Chapter-1

Energy Band Formation

As isolated atoms are brought together to form solids, various interactions occur between neighbouring atoms.

Force of attraction & repulsion b/w atoms will find a balance at a proper interatomic distance in a crystal. I

Due to this, important changes occur in electron energy level configuration & these changes result in various electrical properties of solid.

Energy Band Model

In this model we analyse how the electrons are distributed over a range of energy at a given temperature so that we can find the ē which are free and which are bound.

These consist of 3 parts:

1. Allowed States

~~Electrons~~ (i) Only certain energy states are allowed.

(ii) ē occupy lowest energy state available.

(iii) no 2 ē can occupy same energy state.

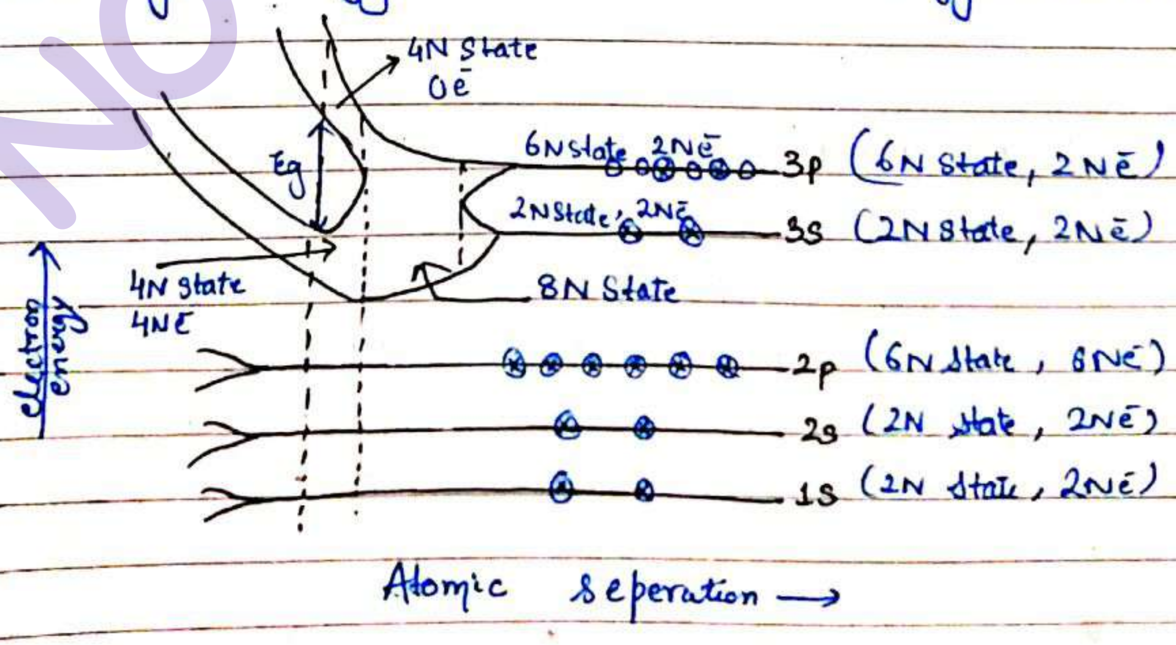
2. Distribution of allowed State over energy is Density of State $N(E)$

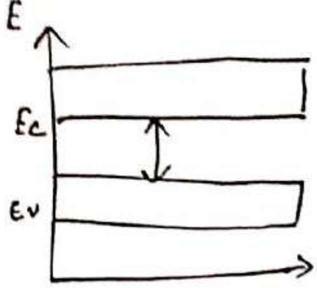
3. At any temp. under equilibrium only a fraction of allowed states are occupied i.e $f(E, T)$

When 2 atoms are completely isolated from each other so that no interaction takes place and can have identical electronic structure.

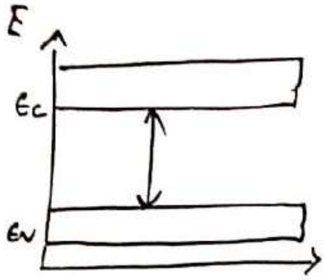
When 2 atoms approaches each other, inter-atomic distance decreases and Pauli's exclusion principle defects that no 2 $\bar{e}$ in an interacting system can stay at same energy level. Due to this splitting of discrete energy level of islated atom into new level belonging to pair of atoms rather than individual atom.

In solids, many atoms are brought together so that split energy level form continuous band of energy known as energy band.

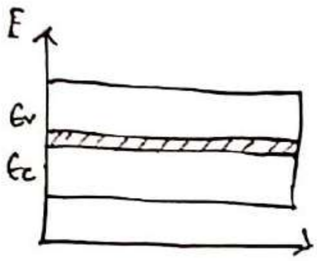




Semiconductor



~~Conductor~~
Insulator



Conductor

- Density of state

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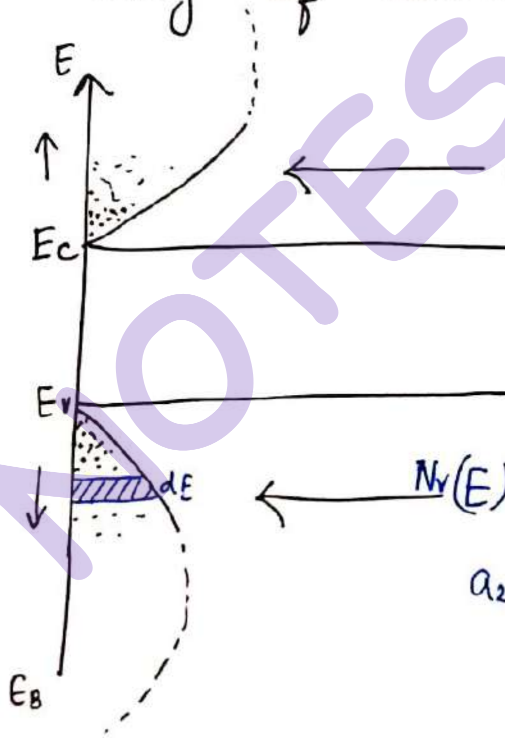


$$N_c(E) = a_1\sqrt{E-E_c}$$

$$a_1 = \frac{8\sqrt{2}\pi m_n^{3/2}}{h^3}$$

$$N_v(E) = a_2\sqrt{E_v - E}$$

$$a_2 = \frac{8\sqrt{2}\pi m_p^{3/2}}{h^3}$$

Density of state refer to the no. of available $\bar{e}$ state for unit volume for unit energy at a certain energy level.

→ Density of state inform the distribution of state over energy.

Valence $\bar{e}$ in Si

$$\rightarrow \int_{E_v}^{E_D} N_v(E)\, dE = 4 \times \underbrace{5 \times 10^{22}}_{\text{No. of atoms available}}$$

Energy interval dE over energy E represent no. of state over dE under shaded area.

Over the entire area, the no. of states will be $4 \times 5 \times 10^{22}$

• Fermi - diarc function

$$f(E,T) = \frac{1}{1 + e^{\left(\frac{E - E_f}{kT}\right)}}$$

E_f = fermi energy level

for $E \rightarrow \infty \Rightarrow f(E,T) = 0$

$E \rightarrow E_f \Rightarrow f(E,T) = 1/2$

$E \rightarrow -\infty \Rightarrow f(E,T) = 1$

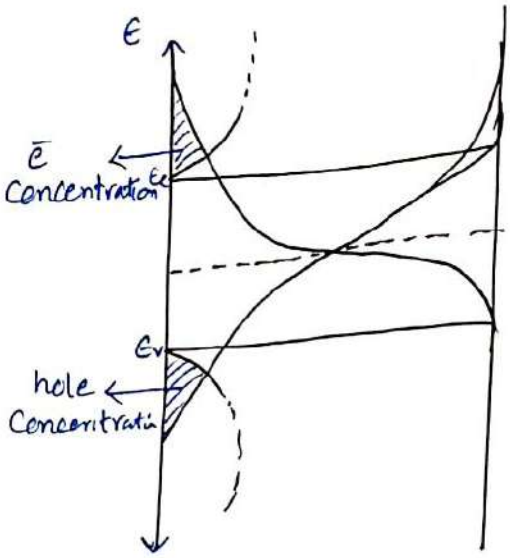
→ At 0K (Absolute temp), the no. of field state greater than E_f is equal to 0.

Below E_f = 1

→ as temp increases, some $\bar{e}$ jump from VB to CB and no. of field state $> E_f$ is non-zero and $< E_f$ is less than 1.

E_f indicates energy below which all allowed states are occupied and above which, all states are unoccupied at T = 0.

→ Energy at which half of available states are occupied at T>0 is also reffered by E_f.



$$n_0 = \int_{E_c}^{E_T} N(E).\, dE . f(E.T)$$

Electron conc. can be found out by integrating the common area between density func. & probability funct. as shown in figure.

The approximation to simplify

(i) $E_T \to \infty$

(ii) Boltzmann Approximation

(iii) Parabolic nature of density function.

⇒ Boltzmann Approximation is valid for $\frac{E - E_f}{kT} > 3$

or < -3

• if $E - E_f > 3kT$,

$$\Rightarrow f_c(E,T) = \frac{1}{1 + e^{\left(\frac{E-E_f}{kT}\right)}} \Rightarrow f_c(E,T) = e^{-\left(\frac{E-E_f}{kT}\right)}$$

By putting $E - E_f > 3kT$ in $f(E,T)$ then we can neglect 1 as exponential term is greater.

• if $\epsilon - \epsilon_f < -3kT$,

$$f(\epsilon, T) = \frac{1}{1 + e^{\left(\frac{\epsilon - \epsilon_f}{kT}\right)}} \quad , \quad \frac{1}{1+x} = 1 - x, \text{ if } x << 1.$$

$$f_c(\epsilon, T) = 1 - e^{\frac{\epsilon - \epsilon_f}{kT}}$$

$$f_v(\epsilon, T) = 1 - f_c(\epsilon, T)$$

$$= e^{\left(\frac{\epsilon - \epsilon_f}{kT}\right)} = e^{-\left(\frac{\epsilon_f - \epsilon}{kT}\right)}$$

$$n_0 = \int_{\epsilon_c}^{\epsilon_T} N(E) . f(E, T) . dE$$

$$= \int_{\epsilon_c}^{\infty} a_1 \sqrt{E - E_c} \cdot e^{-\left(\frac{E - \epsilon_f}{kT}\right)} . dE$$

Let $\frac{E - E_c}{kT} = x$

$E - E_c = xKT$

$E = E_c + xKT$

$dE = KT . dx$

$\frac{dE}{KT} = dx$

for $E = \epsilon_c$, $x = 0$

$E = \infty$, $x = \infty$

$$= \int_0^{\infty} \frac{8\sqrt{2}\pi m_n^{3/2}}{h^3} \sqrt{xKT} \, e^{-\left(\frac{\epsilon_c + xKT - E_f}{kT}\right)} . KT . dx$$

$$= \frac{8\sqrt{2}\pi m_n^{3/2}}{h^3} \int_0^{\infty} \sqrt{x} (KT)^{3/2} . e^{-\left(\frac{\epsilon_c - \epsilon_f}{kT}\right)} e^{-x} . dx$$

$$= \frac{{}^4\cancel{8}\sqrt{2}\pi m_n^{3/2} (kT)^{3/2}}{h^3} . e^{-\left(\frac{\epsilon_c - E_f}{kT}\right)} \underbrace{\int_0^{\infty} \sqrt{x} . e^{-x} dx}_{\frac{\sqrt{\pi}}{2}}$$

$$= \underbrace{2 \left[\frac{2\pi m_n (kT)}{h^2}\right]^{3/2}}_{N_c} . e^{-\left(\frac{E_c - \epsilon_f}{kT}\right)}$$

$$\boxed{n_0 = N_c . e^{-\left(\frac{E_c - \epsilon_f}{kT}\right)}}$$ Electron Concentration

Similarly,

$p_0 = N_v . e^{-\left(\frac{\epsilon_f - \epsilon_v}{kT}\right)}$ Hole Concentration

$$n_i^2 = n_o p_o \quad \text{— Mass action Law}$$

$$n_i^2 = N_c \cdot N_v \cdot e^{\left(\frac{E_v - E_c}{kT}\right)}$$

$$n_i^2 = N_c \cdot N_v \cdot e^{-\left(\frac{E_c - E_v}{kT}\right)}$$

$$n_i^2 = N_c \cdot N_v \cdot e^{-\left(\frac{E_g}{kT}\right)}$$

$$\boxed{n_i = \sqrt{N_c \cdot N_v} \cdot e^{-\left(\frac{E_g}{2kT}\right)}}$$

$$n_i = \sqrt{\left[\frac{4\pi m_n (kT)}{h^2}\right]^{3/2} \cdot \left[\frac{4\pi m_p (kT)}{h^2}\right]^{3/2}} \cdot e^{-\frac{E_g}{2kT}}$$

$$\boxed{n_i = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_n \cdot m_p)^{3/4} \cdot e^{-\frac{E_g}{2kT}}}$$

Intrinsic Concentration

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For intrinsic material,

$\bar{e}$ conc. = hole conc.

i.e $n_o = p_o = n_i$

$$N_c \cdot e^{-\left(\frac{E_c - E_f}{kT}\right)} = N_v \cdot e^{-\left(\frac{E_f - E_v}{kT}\right)}$$

$$\frac{N_c}{N_v} = e^{\frac{-E_f + E_v + E_c - E_f}{kT}}$$

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

$$kT \cdot \ln\left(\frac{N_c}{N_v}\right) = E_v + E_c - 2E_f$$

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

very small (this is the reason why fermi level is not in the centre. by $\left(\frac{m_n}{m_p}\right)$ value)

$$\boxed{E_f \simeq \frac{E_c + E_v}{2}} \quad \text{(for intrinsic material)} \quad \text{— (1)}$$

$$\epsilon_c - \epsilon_v = \epsilon_g$$

$$\epsilon_c = \epsilon_v + \epsilon_g \quad \text{——} \quad (2)$$

$$\epsilon_f = \frac{\epsilon_v + \epsilon_g + \epsilon_v}{2} - \frac{3}{4} kT \ln\left(\frac{m_n}{m_p}\right)$$

$$= \epsilon_v + \frac{\epsilon_g}{2} - \frac{3}{4} KT \ln\left(\frac{m_n}{m_p}\right)$$

For in m, the fermi level will not be exactly at the centre due to effective mass difference b/w $\bar{e}$ and hole.

