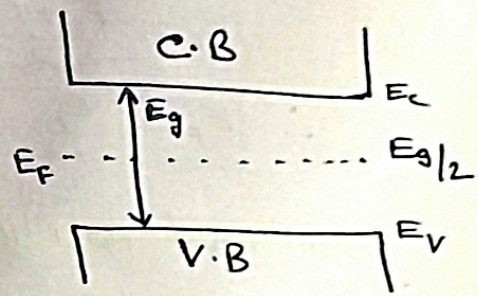
Fermi Level in Intrinsic Semiconductor:-

Intrinsic semiconductor acts as an insulator at absolute zero temp, so there is zero probability of finding a hole in valence band, so there are no charge carriers.
No. of electrons = No. of holes

Fermi level is exactly at midway between forbidden gap. Fermi level in centre indicates, equal concentration of electrons and holes.

Expression for position of fermi level in an intrinsic semi conductor:-



The e^- concentration in C.B is given by $n = N_c e^{-(E_c - E_F)/KT}$ → (1)

The hole concentration in V.B is given by $P = N_V e^{-(E_F - E_V)/KT}$ → (2)

At equilibrium $n = P$ → (3)

$$N_c e^{-(E_c - E_F)/KT} = N_V e^{-(E_F - E_V)/KT}$$

Taking log on both side.

$$\log N_c - \left(\frac{E_c - E_F}{KT}\right) = \log N_V - \left(\frac{E_F - E_V}{KT}\right)$$

$$\log N_c - \log N_V = \frac{1}{KT}\left[E_c - E_F - E_F + E_V\right]$$

$$KT \log \frac{N_c}{N_V} = E_c + E_V - 2E_F$$

$$2E_F = (E_c + E_V) - KT \log \frac{N_c}{N_V}$$

$$2E_F = (E_c + E_V) + KT \log \frac{N_V}{N_c}$$

$$E_F = \frac{(E_c + E_V)}{2} + \frac{KT}{2} \log \frac{N_V}{N_c} \rightarrow (4)$$

Here $N_c = 2\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/2}$

$N_V = 2\left[\frac{2\pi m_h^* KT}{h^2}\right]^{3/2}$

So $\frac{N_V}{N_c} = \left(\frac{m_h}{m_e}\right)^{3/2}$

$$\log \frac{N_V}{N_c} = \frac{3}{2} \log \frac{m_h}{m_e} \longrightarrow (5)$$

from eq^n (4) and (5)

$$E_F = \left(\frac{E_c+E_V}{2}\right) + \frac{KT}{2} \cdot \frac{3}{2} \log\left(\frac{m_h}{m_e}\right)$$

$$= \left(\frac{E_c+E_V}{2}\right) + \frac{3}{4} KT \log\left(\frac{m_h}{m_e}\right) \longrightarrow (6)$$

if $m_e = m_h$ then $\log \frac{m_h}{m_e} = 0$

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

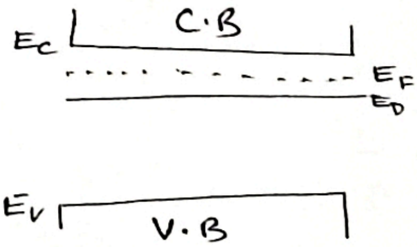
$$\therefore \boxed{E_F = \frac{E_g}{2}}$$

Fermi level position in Extrinsic semiconductor:-

In n-type semi conductor :-

In n-type S.C, a donor impurity is added. Each donor atom donates one free electron and there are large no. of free e-s available in the C.B. so $n_e > n_h$.

So in n-type material the fermi level E_F gets shifted towards the C.B. The majority of e-s is almost due to extrinsically supplied electrons from the donor atoms here.



