}}^{p_n(0)} \frac{dp}{p} = -\int_{0}^{(V_0-V)} \frac{dV}{V_T}$$

$$\ln[P]\Big|_{P_{p0}}^{P_n(0)} = -\frac{(V_0-V)}{V_T}$$

$$\ln\left[\frac{P_n(0)}{P_{p0}}\right] = -\frac{(V_0-V)}{V_T}$$

$$P_n(0) = P_{p0}\, e^{-\frac{(V_0-V)}{V_T}} \quad - ②$$

we know that: $P_{n0} = P_{p0} \cdot e^{-(V_0)|V_T}$ — ③

From above two equations ② & ③

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

$$\frac{P_n(0)}{P_{n0}} = e^{V|V_T}$$

$$P_n(0) = P_{n0}\, e^{V|V_T} \quad - ④$$

Substitute ④ in ①

$$I_{pn}(0) = \frac{qAD_p}{L_p}\left[P_{n0}\, e^{V|V_T} - P_{n0}\right]$$

$$I_{pn}(0) = \frac{qAD_p}{L_p}\left[P_{n0}\,(e^{V|V_T}-1)\right]$$

similarlly

$$I_{np}(0) = \frac{qAD_n}{L_n}\left[n_{p0}\,(e^{V|V_T}-1)\right]$$

Now total current through the junction

$$I = I_{np}(0) + I_{pn}(0)$$

$$I = \frac{qAD_p}{L_p}\left[P_{n0}(e^{V|V_T}-1)\right] + \frac{qAD_n}{L_n} n_{p0}\left[e^{V|V_T}-1\right]$$

$$I = \left[\frac{qAD_p P_{n0}}{L_p} + \frac{qAD_n n_{p0}}{L_n}\right] e^{V|V_T} - 1.$$

Let $I_0 = \frac{qAD_pP_{no}}{L_p} + \frac{qAD_n n_{po}}{L_n}$

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

The above equation is called the diode current equation.

where I_0 = reverse saturation current

$$I = I_0 \left[e^{qV/KT} - 1 \right] \quad \left(\because V_T = \frac{KT}{q} \right)$$

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Diode Resistance:

w.k.t $\quad I = I_0 \left[e^{V/\eta V_T} - 1 \right] \quad - ①$

$$I + I_0 = I_0 e^{V/\eta V_T} \quad - ②$$

$\eta = 1$ for Ge

$\eta = 2$ for Si

Differentiate ① w.r.t V

$$\frac{dI}{dV} = I_0 e^{V/\eta V_T} \times \frac{1}{\eta V_T}$$

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

$$\frac{dV}{dI} = \frac{\eta V_T}{I + I_0} \quad [\text{from } ②]$$

$$r_f = \frac{dV}{dI} = \frac{\eta V_T}{I + I_0} = \frac{\eta V_T}{I}$$ ('I_0' is negligible in forward bia

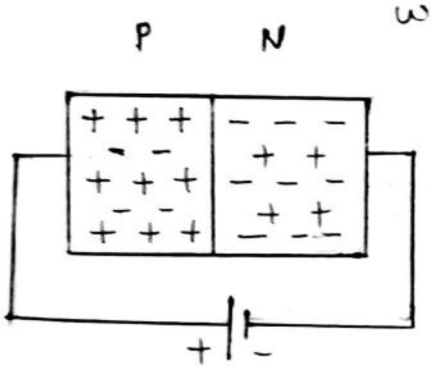
$$\boxed{r_f = \frac{\eta V_T}{I}}$$

Diode capacitance:-

1. Diffusion capacitance:-
2. Transition or, space charge capacitance

Diffusion capacitance: In forward bias p-n junction exhibit capacitance action known as Diffusion capacitance (C_D). It is due to the diffusion of minority carriers on both sides of the junction. These carriers get accumulated near the junction before they diffused. As a result, the holes in n-region and electron in p-region are seperated by a very thin depletion layer which leads to the capacitance.