Q. Ideally in a semiconductor, intrinsic energy level should be in the middle of band gap. Estimate the position of intrinsic fermi level For intrinsic germanium (300K) assuming effective mass of $\bar{e}$ and hole are respectively: $m_e = 0.041 m_0$
$m_p = 0.28 m_0$. Show band diagram

Band Gap (Ge) = 7.2

$$V_T = \frac{KT}{q} = 26 mV$$

$$\epsilon_f = -\frac{3}{4} KT \ln\left(\frac{m_n}{m_p}\right)$$

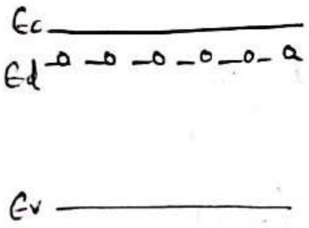
$$= -\frac{3}{4} \times 0.0259 \ln\left(\frac{0.041}{0.28}\right) \quad \left(\begin{matrix} K = 8.633 \\ T = 300 \end{matrix}\right)$$

$$= -\frac{3}{4} \times 0.0259 \ln(0.1464)$$

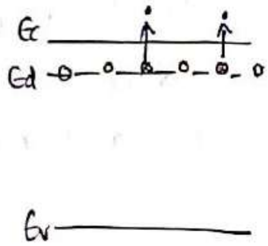
$$= -0.019425 \times -1.9214$$

$$= 0.0373 eV$$

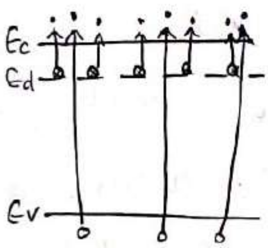
E_d = Donor level

1) 

T = 0K

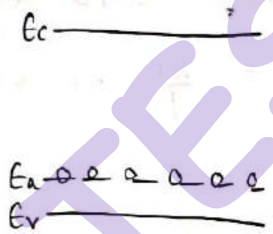
2) 

T = 100K

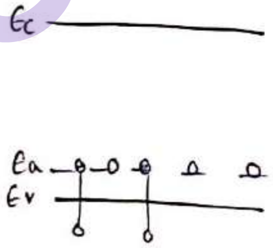
3) 

T = 300K

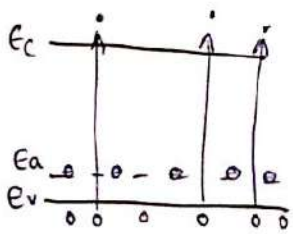
For n-type

1) 

T = 0K

2) 

T = 100K

3) 

T = 300K

For p-type

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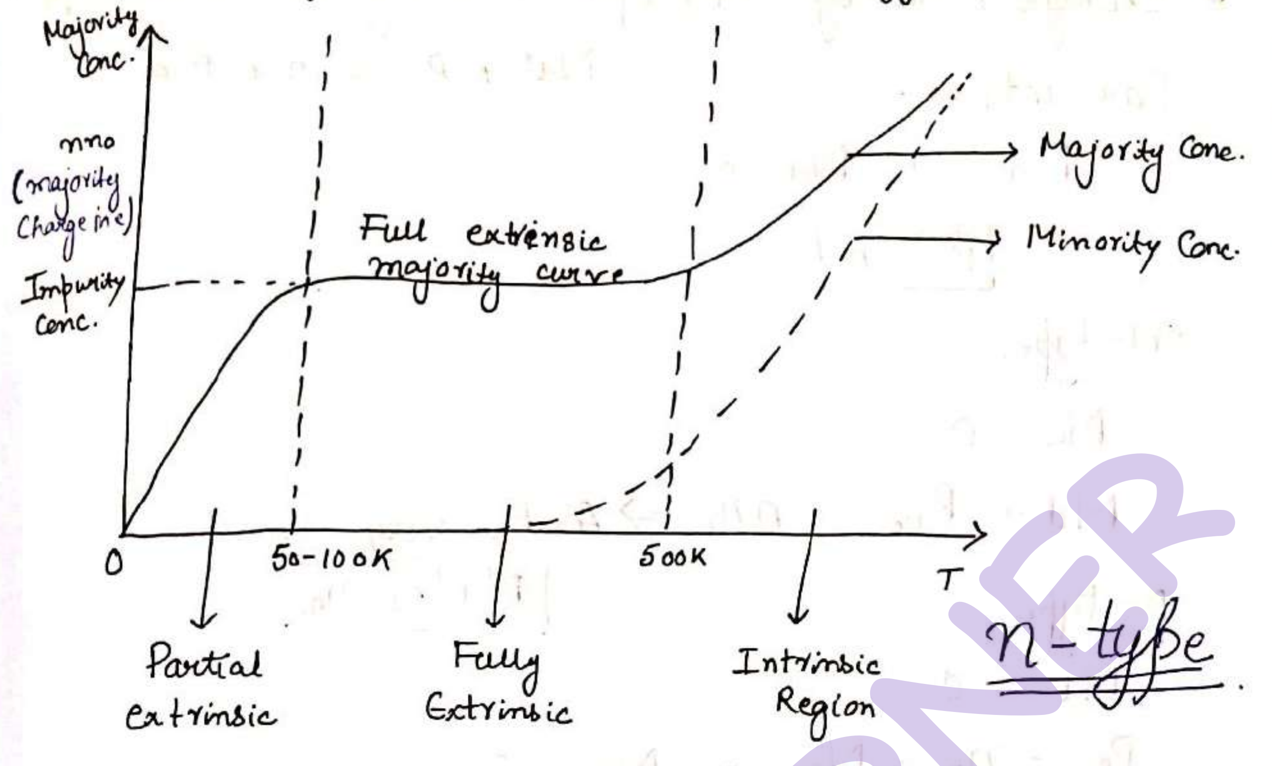
- Behaviour of semiconductor at different temp.



T	e (Impurity Ionisation)	e(BB)	h(BB)	
300K	100	100	100	n > p n type
400K	100	1000	1000	n > p n type
500K	100	10^5	10^5	$n \simeq 10^5 \simeq p (10^5)$ Intrinsic

The semiconductor behaves as insulator at absolute temp and also at very high temp, Extrinsic material behaves as intrinsic material due to dominance of band to band transition over Impurity ionisation. Hence, it is always advisable to operate at room temp.

- Charge neutrality Principle / Charge ~~valency~~ Balance

$N_d^+ + p = n + N_a^-$

For intrinsic,

$N_a = 0, \; N_d = 0$

$$\boxed{P = n}$$

n-type,

$N_a = 0$

$N_d + P_{n_0} = n_{n_0} \Rightarrow$ As P_{n_0} very small

$$\boxed{N_d^+ \simeq n_{n_0}}$$

p-type,

$N_d = 0$

$P_{P_0} = n_{P_0} + N_a^- \Rightarrow N_a^- \simeq P_{P_0}$

Q. Find $\bar{e}$ and hole conc. for a semiconductor if it is doped with pentavalent atoms of 10^{16} atoms/cm³ and given $n_i = 1 \times 10^{10}$ atoms/cm³ at 300 K.

$N_d = 10^{16}$ atoms/cm³ , $n_i = 1 \times 10^{10}$ atoms/cm³

$n_0 = N_d = 10^{16}$ atoms/cm³

Mass action Law, $P_0 = \dfrac{n_i^2}{n_0} = \dfrac{10^{10} \times 10^{10}}{10^{16}}$

$= 10^4$ atoms/cm³

- Deviation of fermi level from intrinsic ~~level~~ material (extrinsic material (Semi conductor)

$n_0 = N_c \, e^{-\left(\frac{E_c - E_f}{kT}\right)}$

$n_i = N_c \, e^{-\left(\frac{E_c - E_i}{kT}\right)}$

$\dfrac{n_0}{n_i} = \dfrac{\cancel{N_c}}{\cancel{N_c}} \cdot e^{\frac{-\cancel{E_c} + E_f + \cancel{E_c} - E_i}{kT}}$

$\dfrac{n_0}{n_i} = e^{+\frac{E_f - E_i}{kT}}$

$$\ln\left(\frac{n_0}{n_i}\right) = \frac{\epsilon_f - \epsilon_i}{kT}$$

$$kT \ln\left(\frac{n_0}{n_i}\right) = \epsilon_f - \epsilon_i$$

$$\boxed{\epsilon_f - \epsilon_i = kT \cdot \ln\left(\frac{n_d}{n_i}\right)} \rightarrow n\text{-type}$$

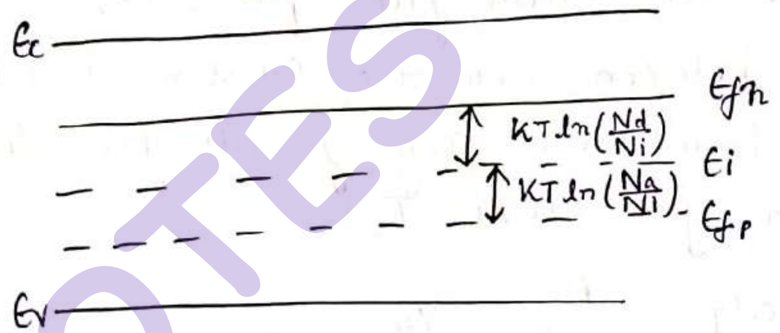
$$p_0 = N_v \cdot e^{-\left(\frac{\epsilon_f - \epsilon_v}{kT}\right)}$$

$$p_i = N_v \cdot e^{-\left(\frac{\epsilon_i - \epsilon_v}{kT}\right)}$$

$$\frac{p_0}{p_i} = \frac{\cancel{N_v}}{\cancel{N_v}} e^{\frac{-\epsilon_f + \cancel{\epsilon_v} + \epsilon_i - \cancel{\epsilon_v}}{kT}}$$

$$\ln\left(\frac{p_0}{p_i}\right) = \frac{\epsilon_i - \epsilon_f}{kT}$$

$$\boxed{\epsilon_i - \epsilon_f = kT \ln\left(\frac{p_0}{p_i}\right)} \longrightarrow p\text{-type}$$



- Random motion

Due to the thermal energy of carriers, $\bar{e}$ or holes moving inside the solid collide with other atoms or carriers and looses its energy and velocity and the process repeats known as Scattering. Types:

1. <u>Lattice Scattering</u> / <u>Phonon Scattering</u> is due to collision of ~~atom~~ carriers with atoms in lattice structure.