$n \simeq N_D$

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

Taking log both side

$$\log N_D = \log N_c - \frac{E_c-E_F}{KT}$$

$$\frac{E_c-E_F}{KT} = \log \frac{N_c}{N_D}$$

$$E_c - E_F = KT \log \frac{N_c}{N_D}$$

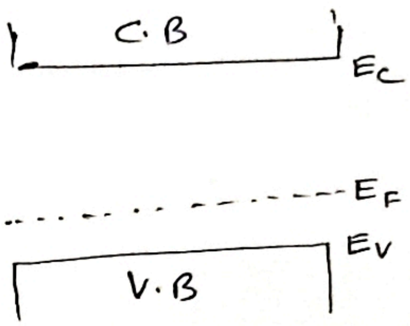
$$\boxed{E_F = E_c - KT \log \frac{N_c}{N_D}}$$

In P-type semi-conductor :- In p type semi-conductor, acceptor impurity is added. Each acceptor atom create one hole and there are large no. of holes available in C.B. Probability of occupying the energy is more towards valance band. So fermi level shift toward the V.B.

no. of holes > no. of electrons

$p \simeq N_A$

$N_A = N_V \, e^{-(E_F - E_V)/KT}$



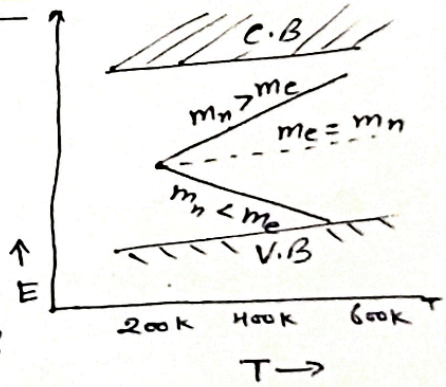
Taking log both side.

$\log N_A = \log N_V - \frac{E_F - E_V}{KT}$

$\frac{E_F - E_V}{KT} = \log N_V - \log N_A$

$$\boxed{E_F = E_V + KT \log \frac{N_V}{N_A}}$$

Variation of fermi-level with temperature :-



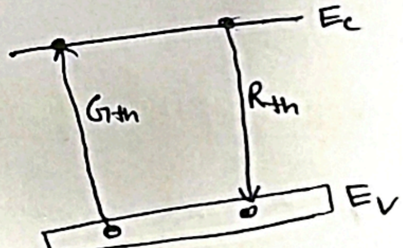
At 0K the fermi level uses at the middle of forbidden gap. But there is slight variation in E_F in high temperature region with increase in temp. the fermi level moves up (if $m_h > m_e$) toward bottom edge of C.B or downward to the top edge of V.B (if $m_h < m_e$).

* In n-type S.C, when temp increases the no. of electron in C.B also increases at high temp. The donor concentraction exceeds and behaves like an intrinsic semiconductor.
400K The fermi level moves downwards as temp increase, at particular temp the fermi level lies in the middle as intrinsic S.C.
* In P-type S.C, As temperature increase more and more acceptor atoms are ionized and hence the fermi level moves upwards. At a particular temp when all acceptor ~~atto~~ atoms ionized, the fermi level lies in the middle of energy Gap as intrinsic S.C.

Carrier generation and recombination:-

Consider a direct band gap semiconductor in thermal equilibrium. The continuous thermal vibration of lattice atoms causes some bonds between neighbouring to be broken. When a bond is broken, an electron-hole pair (EHP) is generated. In terms of the band diagram, the thermal energy enables a valance electron to make an upward transition to the C.B; leaving a hole in the V.B this process is called carrier generation and is represented by Generation rate G^{th} (no. of EHP's generates per cm^3 per second)

When an electron makes a transition downward from the C.B to V.B, an electron-hole pair is annihilated. This reverse process is called recombination. It is represented by the recombination rate R_{th}.



at thermal equilibrium

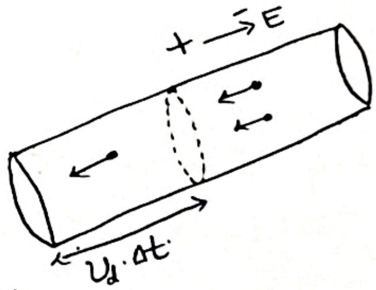
Under thermal equilibrium conditions, the generation rate G_{th} must equal the recombination rate R_{th}. So that carrier concentration remain constant and the condition $n_p = n_i^2$ is maintained.

$$\therefore G_{th} = R_{th}.$$

Carrier Transport: Diffusion and Drift current:-

Under the condition of thermal equilibrium, the electrons and holes are uniformly distributed in the crystal and in the absence of an external stimulus, their average velocity is zero and no current flows through the crystal. This is equally true for an intrinsic or an extrinsic semiconductor.