The diffusion capacitance $C_D = \frac{dQ}{dV}$



w.k.T $dQ = T\,dI$ $\qquad i = \frac{dq}{dt}$

$C_D = \frac{T\,dI}{dV}$

$\boxed{C_D = \frac{T\,I}{\eta V_T}}$ [from diode resistance]

Transition or space charge capacitance:

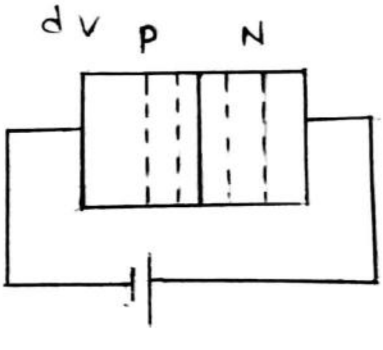
When a diode is in reverse bias, the holes in p-side and electrons in n-side drift away from the junction, thereby increasing the thickness of depletion region. This capacitance due to depletion layer is known as depletion capacitance or, Transition capacitance or, space charge capacitance

The transition capacitance $C_T = \frac{dQ}{dV}$

w.k.T $i = \frac{dQ}{dt}$

$C_T = \frac{dQ}{dt} \times \frac{dt}{dV}$

$C_T = i\,\frac{dt}{dV}$



$$\boxed{i = C_T \frac{dv}{dt}}$$

Effect of temperature on p-n junction diode:

From diode current equation, we can observe that the diode current depends on I_0 and V_t

where I_0 = reverse staturation current.

The increase in reverse saturation current I_0 with temperature is 7 % per degree Centigrade.

If the temperature is increased by fixing the appli voltage 'v', the current increases. To keep the curre I a constant value, the value of 'v' should be decrea

i.e $\frac{dV}{dt} = -2.5 \text{ mv}/°c$

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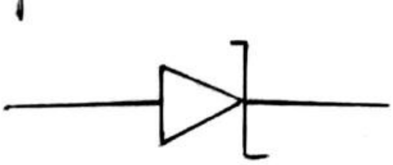
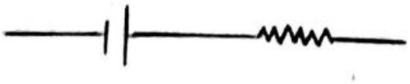
Zener Diode:-

In p-n junction diodes, the doping is low, as a result of this the breakdown voltage is high.

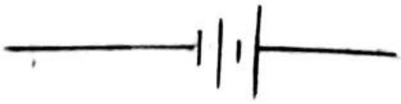
If P & N regions are heavily doped then the breakdown voltage can be reduced. when the doping is heavy, small reverse voltage can break the ban in the depletion region (thin region). Zener breakdow occurs in junctions which is heavily doped and have narr depletion layer.



Zener diode symbol



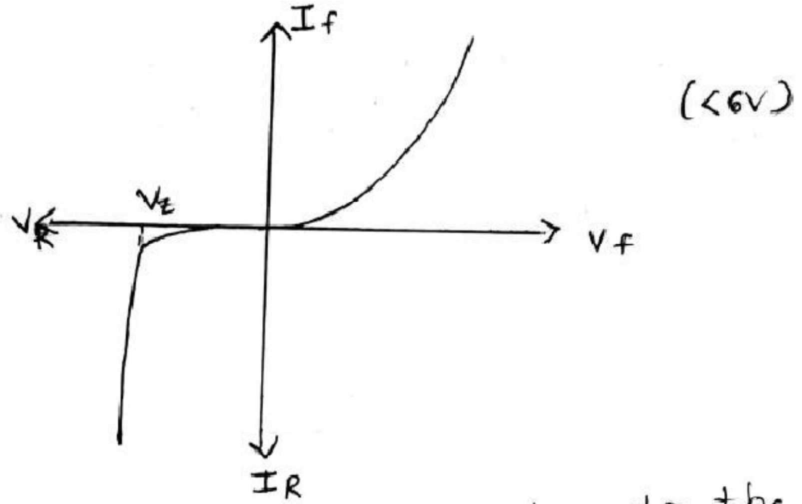
Practical representation



Ideal representation

V-I characteristics of zener diode:

The forward characteristics of zener diode is similar to the p-n junction diode. The reverse characteristics of zener diode is obtained as follows



The reverse current is due to the minority carriers. As the reverse voltage is gradually increased, the covalent bonds in the depletion region break away themselves. This effect is known as "Zener effect".

100V.

After the zener effect, the voltage across the junction is constant. even though current increases rapidly. This voltage is called zener voltage (V_Z). This ability of the diode is called Regulating ability and is an improtant feature of a Zener diode

Applications:

1. Voltage regulator
2. Peak clippers.

3. For reshaping waveforms
4. For meter protection against damage from accidental application of excessive voltage

Breakdown mechanism in semiconductor diodes

When a diode is reverse bias, the depletion layer widens to setup a large potential barrier which prevents the diffusion of majority carrier from one side to other Thus there is no current due to majority carrier Only very small reverse current exist due to minority carriers and is further temperature dependent As the reverse bias voltage is further increase, it reach a point where the reverse current shoots up suddenly.