2. Carrier- Carrier Scattering is due to the collision of carriers with another carrier.

3. Ionised impurity scattering is due to the collision of carriers with impurity ions

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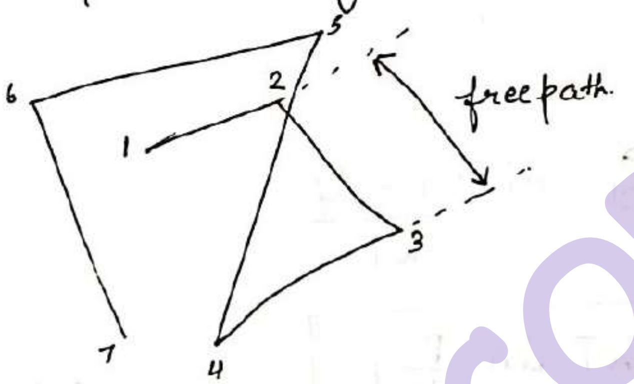
o Random Motion of Carriers:



The distance between any 2 collision is called free path. The avg. of all free path is called as mean free path (l_c).

The time between any two collision is called as free time and avg. of all free time is mean free time (τ_c).

$$\text{Avg. velocity} = \frac{l_c}{\tau_c} = V_{th}$$

Thermal energy of the carrier is V_{th}.

⇒ Property of random motion.

1. The net movement of the carrier across any plane is 0. ⇒ avg $v = 0$, net flux $= 0$

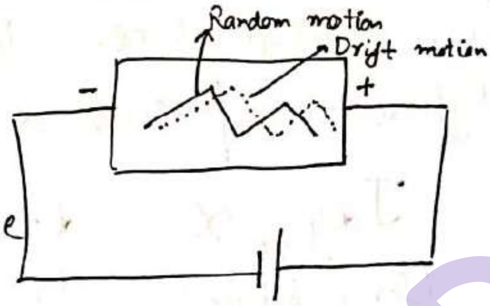
∴ total current $= 0$

2. The carriers having intense motion

$$V_{th} = \frac{l_c}{T_c} = \frac{10^{-5}}{10^{-12}} = 10^7 \text{ cm/s}$$

⇒ There are 2 types of current in semiconductors

- **Drift Current :**



The current due to drifting of $\bar{e}$ from one side to other side by application of $\bar{e}$ field or potential is called drift current.

$$J = \sigma E$$

$$I = \sigma E A$$

$\sigma_n = nq\mu_n$, $n = \bar{e}$ conc

$\sigma_p = pq\mu_n$ p = hole conc.

$\sigma = \sigma_n + \sigma_p$

★ $J = (nq\mu_n + pq\mu_p)E$

J = electric density
E = electric field

$$R = \frac{\rho l}{A}$$

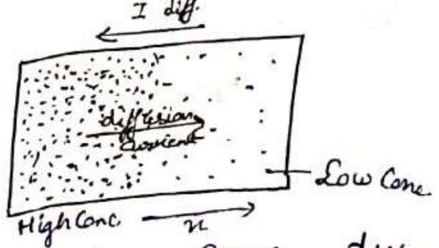
$$\rho = \frac{1}{\sigma}$$

$$V_{th} = -\mu_n E$$

$$\mu_n = -\frac{V_{th}}{E}$$

Drift velocity (V_t) is equal to $-\mu_n E$.
Mobility can be defined as the average drift velocity per unit electric field.

- **Diffusion Current :**



The current due to flow of carriers from high conc. to low conc. due to diffusion process is called diffusion current.

$$J_{diff_{n/p}} \propto \frac{dn}{dx} \Big/ \frac{dp}{dx} \longrightarrow \text{Concentration gradient for } \bar{e} \text{ \& holes}$$

(for $\bar{e}$ & hole) $\frac{dn}{dx}$ ↑ for $\bar{e}$ $\frac{dp}{dx}$ ↑ for hole

* $J_{n\,diff.} = q D_n \frac{dn}{dx}$

* $J_{p\,diff} = -q D_p \frac{dp}{dx}$

D_n, D_p are diffusion coefficient
q - charge of carrier

$$J_n = J_{n\,diff} + J_{n\,drift} = nq\mu_n E + qD_n \frac{dn}{dx}$$

$$J_p = J_{p\,diff} + J_{p\,drift} = pq\mu_p E - qD_p \frac{dp}{dx}$$

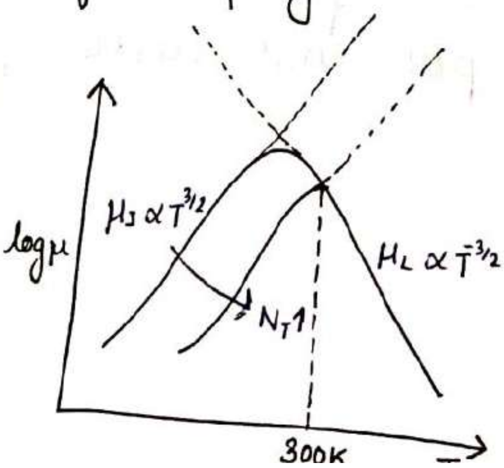
$$\boxed{J = J_n + J_p}$$

$$\left(\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = \frac{KT}{q} = V_{th} \text{ (Thermal Voltage)}\right)$$
$$= 0.0259\,V$$

Einstein Relations

$$\boxed{KT = 0.0259\,eV}$$ for numericals.

- Effect of doping and temperature on mobility



$(N_T = N_D + N_A)$
Doping

$$\mu = \frac{q\tau_c}{2m}$$

$$\mu \propto \tau_c$$

*(Mobility decreas with increase in doping)

$$\frac{1}{\tau_c} = \frac{1}{\tau_I} + \frac{1}{\tau_L}$$

$$\boxed{\frac{1}{\mu} = \frac{1}{\mu_I} + \frac{1}{\mu_L}}$$

τ_c = mean free time.

Mobility due to ion Scattering + Mobility due to lattice scattering

Mobility of a carrier is directly proportional to mean free time of carrier. When doping increases, the chances of collision increases so that more scattering happens and mean free time decreases. So that mobility also decreases as in the graph.

* At low temp, lattice vibration is less & mobility increases as temp. increases. After a certain temp. (300 – 350)K, the lattice vibration increases due to which scattering increases & mobility decreases.

o Excess Carriers

It means the carriers over the equilibrium level. These excess carriers can be generated by photoionisation or impact ionisation or injection. Injection means by any method to generate excess carrier.

Injection level decides upto what extent the semiconductor is distrurbed through equilibrium. Injections are of two type:

1. Low level
2. High level

Excess Carriers are generated in pairs.

$$n + N_a = p + N_d$$
$$p - n + N_d - N_a = 0$$
$$\delta[p - n + N_d - N_a] = 0$$
$$\delta[p - n] = 0 \quad (\because \delta[N_d - N_a] = 0)$$
$$\boxed{\delta p = \delta n}$$

⇒ Depending upon injection, the conc. of minority and majority carrier changes.

- Low level injection

If the excess carrier conc. is less than 1/10th of the majority conc. then majority carrier conc. will not affect by minority conc. will change and this is called as low level injection.

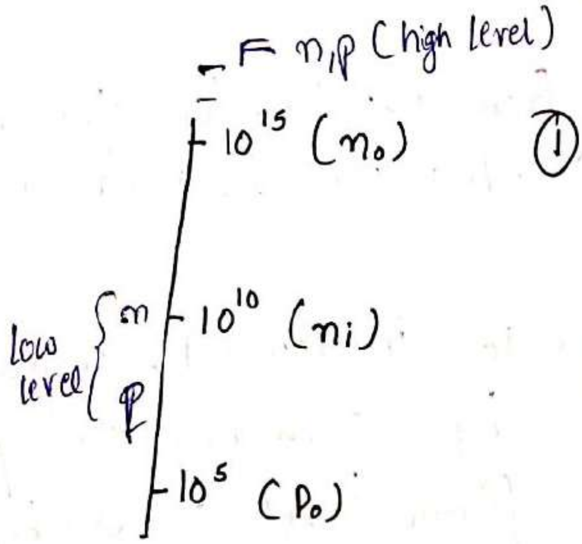
If $\underset{\text{(Excess conc.)}}{\delta n} < \frac{\text{majority conc.}}{10} \Rightarrow n = n_0 + \left(< \frac{\text{majority c.}}{10} \right)$

$$\simeq n_0$$

- **High level injection**

If the excess carrier conc. is more than 10 times of majority carrier conc, the injection is called as high level injection.

If $\delta n > (10 \times \text{majority conc.}) \Rightarrow n = n_0 + \underbrace{(>10 \times \text{maj. conc})}_{\delta n} \simeq \delta n$



① $\delta = 10^{12}/cm^3$

$n = 10^{15} + 10^{12} \simeq 10^{15}/cm^3$

$p = 10^{5} + 10^{12} \simeq 10^{12}/cm^3$

② $\delta = 10^{17}/cm^3$

$n = 10^{15} + 10^{17} \simeq 10^{17}/cm^3$

$p = 10^{5} + 10^{17} \simeq 10^{17}/cm^3$

All the semiconductor analysises are done by considering low level injection because in low level injection only minority conc. are disturbed but in high level, both majority & minority conc. are disturbed. Hence for analysis, low level injection is preferred.

- Quasi - Equilibrium

$$n_o = N_c \cdot e^{-\frac{(E_c - E_f)}{KT}}$$

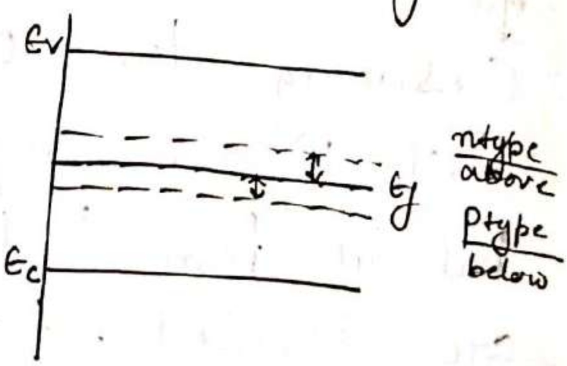
$$p_o = N_v \cdot e^{-\frac{(E_f - E_v)}{KT}}$$

$$n_i = N_c \cdot e^{-\left(\frac{E_c - E_i}{KT}\right)}$$

If System is disturbed from equilibrium, the excess Carrier Conc. increases. So that $n = n_o + \delta n$ will be increase.

Now to maintain Left Side increment, right Side value also increases by changing the gap b/w E_c & E_f. The new fermi level is denoted as E_{fn} (Quasi fermi level)

Q. Ge sample is doped with 10^{14} atoms/cm^3 of arsenic (Pentavalent) material. Find the equilibrium hole Conc. and what is the relative position of fermi level wrt intrinsic fermi level.



$N_d = 10^{14}$ atoms/cm^3

$P_o = ?$

$$E_f - E_i = KT \ln\left(\frac{N_D}{n_i}\right)$$

$$n_o \cdot P_o = n_i^2$$

$=$

$n_i = 1.5 \times 10^{6}$ /cm^3

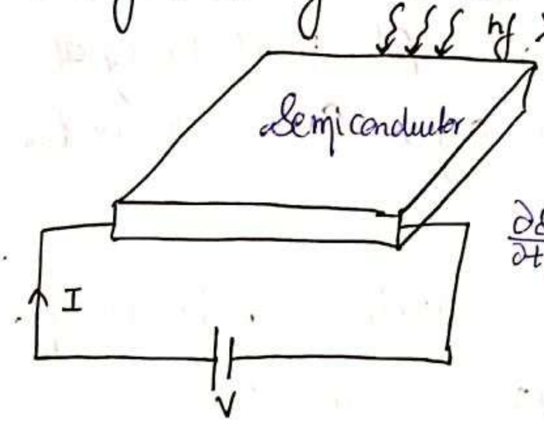
Generation & Recombination

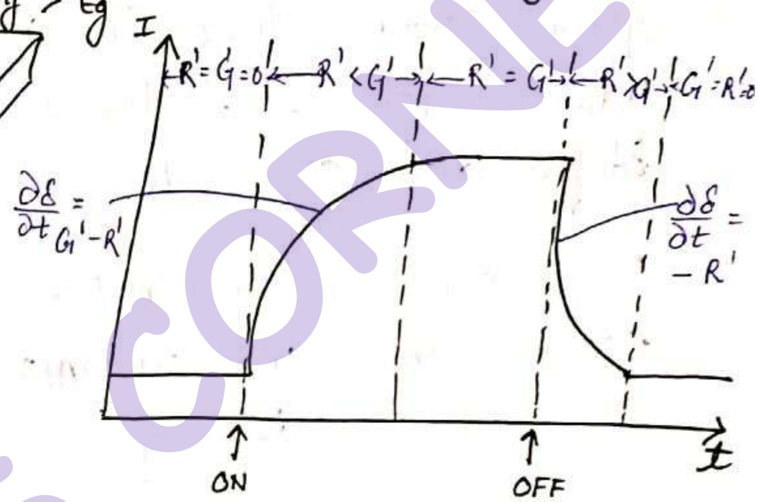
Generation is a process of creating charge carriers (holes & $\bar{e}$). Similarly, recombination is a process to recombine $\bar{e}$ and hole.