Drift current:- When an electric field E is applied across a semiconductor, the charge carrier acquire a directional motion over and above their thermal motion and produce drift velocity. This drift causes current to flow in s.c, under the influence of external electric field. This current, produced due to net drift of charge is called drift current.



When we apply electric field across the s.c, the randomly moving electrons experience an electric force in the direction of $\vec{E}$.

So $\quad F = qE$

acceleration $\quad a = \dfrac{eE}{m}$

drift velocity will be $v_d = a \times \text{time}$.

$$v_d = \left(\frac{eE}{m}\right)\tau \qquad \text{where } \tau = \text{average time}$$

In the time interval Δt each electron will cover the distance $= v_d \cdot \Delta t$

and the volume of the portion is $= v_d \cdot \Delta t \cdot A$.

no. of free electrons in this portion $= n v_d \cdot \Delta t \cdot A$

Hence the average charge crossing the area in time Δt.

$$\Rightarrow \Delta Q = neAV_d \cdot \Delta t$$

drift current $I = \frac{\Delta Q}{\Delta t} = neAV_d$.

drift current density due to free electrons is given by

$$J_n(\text{drift}) = \frac{I}{A} = neV_d = ne\mu_n E \qquad (\because V_d = \mu_n E)$$

So $\boxed{J_n(\text{drift}) = ne\mu_n E}$

Similarly, the drift current density due to holes is

$$\boxed{J_p(\text{drift}) = p \cdot e\mu_p E}$$

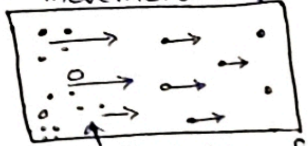
$$J(\text{drift}) = J_n(\text{drift}) + J_p(\text{drift})$$

$$J(\text{drift}) = ne\mu_n E + pe\mu_p E$$

$$\boxed{J(\text{drift}) = n(n\mu_n + p\mu_p)E}$$

⇒ drift current occurs only when external electric field is present across the solid. Although electrons and holes moves in opposite directions, the direction of conventional current flow due to both the carriers in same direction:

Diffusion current :-



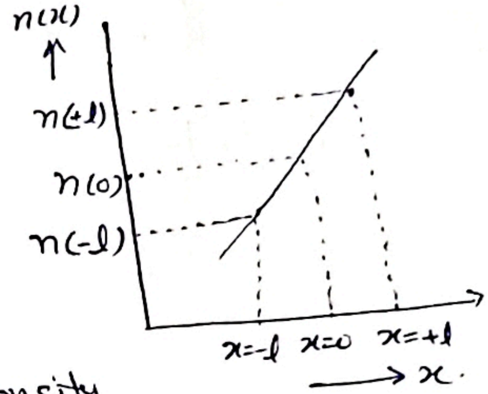
Process of diffusion

Diffusion current occurs due to transport of charges occuring because of non-uniform concentration of charged particles in a s.c.
Consider a piece of s.c which is non uniformly doped. Due to such non-uniformity doping, one type of charge carriers occur at one end of the piece of s.c. The charge carriers are either electrons or holes, of one type depending upon impurity used. They have the same polarity and hence experience a repulsion between them.

The result is that there is a tendency of charge carriers to move gradually. i.e to diffuse from the region of the high carrier density to the low carrier density. This process is called is diffusion.

The movement of charge carriers under the process of diffusion constitutes a current called diffussion current.

fig shows the variation of electron concentration with distance. due to this concentration gradient diffusion current flows.