This occurs due to the junction breakdown. There are 2 types of junction breakdown mechanism

1 Avalanche breakdown
2. Zener breakdown

1 Avalanche breakdown mechanism

This breakdown occurs in lightly doped diode where the depletion layer is very wide. The reverse voltage imparts the high energy to minority carriers The minority carriers with sufficient kinetic energy disrupts covalent bonds in the junction there by releasing the free charge carriers. The newly released free charge carriers gain enough energy to disrupt other covalent bonds. This process is continuous chain reaction and is a cumulative process. It is known as Avalanche multiplication, which leads to Avalanche (or) flood of charge carriers. Thus increasing the reverse current drastically.

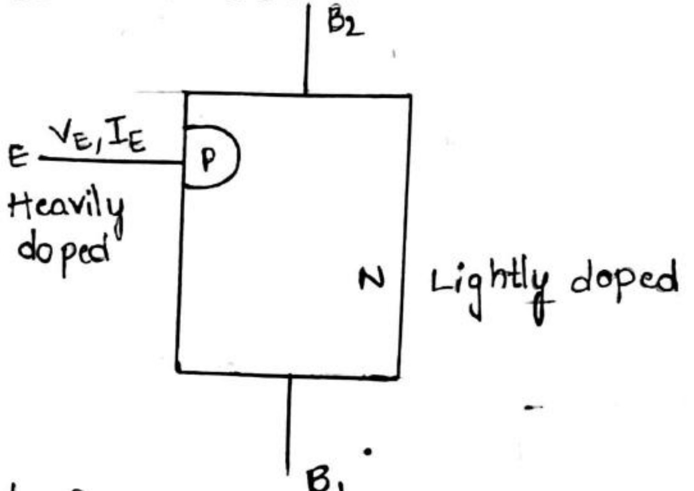
2. <u>Zener breakdown:</u>

This breakdown occurs in heavily doped diodes. These diodes have very thin depletion layer. When the reverse voltage is increased, the electric field breaks covalent bonds and creates new electron and hole pairs. It increases the reverse current drastically

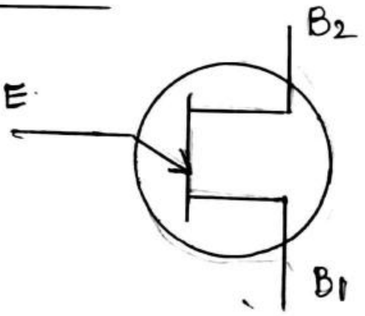
Avalanche breakdown	Zener breakdown.
1. It occurs in lightly doped junction	1. It occurs in heavily doped junction
2. It ~~is~~ occurs in p-n junction diode in reverse voltage greater than 6V	2. It occurs in zener diode with reverse voltage less than 6V.
3. The reverse bias V-I characteristics curve is not sharp	3. The reverse bias V-I characteristics curve is very sharp in break down region
4. Temperature coefficient is positive	4. Temperature coefficient is negative

Unijunction Transistor (UJT):

As the name implies, it has only one p-n junction but it is a three terminal silicon diode. It doesnot amplify like BJT & FET. It has the negative resistance characteristics which makes it useful as an oscillator.



Symbol of UJT:



The basic construction of UJT is as shown below. It consists of lightly doped N-type silicon bar sandwitched with heavily doped p-type material for producing single p-n junction. There are three terminals named as emitter, base 1 and base 2. The arrow points the direction of ~~b~~ convenctional current when the diode is in ON state.

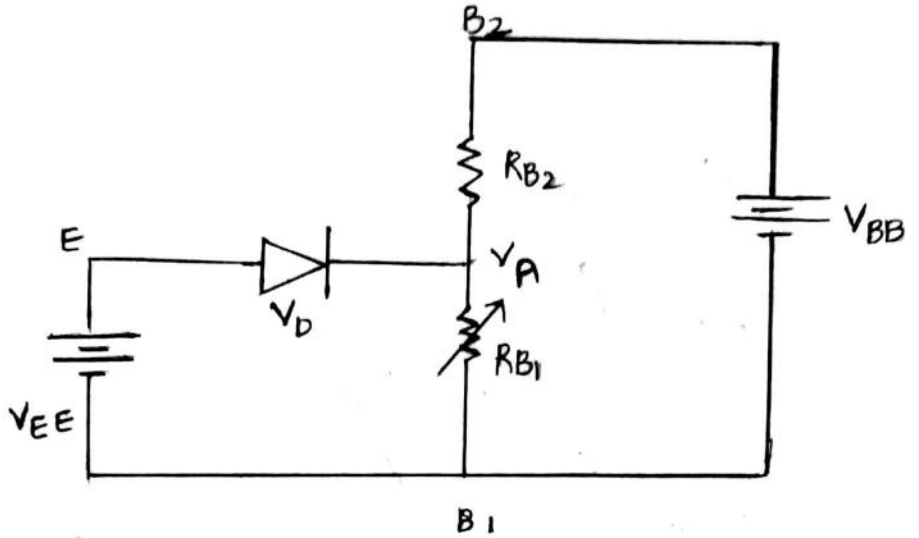
Equivalent circuit of UJT:

The equivalent circuit of UJT is as shown in below figure. It consists of a diode and resistor 'R_{BB}'.

where $R_{BB} = R_{B_1} + R_{B_2}$

$R_{B_1} = 60\%$ of R_{BB}

$R_{B_2} = 40\%$ of R_{BB}



'R_{BB}' represent the total resistance between base-1 & base-2 terminals. A part of 'V_{BB}' is dropped over R_{B_1} & R_{B_2}. The drop across R_{B_1} is given by $V_A = V_{BB} \cdot \left[\frac{R_{B_1}}{R_{B_1}+R_{B_2}}\right]$

where $\frac{R_{B_1}}{R_{B_1}+R_{B_2}}$ is given a special symbol 'η' is intrinsic standard of ratio.

$$V_A = V_{BB}\,\eta$$

Usually 'η' lies between 0.5 to 0.8

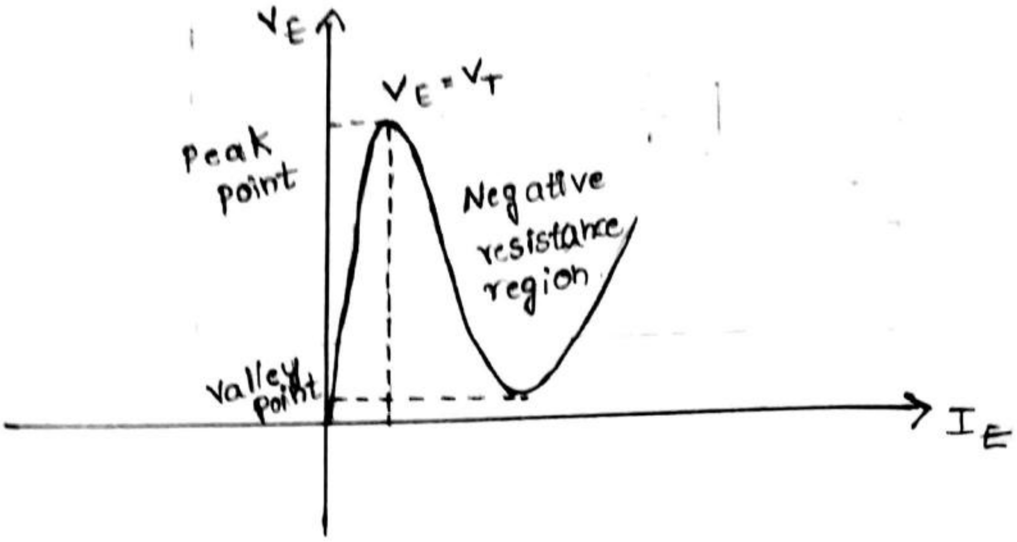
Operation: When no voltage is applied at the emitter, Base 'B_1' reverse biases the p-n junction and hence emitter current is 'cut-off'. Here a small lekage current flows from 'B_2' to emitter due to minority carriers

When a positive voltage is applied at the emitter and 'EV_{BB}' is switched ON, a voltage 'V_A' is developed across 'R_B'. The total reverse bias voltage $V_T = V_D + V_A$.

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

when the emitter voltage exceeds, the total reverse bias voltage V_T, then the diode becomes forward bias. This emitter voltage is called 'peak voltage' Since the diode starts conduct, the current 'I_P' flows through 'R_{B_1}'. This increase in 'I_E' increases

Voltage drop across R_{B_1} (V_A) and 'V_E' decreases wh I_E increases, so UJT posses negative resistance



Applications.

1. switching circuits
2. Pulse generation
3. saw tooth generation
4. Trigger circuits
5. Voltage regulated supplies.