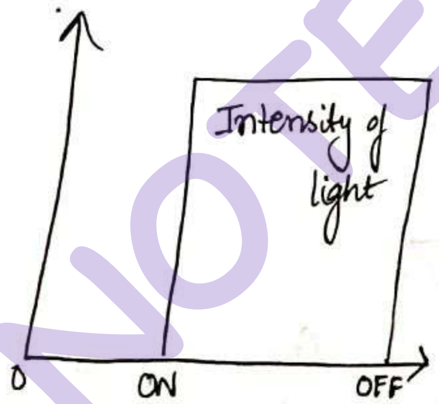
Generation & recombination happens simultaneously & at thermal equilibrium, generation rate = recombination rate

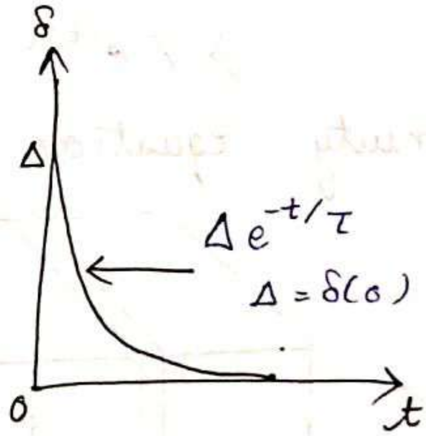
$$G = R$$

→ Lifetime of excess carrier or minority carrier.









Recombination rate $= \dfrac{\delta}{\tau}$ τ = mean time of carrier

$$\frac{\partial \delta}{\partial t} = -R' = -\frac{\delta}{\tau}$$

$$\frac{\partial \delta}{\partial t} = -\frac{\delta}{t} \Rightarrow \Delta e^{-t/\tau}$$

Let us take a semiconductor and light is incidented on it. A voltage source is connected to flow the current.

Let the light intensity is low and it is a low level injection. When light falls on a semiconductor, rate of increase in the excess

$$\text{Conc.} = \frac{\partial \delta}{\partial t} = G' - R'$$

$G' \rightarrow$ excess generation, $R' \rightarrow$ excess recombination.

After certain time G' and R' will be equal. When light is switched off, excess generation stops and $\frac{\partial \delta}{\partial t} = -R'$.

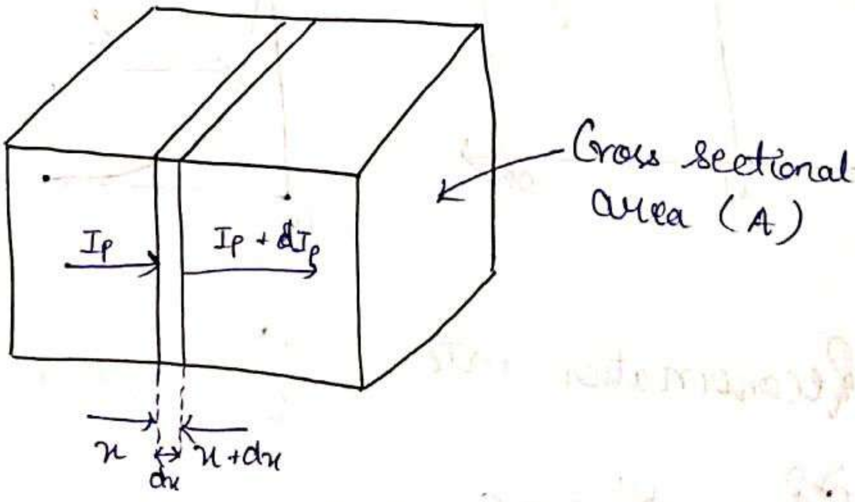
We know recombination rate depends upon excess conc. and meanfree time of carrier.

$$R' = \frac{\delta}{\tau}$$

$$\frac{\partial \delta}{\partial t} = -\frac{\delta}{\tau}$$

$$\Rightarrow \Delta e^{-t/\tau}$$

- Continuity Equation



Continuity eq. is valid for non-uniformly doped semiconductors. If semiconductor is non-uniformly doped, the conc. of charge carriers will be different along the length (x) of semiconductor. The conc. of charge in the semiconductor is a function of time & distance.

Dependency of conc. of charge carriers over time and distance can be represented by partial diff. eq. called as continuity eq.

Consider a semiconductor with crossectional area as A and differencial length as dx and assume that conc. varies in x-direction. Current entering the differential length is I_p and leaving the differential length is $I_p + dI_p$ (incremental current).

Conc. of holes in the incremental area (V) is due to:

1. Recombinational Rate

$$\boxed{R = \frac{P}{\tau}}$$

2. Current entering the volume is i_p and leaving the volume is $i_p + di_p$. So there is a net decrease in hole conc.

$$dI_p = q\,dp \Rightarrow \boxed{dp = \frac{dI_p}{q}}$$

→ Decrease in hole conc. per unit volume per unit time

$$\frac{dP}{dx \cdot A} = \frac{dI_p}{q \cdot A \cdot dx} = \frac{1}{q}\frac{dJ_p}{dx}$$

→ Generation rate in semiconductor at equilibrium : $G = \frac{P_0}{\tau}$

As charge can not be created or destroyed.

$$\frac{dP}{dt} = G - \left(R + \frac{1}{q}\cdot\frac{dJ_p}{dx}\right)$$

$$= \frac{P_0}{\tau} - \left(\frac{P}{\tau_p} + \frac{1}{q}\frac{\partial J_p}{dx}\right) \qquad \left(\begin{matrix} P = P_0 + \delta p \\ P - P_0 = \delta p \end{matrix}\right)$$

$$\frac{dP}{dt} = -\frac{1}{q}\frac{\partial J_p}{\partial x} - \left(\frac{P - P_0}{\tau_p}\right)$$

⇒ Minority Conc. in terms of diffusion length:

$$\boxed{\frac{\partial p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} - \frac{\delta p}{\tau_p}}$$ for holes

$$\boxed{\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} - \frac{\partial n}{\tau_n}}$$ for electrons

$$P = P_0 + \delta P \Rightarrow \delta P = P - P_0$$

$$n = n_0 + \delta n \Rightarrow \delta n = n - n_0$$

$$\frac{\partial(\delta P)}{dt} = \frac{\partial P}{\partial t} + 0$$

$$\frac{\partial(\delta n)}{dt} = \frac{\partial n}{\partial t}$$

$$J_{P\,diff.} = -q D_p \frac{dp}{dx}$$

$$= -q D_p \frac{\partial(\delta P)}{\partial x}$$

Replacing above in

$$\frac{\partial(\delta p)}{\partial t} = D_p \frac{\partial^2(\delta p)}{\partial x^2} - \frac{\delta p}{\tau_p}$$

Similarly, $\frac{\partial(\delta n)}{\partial t} = D_n \frac{\partial^2(\delta n)}{\partial x^2} - \frac{\delta n_{excess}}{\tau_n}$

At steady state, change in concentration.

i.e $\frac{\partial(\delta P)}{\partial t} = 0$, $\frac{\partial(\delta n)}{\partial t} = 0$

$$D_p \frac{\partial^2(\delta p)}{\partial x^2} - \frac{\delta p}{\tau_p} = 0$$

$$\frac{\partial^2(\delta p)}{\partial x^2} = \frac{\delta p}{D_p \tau_p} \quad \text{(holes)}$$

$$D_n \frac{\partial^2(\delta n)}{\partial x^2} - \frac{\delta n}{\tau_n} = 0$$

$$\frac{\partial^2(\delta n)}{\partial x^2} = \frac{\delta n}{D_n \tau_n} \quad \text{(electron)}$$

Let $\sqrt{D_p \tau_p} = L_p$, $\sqrt{L_n \tau_n} = L_n$.

L_p, L_n - diffusion lenth of hole and electron respectively.

$$\frac{\partial^2(\delta p)}{\partial x^2} + \frac{\delta p}{L_p^2} = 0$$

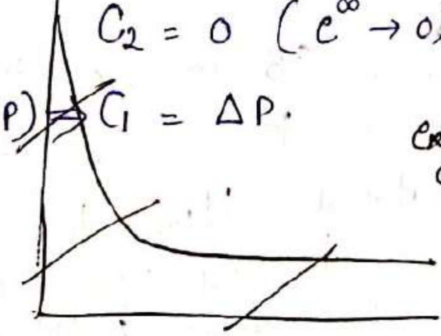
$$\delta P(x) = C_1 e^{-x/L_p} + C_2 e^{x/L_n}$$

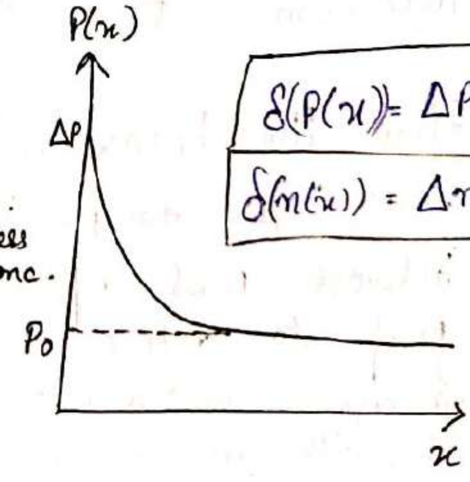
if $x = \infty$, $\delta P(x) = 0$

if $x = 0$, $\delta P(x) = \Delta p$

$C_2 = 0$ $(e^{\infty} \to 0)$

$\because (C_1 + C_2 = \Delta P) \Rightarrow C_1 = \Delta P.$

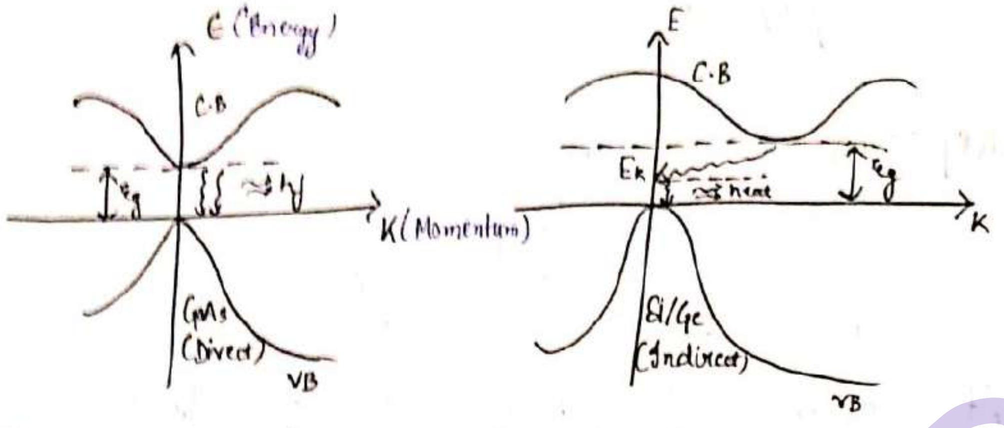




$$\boxed{\delta(P(x)) = \Delta P e^{-x/L_p}}$$

$$\boxed{\delta(n(x)) = \Delta n e^{-x/L_n}}$$

* Direct and Indirect Band gap Material



The actual band gap of semiconductor is much more complex. If we plot E vs K then the distinguish feature of semiconductor is the location of CB_{min} and VB_{max} in the E-K diagram

The band structure in GaAs (direct material) has a minimum in CB and max in VB for the same k = 0. When ē jumps from CB to VB, making smallest energy transitions without changing K, then light is emitted. Such materials are called direct Band gap material.

The band structure of Si has a VB maximum at a different value of K

Here the transition from CB to VB requires ~~more~~ some change in K, hence they are called indirect band gap material. Here the ē may jump to defect state having energy E_k by making same K and after that it jumps to the VB and in this process, energy is released in the form of heat.