Electron concentration vs distance.

Electron diffusion current density $\propto$ charge density

$$J_n \text{(diffusion)} \propto e \cdot \frac{dn}{dx}.$$

$$\boxed{J_n(\text{diff}) = e D_n \frac{dn}{dx}}$$

where $D_n \rightarrow$ Electron diffusion coefficient

$$D_n = \mu_n \frac{KT}{q}$$

Similarly, the hole diffusion current density is proportional to the hole density gradient and to the electronic charge,

so $J_p \text{(diffusion)} \propto e \frac{dp}{dx}$

$$J_p \text{(diffusion)} = -D_p \cdot e \frac{dp}{dx}$$

(- sign represents that the conventional diffusion current density due to hole is in negative direction)

Hence, $D_p \rightarrow$ hole diffusion coefficient ($D_p = \mu_p \cdot \frac{KT}{q}$)

The diffusion current continues till the carriers are evenly distributed through out the material.

A diffusion current is possible only in case of non-uniformly doped s.c.

Total current density:-

Drift and diffusion current coexist in S.C, the total current density due to drift and diffusion of electrons, may be written as

$$J_n = J_n(\text{drift}) + J_n(\text{diff})$$

$$\boxed{J_n = e\left(n\mu_n E + D_n \frac{dn}{dx}\right)}$$

Similarly for holes

$$J_p = J_p(\text{drift}) + J_p(\text{diff})$$

$$\boxed{J_p = e\left(P\mu_p E - D_n \frac{dp}{dx}\right)}$$

Continuity Equation:- The fundamental law governing the flow of charge is called the continuity equation.

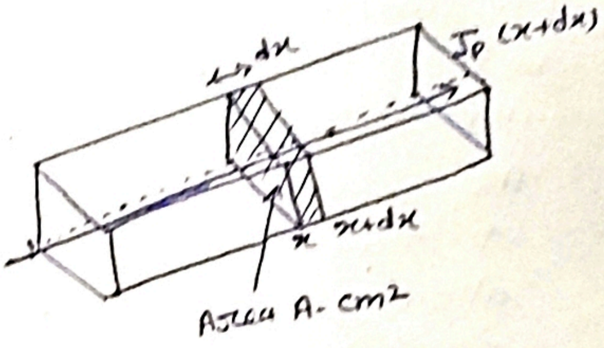
The continuity equation as applied to semiconductors describes how the carriers concentration in a given element volume of the crystal varies with time and distance.

$$\left.\frac{dP_n}{dt}\right|_{x\to x+\Delta x} = \frac{1}{e}\,\frac{J_p(x)-J_p(x+\Delta x)}{dx} - \frac{\Delta p}{\tau_p} \longrightarrow (1)$$

$\frac{dP_n}{dt}$ → Rate of holes build up

$\frac{J_p(x)-J_p(x+\Delta x)}{dx}$ → increase of hole conc^n in $\Delta x \cdot A$ per unit time

$\frac{\Delta p}{\tau_p}$ → Recombination Rate



As dx aproaches to zero we can write the current change in derivative form

$$\frac{dP_n}{dt} = \frac{d(\Delta p)}{dt} = -\frac{1}{e}\frac{dJ_p}{dx} - \frac{\Delta p}{\tau_p} \longrightarrow (2)$$

equation (2) is called the continuity equation for hole

similarly for e^-, we can write

$$\frac{d\Delta n}{dt} = \frac{1}{e}\frac{dJ_n}{dx} - \frac{\Delta n}{\tau_n} \longrightarrow (3)$$ [Since the charge is negative]