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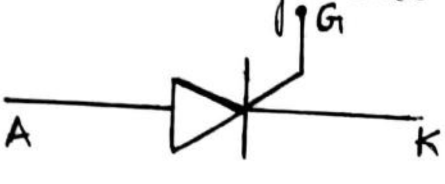
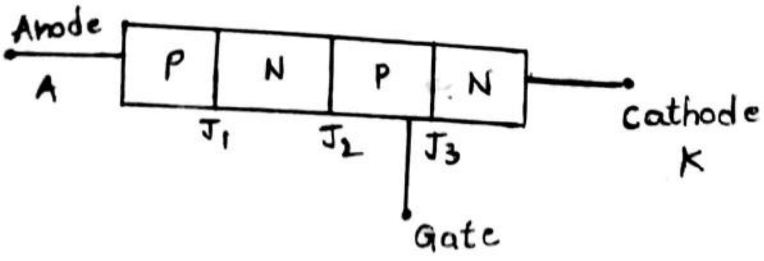
Silicon Controlled Rectifier (SCR):

It is a four layer, three terminal device. It is widely used as switching device in power control applications.

Symbol:

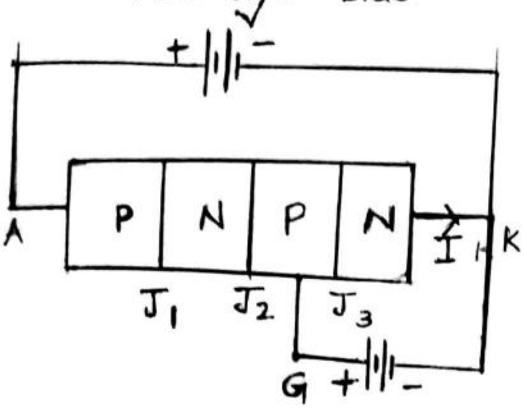




The junctions are marked as J_1, J_2, J_3. whereas the terminals are anode (A), cathode (K) and Gate (G)

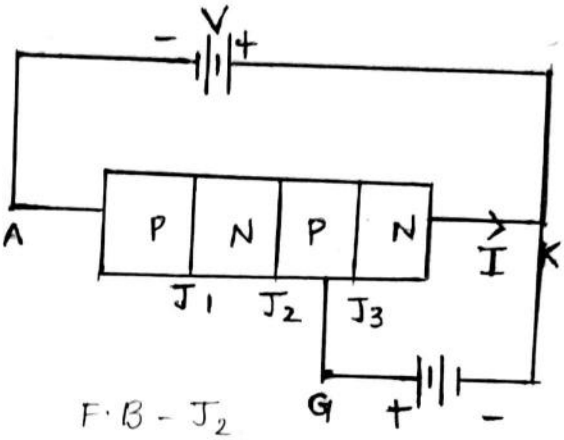
The gate terminal is connected to inner p-layer an it controlls the firing (or) switching of SCR. The biasing of SCR is shown in below figure

Forward Bias



F·B − J_1, J_3
R·B − J_2

Reverse Bias

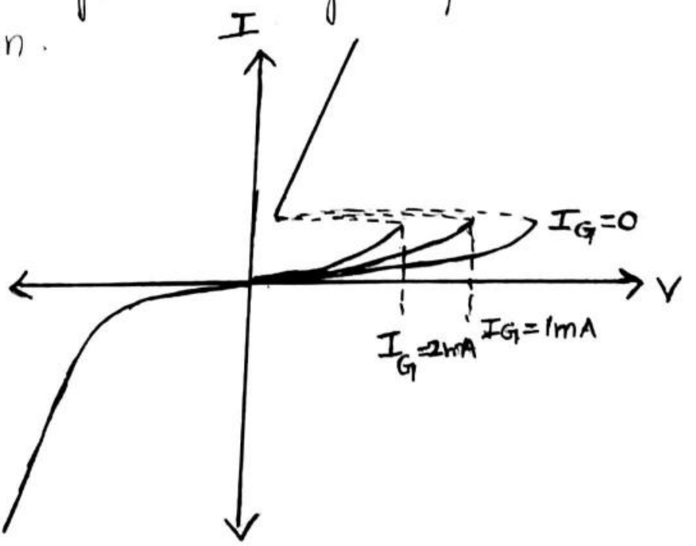


F·B − J_2

R·B − J_1, J_3

In forward bias, the junction J_1 & J_3 are in forward bias & J_2 is in reverse bias

As the supply voltage is increased, we will get the current due to minority carriers across the junction J_2. If you further increase the biasing voltage then Junction J_2 will break down which leads to a large amount of current as shown below. As the current is increased suddenly, the voltage drop will occur at the supply position.