Q. Calculate the probability that is the state in the CB is occupied by an $\bar{e}$ and calculate thermal equilibrium, $\bar{e}$ conc at temp = 300 assuming fermi level is 0.25eV below the CB and $N_C = 2.8 \times 10^{19}$/cm³

$\Rightarrow$ $N_C = 2.8 \times 10^{19}$ /cm³

$T = 300K$

$E_c - E_f = 0.25 eV$ 6.43 x10⁻¹⁵

$n_0 = ?$ 1.8 x 10¹⁵ /cm³

$$f_c(E,T) = \frac{1}{1 + e^{\frac{(E_c - E_f)}{KT}}} = \frac{1}{1 + e^{\frac{0.25}{0.0259}}}$$

$$= \frac{1}{1 + e^{9.652}} = \frac{1}{1 + \cancel{00.00}\ 15552.86} = \frac{1}{\cancel{27.23}\ 15553.86}$$

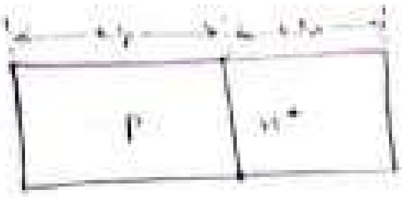
$= \cancel{0.03667}$ 6.43×10^{-5}

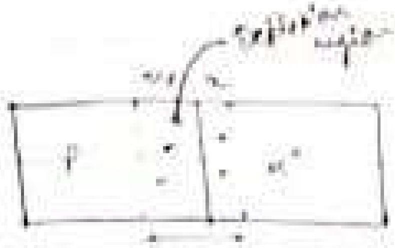
$$n_0 = N_c\, e^{-\left(\frac{E_c - E_f}{KT}\right)}$$

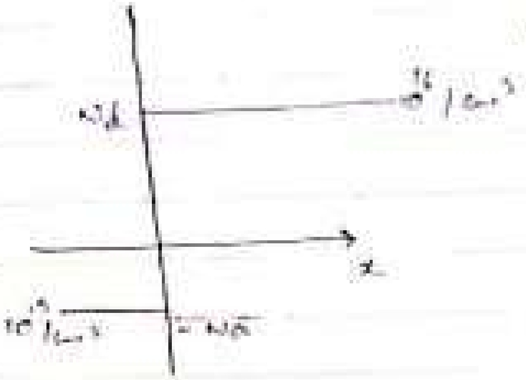
$$= 2.8 \times 10^{19} \cdot e^{-\left(\frac{0.25}{0.0259}\right)}$$

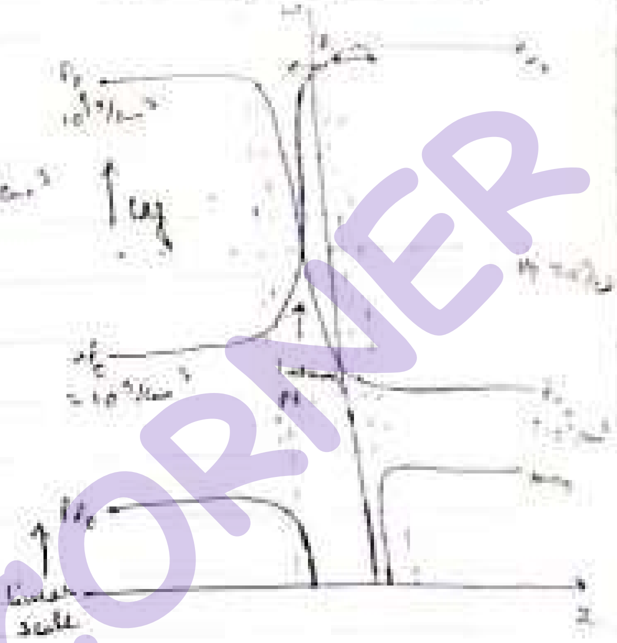
$$= 2.8 \times 10^{19} \cdot e^{-9.652}$$

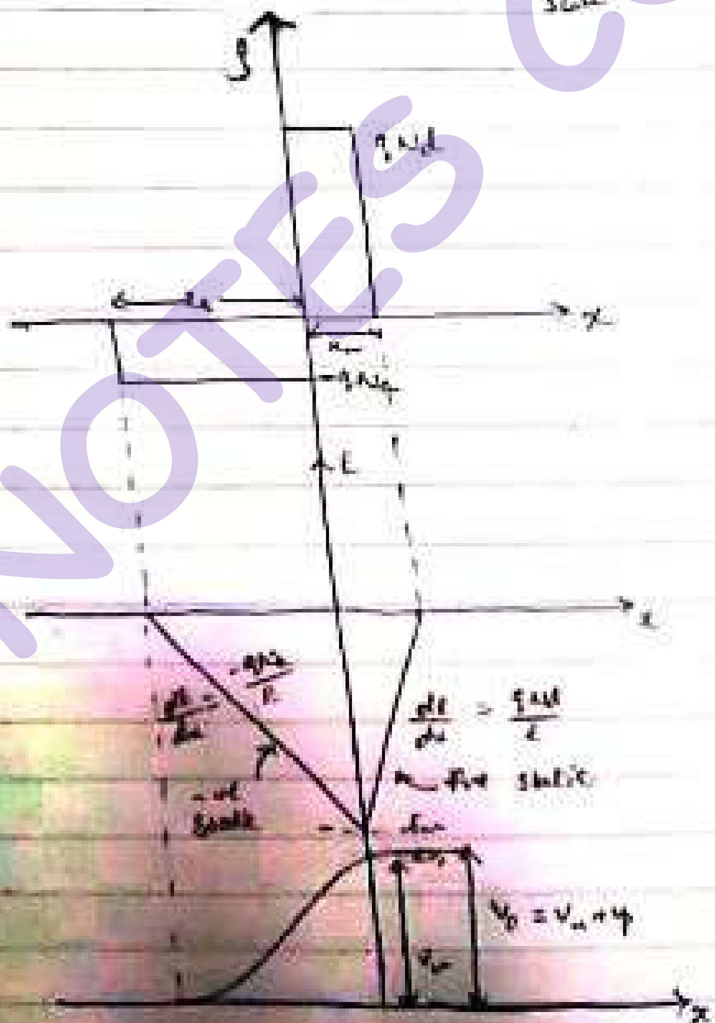
PN Junction Diode :-











$\rho = q(N_d)$

$\rho = -qN_a$

$qN_d x_n = qN_a x_p$

$\frac{x_n}{x_p} = \frac{N_a}{N_d}$

$\boxed{x_p = 10^{?} x_n}$

- Let us consider a pn junction with abrupt junction and uniformly doped on both sides. Let us assume, n side is highly doped compare to p side and x_p must be more than x_n and x_p, x_n should be much more lighter than the diffusion length of minority carriers.

- Though the doping changes abruptly, the conc^n change is continuous otherwise $\frac{dp}{dx}$ / $\frac{dn}{dx}$ will be infinite which is not possible.

- Intrinsic point is in the lighter doping side. In the depletion region, majority carrier conc^n is 0 & extend of depletion region is more in lighter doped side & less in heavier side.

- The charge density in n side $= q(N_d)$ & in p-side $= -qN_a$.

- According to Gauss law,

$$\frac{dE}{dx} = \frac{\rho}{\epsilon} \text{ (given)}$$

$\Rightarrow$ for n-side, $\frac{dE}{dx} = \frac{qN_d}{\epsilon}$ & in p-side, $= \frac{-qN_a}{\epsilon}$

- According to charge balance eq^n, the total charge across the depletion ~~[illegible]~~ region is 0 i.e. net charge = 0.

$$\frac{x_p}{x_n} = \frac{N_d}{N_a} = \frac{10^{[illegible]}}{10^{[illegible]}}$$

$$\frac{x_n}{x_p} = \frac{N_a}{N_d}$$

$$\boxed{x_p = 10x_n}$$

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Even though there is a ~~depletion~~ potential developed across the depletion region, there will be no current at the equilibrium because the generated EF oppose the flow of $\bar{e}$ or drift tendency neutralises diffusion tendency.

$$J_n = J_p = 0$$

$J_p = 0$ (hole conc.)

$$J_{p\,diff} + J_{drift} = 0$$

$$-q D_p \frac{dp}{dx} + p q \mu_p E = 0$$

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

$$E = \frac{V_t}{p} \cdot \frac{dp}{dx}$$

$$V_0 = -\int_{p\,side}^{n\,side} E \cdot dx = -\int_{P_{p_0}}^{P_{n_0}} E \cdot dx$$

$$V_0 = -\int \frac{V_t}{p} \cdot \frac{dp}{dx} \cdot dx = -V_t \cdot \log_e (P_{n_0} - P_{p_0})$$

$$\boxed{V_0 = +V_t \ln\left(\frac{P_{p_0}}{P_{n_0}}\right)}$$

when hole, $\bar{e}$ conc. is given

$$P_{p_0} = N_a \quad , \quad P_{n_0} = \frac{n_i^2}{N_d}$$

$$\boxed{V_0 = V_t \ln \frac{N_a N_d}{n_i^2}}$$

when donor & acceptor conc is given.

$$\boxed{\frac{P_{p_0}}{P_{n_0}} = e^{V_0/V_t} = e^{qV_0/KT}}$$

$$\frac{1}{2} \cdot \epsilon_m \times (x_p + x_n) = V_0$$

$$\frac{1}{2} \epsilon_m \left(\frac{x_p}{x_n} + 1 \right) x_n = V_0$$

$$\frac{x_p}{x_n} = \frac{N_d}{N_a}$$

$$\frac{1}{2} \epsilon_m \left(\frac{N_d}{N_a} + 1 \right) x_n = V_0 \quad — ①$$

Slope: $\frac{E_m}{x_n} = \frac{q N_d}{\epsilon}$

$$x_n = \frac{\epsilon E_m}{q N_d} \quad — ②$$

$$\boxed{V_0 = \frac{1 \epsilon E_m^2}{2 q} \left(\frac{1}{N_a} + \frac{1}{N_d} \right)} \quad (2 \text{ in } 1)$$

$$\sqrt{\frac{2q V_0}{\epsilon} \left(\frac{N_d N_a}{N_a + N_d} \right)} = E_m$$

$$V_0 = \frac{1}{2} E_m W$$

$$V_0^{\cancel{2}} = \frac{1}{2 \cdot \cancel{4}} \left(\frac{2 q \cancel{V_0}}{\epsilon} \left(\frac{N_d N_a}{N_a + N_d} \right) \right) W^2$$

$$\boxed{V_0 = \frac{q}{2E} \left(\frac{N_d N_a}{N_a + N_d} \right) W^2}$$

$$\sqrt{\frac{2 E V_0}{q} \left(\frac{N_a + N_d}{N_a N_d} \right)} = W$$

$$x_p + x_n = \sqrt{\frac{2 E V_0}{q} \left(\frac{N_a + N_d}{N_a N_d} \right)}$$

$$\frac{x_p}{x_n} = \frac{W}{x_n} - \frac{x_n}{x_n}$$

$$\times \begin{cases} \dfrac{N_d}{N_a} = \dfrac{1}{x_n} \sqrt{\dfrac{2 E V_0}{q} \left(\dfrac{1}{N_a} + \dfrac{1}{N_d} \right)} - 1 \\ x_n = \dfrac{N_a}{N_d} \sqrt{\dfrac{2 E V_0}{q} \left(\dfrac{1}{N_a} + \dfrac{1}{N_a} \right)} - 1 \end{cases}$$

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$$\frac{x_n}{x_p} = \frac{N_a}{N_d} \Rightarrow x_n = \frac{N_a}{N_d} x_p$$

$$x_p = W - \frac{N_a}{N_d} \cdot x_p$$

$$x_p \left(1 + \frac{N_a}{N_d}\right) = W$$

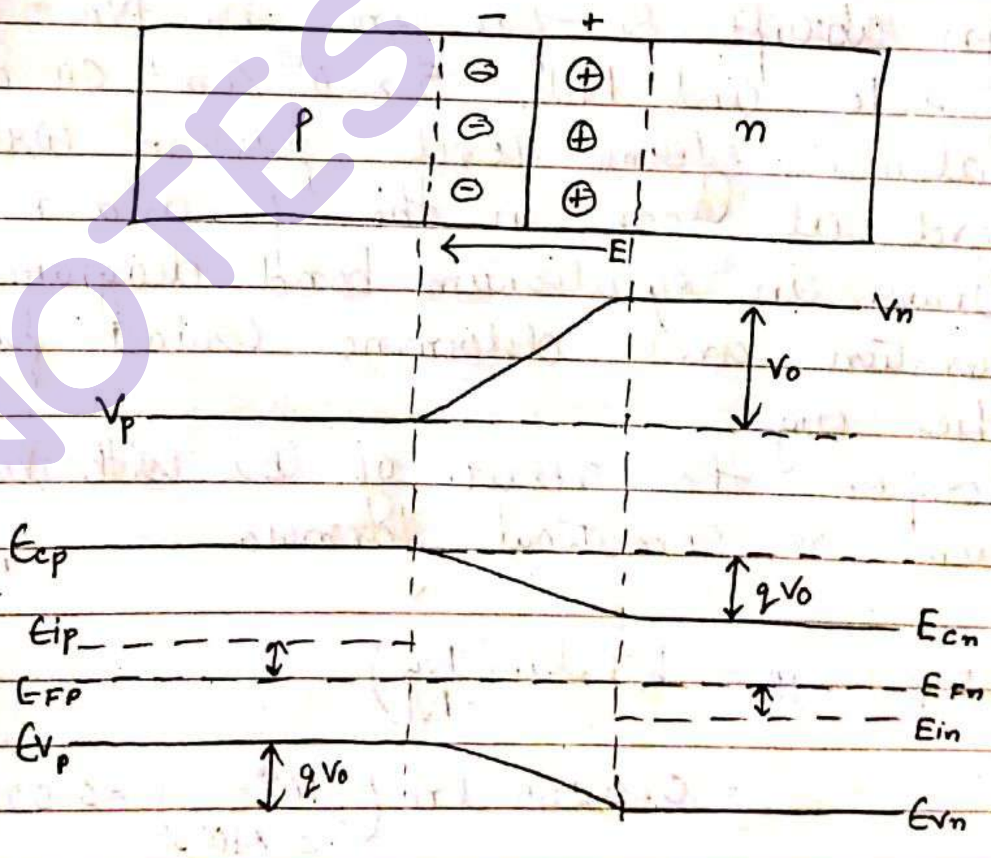
$$x_p = \frac{W}{1 + \frac{N_a}{N_d}} = \frac{W N_d}{N_d + N_a}$$

$$x_p = \sqrt{\frac{2\varepsilon V_0}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)} \cdot \frac{N_d}{N_d + N_a}$$

$$\cancel{x_p = \sqrt{\frac{2\varepsilon V_0}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)} \cdot \frac{N_d}{N_d + N_a}}$$

$$\boxed{x_p = \sqrt{\frac{2\varepsilon V_0}{q}\left[\frac{N_d}{N_a(N_a + N_d)}\right]}}$$