Now using diffusion current as

$$J_n(\text{diff}) = eD_n\frac{dn}{dx}$$

and $$J_p(\text{diff}) = -eD_p\frac{dp}{dx}$$

So eq^n (2) & (3) reduced to

$$\frac{d\Delta p}{dt} = D_p\frac{d^2p}{dx^2} - \frac{\Delta p}{\tau_p} \longrightarrow (4)$$

$$\frac{d\Delta n}{dt} = D_n\frac{d^2n}{dx^2} - \frac{\Delta n}{\tau_n} \longrightarrow (5)$$

in steady state $\frac{d\Delta p}{dt} = \frac{d\Delta n}{dt} = 0$ then eq^n (4) & (5) becomes

$$0 = D_p\frac{d^2p}{dx^2} - \frac{\Delta p}{\tau_p} \Rightarrow \boxed{\frac{d^2p}{dx^2} = \frac{\Delta p}{D_p\cdot\tau_p} = \frac{\Delta p}{L_p^2}} \longrightarrow (6)$$

$$0 = D_n\frac{d^2n}{dx^2} - \frac{\Delta n}{\tau_n} \Rightarrow \boxed{\frac{d^2n}{dx^2} = \frac{\Delta n}{D_n\tau_n} = \frac{\Delta n}{L_n^2}} \longrightarrow (7)$$

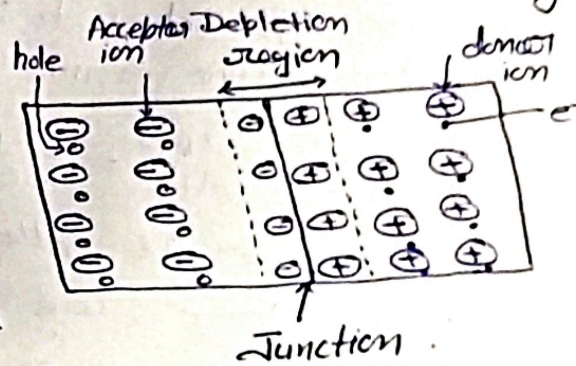
Where L_n and L_p are defined as $\sqrt{D_n\tau_n}$ and $\sqrt{\tau_p D_p}$ are called diffusion length.

PN-Junction :- Semiconductors that are doped with impurities form the basis of the practical devices. A semiconductor that has been doped with acceptor impurities and into the surface of which donor atoms are diffused form a P-N-Junction diode.

PN Junction is the boundary b/w one region of S.C with p-type impurities and another region containing n-type impurities.

The most remarkable property of a p-n Junction is that it has a non-linear conduction characteristics and allows current in one direction and opposes it in the opposite direction. This is known as rectifying property

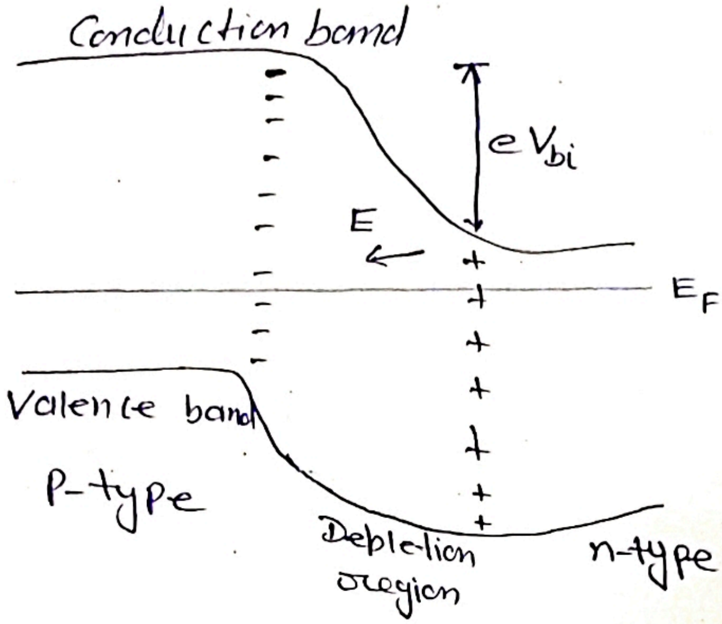
PN Junction with no external Voltage :-



A P-n Junction is shown in the figure. The P-type region has holes as majority charge carrier, and an equal no. of fixed negatively charged acceptor ions. Similarly the N-type region has electrons as majority charge carrier and an equal no. of fixed positively charged donor ions.