Now the SCR is in ON state whenever the breakdown occurs at junction J_2. The current flowing through SCR is limited only by Anode supply voltage

In Reverse bias of SCR, the junctions J_1, J_3 are in reverse bias & J_2 is in forward bias. If the applied reverse voltage is small, the SCR is off and hence no current flows through the device. If the reverse voltage is increased to breakdown the

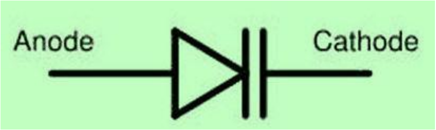
J_1 & J_3, the Avalanche breakdown will occur th
allows current to flow through SCR.

Applications

1. Relay control
2. Motor control
3. Heater control
4. Regulated power supply

Varactor Diode:

Varactor diode is a one kind of semiconductor microwave solid-state device and the applications of this diode mainly involve in where variable capacitance is preferred which can be accomplished by controlling voltage. These diodes are also named as varicap diodes. Even though the outcome of the variable capacitance can be showed by the normal P-N junction diodes, but these diodes are chosen for giving the desired capacitance changes as they are special types of diodes. Varactor diodes are specifically fabricated and optimized such that they permit a high range of changes in capacitance.

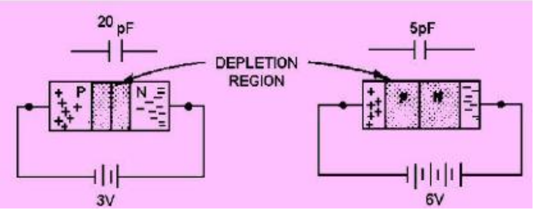


The different types of Varactor diodes are available in the market such as hyperabrupt, abrupt and gallium-arsenide Varactor diodes. The symbol of the Varactor diode is shown in the above figure that includes a capacitor symbol at one end of the diode that signifies the characteristics of the variable capacitor of the Varactor diodes.

The symbol of the Varactor diode looks like a common PN- junction diode that includes two terminals namely the cathode and the anode. And at one end this diode is inbuilt with two lines that specify the capacitor symbol.

Working of a Varactor Diode:

To know the Varactor diode working principle, we must know the function of capacitor and capacitance. Let us consider the capacitor that comprises of two plates alienated by an insulator as shown in the figure.



We know that, the capacitance of a capacitor is directly proportional to the region of the terminals, as the region of the terminals increases the capacitance of the capacitor increases. When the diode is in the reverse biased mode, where the two regions of P-type and N-type are able to conduct and thus can be treated as two terminals. The depletion area between the P-type & N-type regions can be considered as insulating dielectric. Therefore, it is similar to the capacitor shown above.

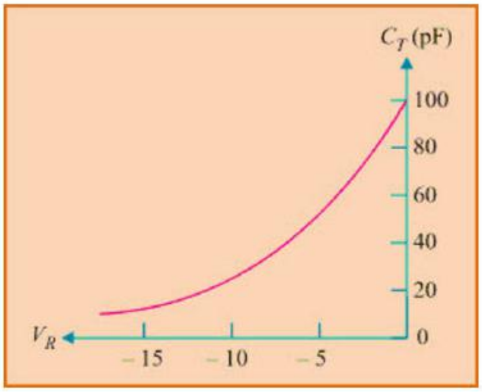
The volume of the depletion region of the diode varies with change in reverse bias. If the reverse voltage of the diode is increased, then the size of the depletion region increases.

Likewise, if the reverse voltage of the Varactor diode is decreased, then the size of the depletion region decreases. Hence, by changing the reverse bias of the diode the capacitance can be changed.

Characteristics of Varactor Diode:

The characteristics of Varactor diode have the following:

- These diodes significantly generate less noise compared to other diodes.
- The cost of these diodes is available at lower and more reliable also.
- These diodes are very small in size and very light weight.
- There is no useful when it is operated in forward bias.
- In reverse bias mode, Varactor diode enhances the capacitance as shown in the graph below.



Applications of Varactor Diode:

A few of the main applications of Varactor diodes can be listed below:

- These diodes can be used as frequency modulators and RF phase shifters.
- These diodes can be used as frequency multipliers in microwave receiver.
- These diodes are used to change the capacitance in tank LC circuits.