2.8.19



Band Bending (No-biased Condition)

$$\frac{P_{po}}{P_{no}} = e^{\frac{qV_0}{KT}}$$

$$P_{po} = N_V \cdot e^{\frac{-(E_{fp} - E_{vp})}{KT}}$$

$$P_{no} = N_V \cdot e^{\frac{-(E_{fn} - E_{vn})}{KT}}$$

$$e^{\frac{qV_0}{KT}} = e^{\frac{-(E_{fp} - E_{vp} + E_{fn} \mp E_{vn})}{KT}}$$

$$\frac{qV_0}{KT} = -E_{fp} - E_{vp} + E_{fn} + E_{vn}$$

$$e^{\frac{qV_0}{KT}} = e^{\left(\frac{E_{fp} - E_{fn}}{KT}\right)} \cdot e^{\left(\frac{E_{vp} - E_{vn}}{KT}\right)}$$

$$\frac{qV_0}{KT} = \frac{E_{vp} - E_{vn}}{KT}$$

or $\boxed{E_{vp} - E_{vn} = qV_0}$

- The energy band on either side of the junction are seperated by contact potential V_0 times the electronic charge (q).

Q An abrupt Si-pn junc. has $N_a = 10^{18}/cm^3$ on 1 side and $N_d = 5 \times 10^{15}/cm^3$ on other side.

(a) Calculate fermi level position wrt intrinsic level at 300K in the p and n region.

(b) Draw an equilibrium band diagram for the junction and determine contact potential from the dig.

(c) Compare the result of (b) with V_0 calculated from mathematical formula.

$n_i = 1.5 \times 10^{10}$

$$E_{ip} - E_{fp} = KT \ln\left(\frac{N_a}{N_i}\right)$$

$$= 0.0259 \ln\left(\frac{10^{18}}{1.5 \times 10^{10}}\right) = 0.0259 \ln(6.6 \times 10^{7}$$

0.4054

$$E_{fn} - E_{in} = KT \ln\left(\frac{N_d}{N_i}\right)$$

$= 0.0259 \ln($

$= 0.0467 \text{ eV}$

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$= 0.0259 \ln\left(\frac{5 \times 10^{15}}{1.5 \times 10^{10}}\right)$

$= 0.0259 \ln (3.33 \times 10^{5})$

$= 0.329 eV$

$qV_0 = 0.467 + 0.329$, $qV_0 = \left(KT \ln \frac{N_a N_d}{N_i^2}\right)$

$= 0.796 eV$

$= 0.0259 \ln\left(\frac{5 \times 10^{33}}{(1.5 \times 10^{10})^2}\right)$

$= 0.796$

Q2. A pn junction diode having $n_a = 10^{18}$ and $n_d = 5 \times 10^{15}$ /cm^3 has a circular cross section area with diameter of 10 micrometer. Calculate x_{n_0}, x_{p_0}, E_0, Q_+, for this junction at equilibrium at 300K. Also sketch EF wrt x and charge density (ρ) to scale. Permitivity of Si $(\epsilon_r) = 11.8$

$\epsilon = \epsilon_0 \cdot \epsilon_r$

$x_{n_0} = \sqrt{\frac{2 \epsilon V_0}{q}\left(\frac{N_a}{N_a(N_a+N_d)}\right)}$

$= 8.85 \times 10^{-14} \times 11.8$

$= 104.43 \times 10^{-14}$

$V_0 = 0.0259 \ln\left(\frac{10^{18} \times 5 \times 10^{15}}{(1.5 \times 10^{10})^2}\right)$

$= 0.796$

$x_{n_0} = \sqrt{\frac{2 \times 104.43 \times 10^{-14} \times 0.796}{1.6 \times 10^{-19}} \times \left(\frac{10^{18}}{5 \times 10^{15}(5 \times 10^{33})}\right)}$

$= 0.455 \mu m$

$x_{p_0} = \sqrt{\frac{2 \times 104.43 \times 10^{-14} \times 0.796 \times 5 \times 10^{15}}{1.6 \times 10^{-19} \; (10^{18}(5 \times 10^{33}))}}$

$= 2.27 \times 10^{-3} \mu m$

$E_0 = -\frac{q N_d}{\epsilon} \cdot x_n = \frac{-1.6 \times 10^{-19} \times 5 \times 10^{15} \times 0.455 \times 10^{-6}}{104.43 \times 10^{-14}}$

$= \frac{-3.64 \times 10^{-10}}{104.43 \times 10^{-14}} = 0.03485 \times 10^{4}$

$= 348.5$

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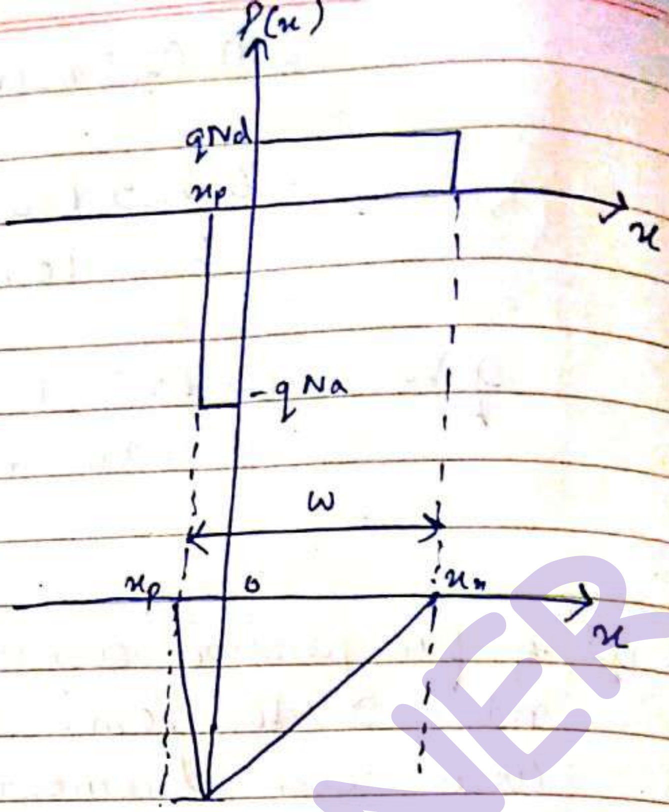
$Q_+ = q N_d x_n \cdot A$