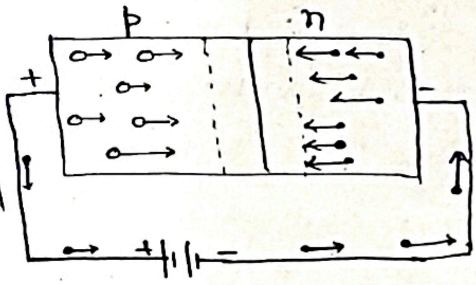
As soon as P-n Junction is formed, there is an immediate diffusion of the majority charge carriers across the Junction due to thermal agitation. Some electrons in n-regions diffuse into the P-region, while some of the holes in the P region diffuse in n-region. Thus at Junction, Positive charge is built n-side and negative charge built on P-side. This set up a potential difference across the Junction. The region on either side of the Junction which becomes depleted (free) of the mobile charge carrier is called the depletion region.

The width of the depletion region is of order of 10^{-6} m. The potential difference developed across the depletion region is called the potential barrier. it is about 0.3V for Ge p-n Junction and about 0.7 V for Si pn-Junction



P-N- Junction on forward bias :-

A Junction is said to be in forward-bais when, positive terminal is connected to p-type and negative terminal is connected to n-type region.



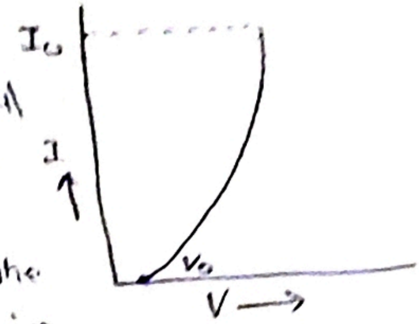
In this condition, an external electric field is E directed from p towards n set up. Majority charge carriers start to move towards the Junction. These holes and electrons recombine and cease to exist. for each combination a covelent bond breaks up in p-region near the positive terminal of battery. and electron & holes produced. Hole move toward the Junction and electron enters the positive terminal of the battery throug connecting wire.

At the same time an electron is released from the negative terminal of the bettery and enters to the n-type region to replace the electron lost by the combination with hole at the Junction. Thus the motion of majority charge carriers constitutes a current across the Junction. This is called forward current.

In addition to this large current, there is a small reverse current due to motion of minority carriers, but it is almost negligible.

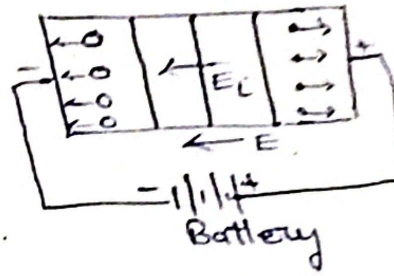
In forward biased junction the applied field E dominates the small barrier field Ei. Hence the width of the depletion region decreases and offer a low resistance for the current to flow in forward bias.

The curve b/w V & I is called characteristic when we apply external field, once the external field exceeds the barrier potential, the current rises sharply. The voltage at which the current starts to rise is called cut in or knee voltage (V_0). A millimeter is used to measure the current.



P-n Junction on Reverse bias:-

A junction is said to be in reverse biased, when the positive terminal of battery is connected to n-region and negative terminal is connected to p-region.



In this situation, the external field E is directed from n to p and thus aids the integral barrier field Ei. Hence holes in p-region and electrons in n-region pushed away from the junction. So no current flows due to majority carriers.

In reverse bias, a small current flows across the junction due to minority charge carriers. This current is very much temp. dependent and increases with increasing in temp.

In reverse bias, the width of depletion region increases. due to this reason, the diode offers high resistance for current. Graph shows the V-I characteristic in reverse bias. The current is very low (μA). if reverse bias is made too large the current increases abruptly. The voltage at which this occur is called break down voltage.