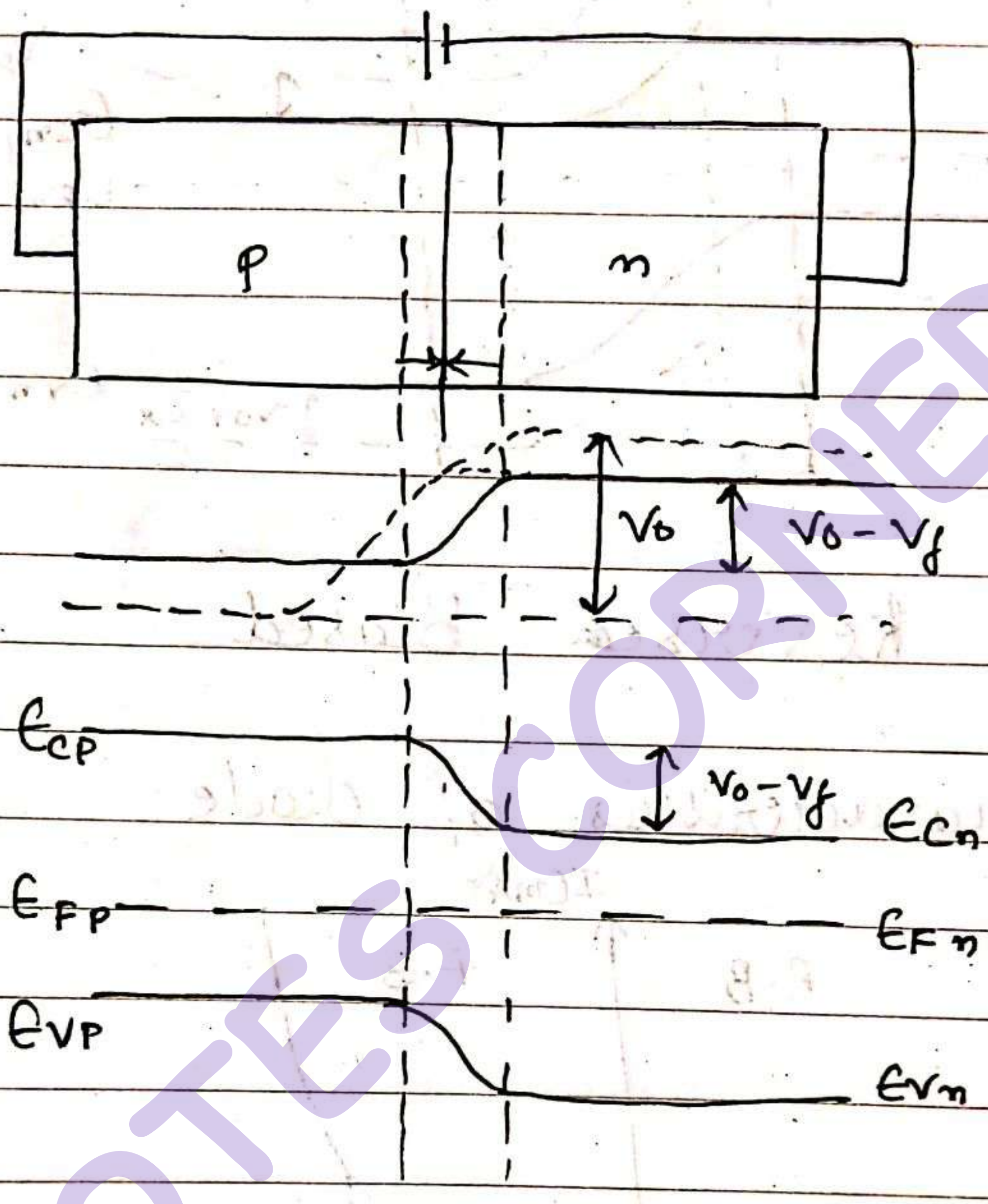


6.7.8.19

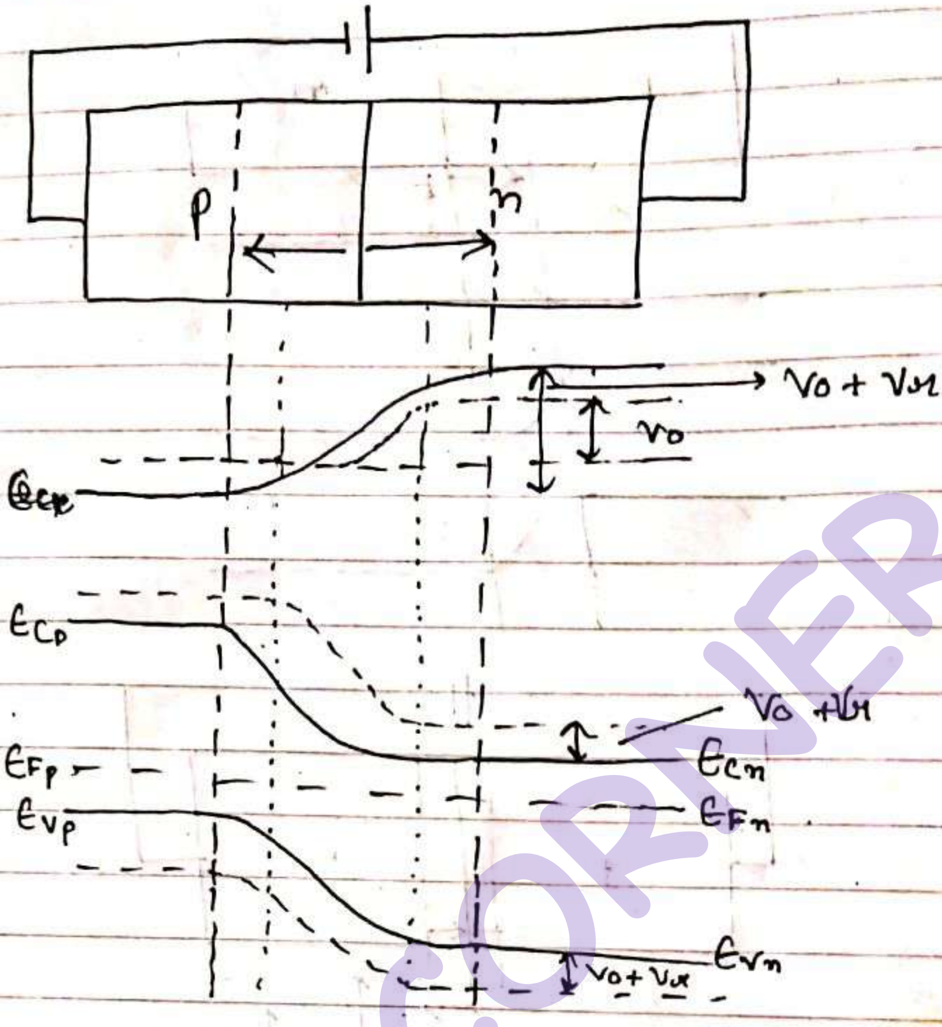
- Changes due to FB & RB Conditions

When applied voltage changes, the built-in potential and thus electric field will also change across the depletion region.
An applied voltage also change the band bending. For forward biased condition, the potential barrier across the junction will reduce by $(V_0 - V_f)$ where V_f is the applied / forward voltage.
Similarly of reverse biased, the built in potential or potential barrier will increase by V_r, total $(V_0 + V_r)$.
EF will reduce in forward conditions and increase in reverse biased.

W, x_{p0}, x_{n0} and E_0 can be found by replacing V_0 by $(V_0 - V_f)$ or $(V_0 + V_r)$ depending upon supplied voltage.

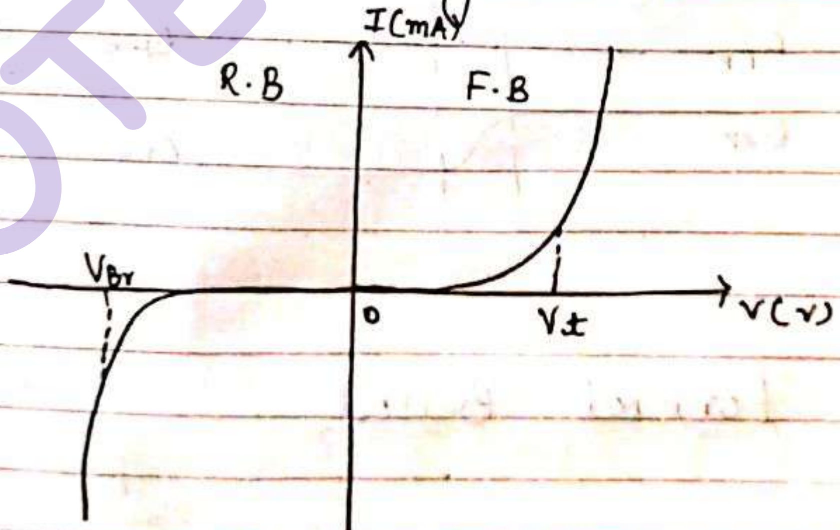


Forward Biased.



Reversed Biased

- V-I Characteristics of diode



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

$V = 0 \rightarrow I_D = 0$

$V > 0 \rightarrow I_D = I e^{V/\eta V_T}$

$V < 0 \rightarrow I_D = -I_s$

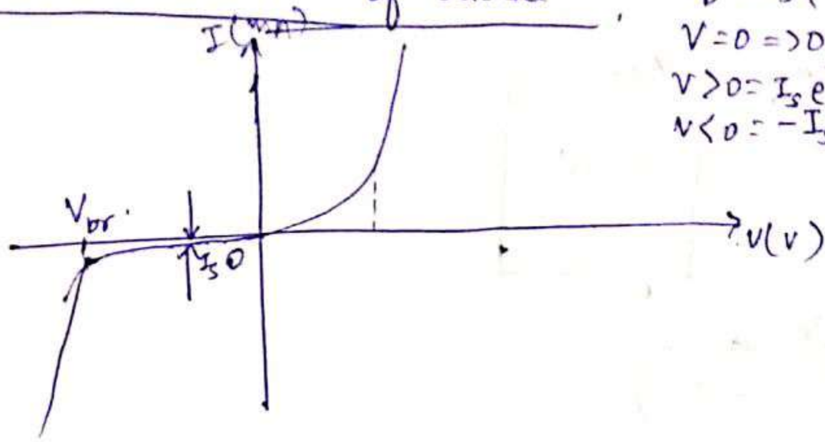
V-I characteristic of diode.

$I_D = I_s(e^{V/V_T} - 1)$.

$V = 0 \Rightarrow 0$.

$V > 0 = I_s e^{V/V_T}$.

$V < 0 = -I_s$.

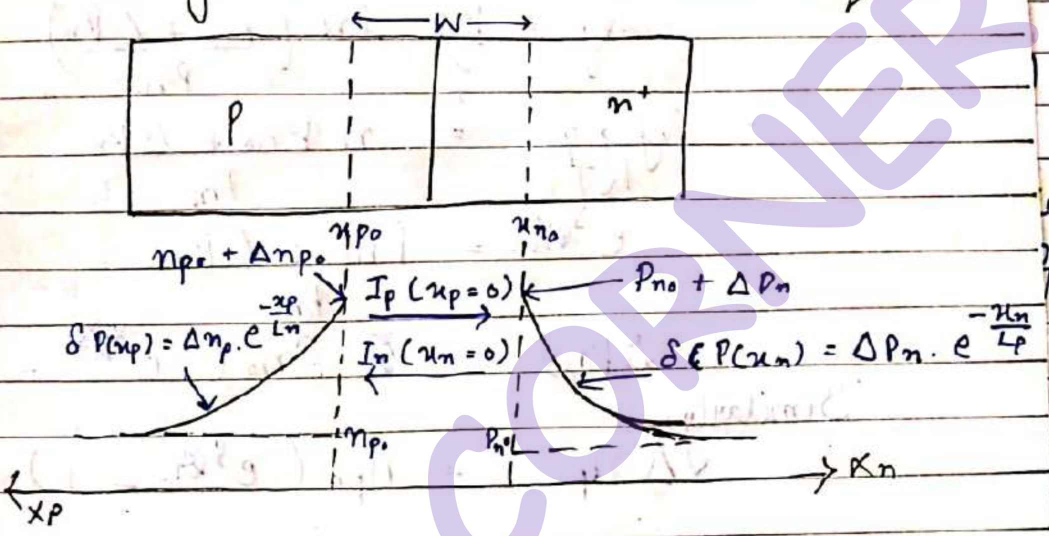


$$I = \begin{cases} I_{diff} - I_{gen} = 0 & V = 0 \\ I_s e^{\frac{V_f q}{KT}} & V > 0 \\ -I(gen.) = -I_s & V < 0 \end{cases}$$

- The drift current is relatively insensitive to the barrier potential. The drift current is due to minority carriers in the depletion region & depend upon the no. of minority charge carriers generate within the depletion region.
- The supply of minority carries on each side of the junction require to participate in the drift component of current is generated by thermal excilation of EHP generation.
- The current due to drift of generated carriers across a junction is commonly called as generation current since its magnitude entirely depend upon rate of generation of minority carries.
- The total current crossing the junction is composed of some of diffusion & drift current.
- At eqbm. the net current crossing the junction is 0 since the drift & diffusion component cancel each other. Under reverse biase condition diffusion current is negligible due to large barrier potential & only generation current close from n-side to p-side.
- There is an increase in pobability that the majority carries will diffuse across the junction by the factor $e^{\frac{Vf}{KT}}$ or $e^{\frac{V_f}{V_t}}$.

$$I = \begin{cases} I_{diff} = I_{drift} \;(I = 0) & V = 0 \\ I_{diff} & V > 0 \\ -I_{generation} = I_s & V < 0 \end{cases}$$

Carrier Injection / Diode Current Eqn:-



$$\frac{p_{po}}{p_{no}} = e^{V_o/V_t}$$

$$V_o = \frac{kT}{q} \ln \frac{p_{po}}{p_{no}} \quad \text{— (1)}$$

$V_o - V_f$

$$\frac{p_p}{p_n} = \frac{p_{po} + \delta n}{p_{no} + \delta p}$$

By applying forward voltage V_f, the depletion layer will reduce. i.e $V_o' = V_o - V_f$ which is given as the new conc.

$$\frac{p_p}{p_n} = \frac{p_{po} + \delta n}{p_{no} + \delta p}$$

Assuming it a low level injection ($\delta n \to 0$)

$$\frac{p_p}{p_n} = \frac{p_{po}}{p_{no} + \delta p} \quad \text{(New built in potential)}$$

$$V_o - V_f = \frac{kT}{q} \ln \frac{p_{po}}{p_{no} + \delta p} \quad \text{— (2)}$$

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Subtracting 2 from 1.

$$V_0 - (V_0 - V_f) = \frac{KT}{q}\left[\ln\frac{P_{P_0}}{P_{n_0}} - \ln\frac{P_{P_0}}{P_{n_0}+\delta P}\right]$$

$$V_f = \frac{KT}{q}\left[\ln\left(\frac{P_{n_0}+\delta P}{P_{n_0}}\right)\right]$$

Assuming at the edge of depletion region, excess conc. $\delta P(x_n) = \Delta P_n$

$$V_f = \frac{KT}{q}\ln\left(\frac{P_{n_0}+\Delta P_n}{P_{n_0}}\right)$$

$$\frac{V_f \times q}{KT} = \ln\frac{P_{n_0}+\Delta P_n}{P_{n_0}}$$

$$e^{\frac{V_f q}{KT}} = \frac{P_{n_0}+\Delta P_n}{P_{n_0}}$$

$$\Delta P_{n_0} = P_{n_0}\left(e^{\frac{qV_f}{KT}} - 1\right)$$

Similarly,

$$\Delta n_p = n_{p_0}\left(e^{\frac{qV_f}{KT}} - 1\right)$$

As the holes are diffused from p-side to n-side, they recombine with $\bar{e}$ on n-side, resulting excess concentration distribution along the length is given by

$$\delta P(x_n) = \Delta P_n . e^{-\frac{x_n}{L_P}}$$

$$= P_{P_0}\left(e^{\frac{qV_f}{KT}} - 1\right). e^{-\frac{x_n}{L_P}}$$

$$\delta n(x_p) = \Delta n_p . e^{-\frac{x_p}{L_n}}$$

$$= n_{p_0}\left(e^{\frac{qV_f}{KT}} - 1\right). e^{-\frac{x_p}{L_n}}$$

Due to the diffusion of hole across the n-side, the diffusion current is given as

$$J_p = -qD_p\frac{dP}{dx}$$

$$J = \frac{I}{A}$$

$$I_{P(diff.)} = -Aq D_p \frac{d\delta P(x_n)}{d(x_n)}$$
$$= Aq \frac{D_p}{L_p} \cdot \Delta P_n \cdot e^{-\frac{x_n}{L_p}}$$
$$= Aq \frac{D_p}{L_p} \cdot \delta P(x_n)$$

At the edge of depletion region, the diffusion current $I_{P(x_n=0)} = Aq \frac{D_p}{L_p} \cdot \Delta P_n$

$$= Aq \frac{D_p}{L_p} \cdot P_{n_0} (e^{\frac{qV_f}{KT}} - 1)$$

Similarly we can find out the diffusion current p-side for e at the edge of depletition region.

$$I_n(x_{p=0}) = -Aq \cdot \frac{D_n}{L_n} n_{p_0} (e^{\frac{qV_f}{KT}} - 1)$$

Assuming in the depletion region, no recombinational movement. The total diode current is given by

$$I = I_P(x_{n=0}) - I_n(x_{p=0})$$
$$= Aq \frac{D_p}{L_p} \cdot P_{n_0} (e^{\frac{qV_f}{KT}} - 1) + Aq \frac{D_n}{L_n} n_{p_0} (e^{\frac{qV_f}{KT}} - 1)$$

$$= Aq \left(\frac{D_p}{L_p} P_{n_0} + \frac{D_n}{L_n} n_{p_0} \right) (e^{\frac{qV_f}{KT}} - 1)$$

Similarly,

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

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Q An abrupt silican diode junction ($A = 10^{-4}$ cm^2) as the following propertis at 300K. At p-side, $n_A = 10^{17}$ (cm^3)
$\tau_n = 0.1 \mu s$, $\mu_p = 200\ cm^2$
$\mu_n = 700\ cm^2/vol\ sec$.
for n side ($n_d = 10^{15}/cm^3$, $\tau_p = 10 \mu s$
$\mu_n = 1300\ cm^2$, $\mu_p = 450\ cm^2/volt\ sec$.

The diode is forward biased by 0.5 volt and reverse biased by -0.5V. find corresponding diode current.

o Capacitance in PN Junction Diode
1. Depletion Capacitance (reverse bi-) Junction C_J
2. Storage Capacitan (forwar bias) C_s

1. There are two types of capacitance associated with p-n junction which is due to the dipole in the transition region.
2. Storage capacitance is also known as diffusion capacitance due to charge storage effect.

→ Junction Capacitance
Junction capacitance is dominating in reverse bias and charge storage capacitance is dominating in forward bias.

The uncompensated acceptors on p-side provides negative charge and donar ions on n-side provides positive charge in depletion region.

The capacitance of the resulting dipole can be found by $\left| C = \frac{dQ}{dV} \right|$ instead of Q/V due to charge on each side of the transition region varies non linearly with applied voltage. $W = \sqrt{\frac{2 \epsilon V_0}{q} \frac{(N_a + N_d)}{(N_a N_d)}}$

by the application of reverse biased voltage. new width will be $W = \sqrt{\frac{2 \epsilon (V_0 - V)}{q} \left(\frac{N_a + N_d}{N_a N_d}\right)}$

$$|Q| = qAx_nN_d = qAx_pN_a$$

$$|Q| = qA\left(\frac{N_aN_d}{N_a+N_d}\right)W$$

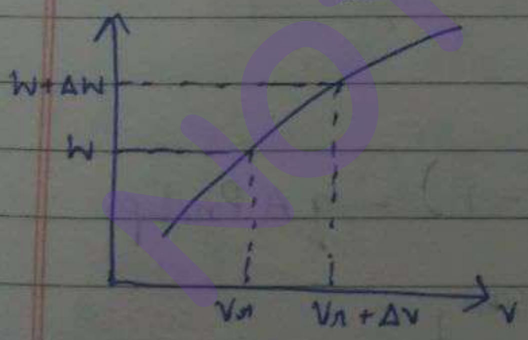
$$|Q| = qA\frac{N_aN_d}{N_a+N_d}\sqrt{\frac{2\epsilon(V_0-V)}{q}\left(\frac{N_a+N_d}{N_aN_d}\right)}$$

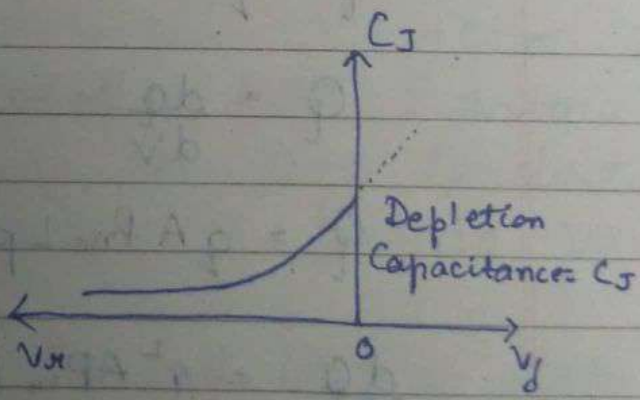
$$|Q| = A\sqrt{q2\epsilon(V_0-V)\left(\frac{N_aN_d}{N_a+N_d}\right)}$$

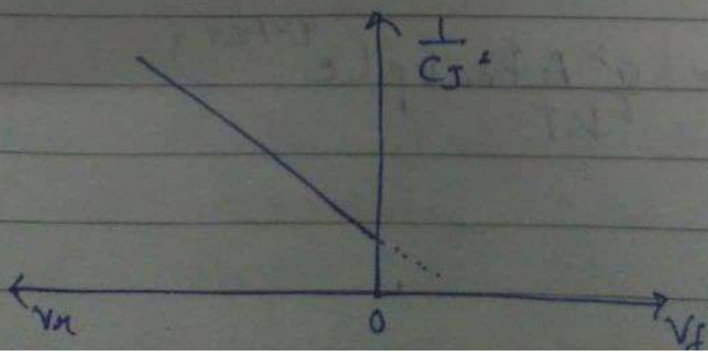
$$\frac{dQ}{d(V_0-V)} = \frac{A}{2}\sqrt{\frac{2\epsilon q}{(V_0-V)}\left(\frac{N_aN_d}{N_a+N_d}\right)}$$

$$C_i \propto \frac{1}{\sqrt{V_0-V}} \qquad C_i = \frac{A}{2}\sqrt{\frac{2\epsilon q(N_aN_d)}{(V_0-V)(N_a+N_d)}}$$

$$C_i = \frac{A\epsilon}{W}$$







2. Storing capacitance

By the application of forward bias voltage, the barrier height decreases, depletion region decreases and injection of majority carriers across the depletion region into opposite side where they show minority carrier.

The density of excess minority carriers increases with forward bias.

$$\delta P(x_n) = \Delta P_n \cdot e^{-x_n/L_p}$$

$$= P_{n_0}(e^{qV/KT} - 1)\, e^{-x_n/L_p}$$

$$Q = qAN\,dx_n$$

$$Q_{x_n} = qA \int^{x_n} \delta\, P(x_n)$$

$$Q = qA \int_0^{x_n} \Delta P_n e^{-x_n/L_p}\, x_n$$

$$= qA \int_0^{\infty} (\Delta P_n e^{-x_n/L_p})\, dx_n$$

$$Q = qA\Delta P_n \int e^{-x_n/L_p}\, dx_n$$

$$Q = qA\Delta P_n \int e^{-x_n/L_p}\, dx_n$$

$$Q = qAP_{n_0}(e^{\frac{qV}{KT}} - 1)\left[-\frac{e^{-\frac{x_n}{L_p}}}{x_n} L_p \right]_0^{\infty}$$

$$Q = qAP_{n_0}(e^{(qV/KT)} - 1)\, L_p$$

$$Q = \frac{dQ}{dV}$$

$$Q = qAP_{n_0}L_p(e^{qV/KT} - 1) - qAP_{n_0}L_p$$

$$\frac{dQ}{dV} = q^2 AP_{n_0} L_p (e^{qV/KT})$$

$$C_s = \frac{q^2 AP_{n_0} L_p (e^{qV/KT})}{KT}$$

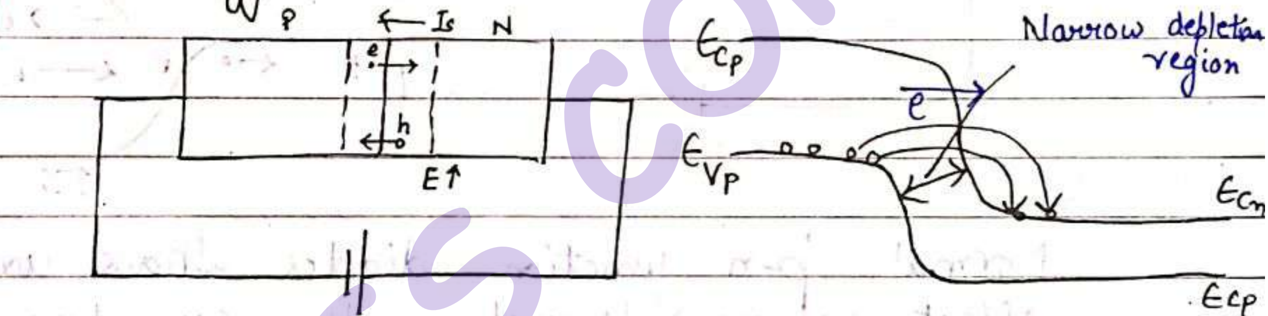
- Breakdown diodes

Diodes which are especially designed to operate in reverse biased Conditions are breakdown diodes. When the diode is reverse biased, after a critical volt. (V_{br}), Current increases sharply. At this huge current may damage the diode.

This increase in Current or breakdown mechanism is due to 2 processes

1. Zener Effect
2. Avalanche effect

1. Zener Effect / breakdown

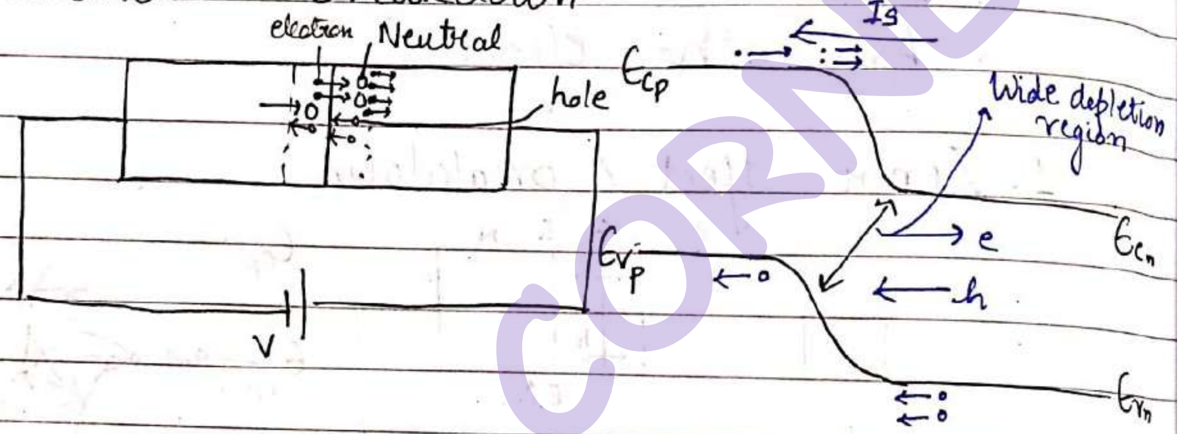


Zener diodes are heavily doped diodes. The energy band diagram of zener diode shown in the fig which has narrow depletion region and n-side Conduction band appears opposite to p-side Valence band.

Due to this, Large no. of empty states in the n-side of Conduction band available which may be filled by the states from valence band from p side. This process is called as tunneling of ē from p side to n side which will give reverse current from n side to p-side.

Tunneling effect depend upon width of the barrier. As width is narrow, tunneling is more.
The electric field for this type of process is in the order of 10^6 V/cm. In covalent bond model, Zener effect is due to field ionisation. The high electric field breaks the band and carriers are generated which will constitute minority current.

2. Avalanche breakdown



Normal p-n junction diodes shows avalanche effects where tunneling is very less. The breakdown effect involves impact ionisation by the energetic carriers.
If the EF in transition region is large, the $\bar{e}$ entering from p-side accelerated with high KE to cause collision with lattice structure.
This collision will create carrier multiplication i.e original $\bar{e}$ with newly generated $\bar{e}$ which will move towards n side and again colloid with lattice structure to create more multiplication. This is cummilative process and called as avalanche process which cause increase in reverse current that may breakdown the diode.

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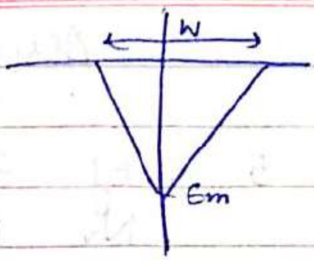
$$|E_m| = \frac{2V_0}{W} \qquad \left(\frac{1}{2} E_m W = V_0\right)$$

Maximum electric field



$$W = \sqrt{\frac{2V_0 \epsilon}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)}$$

$$|E_m| = \frac{2(V_0 - V)\, q}{\sqrt{2(V_0 - V)\epsilon}}\left(\frac{N_a N_d}{N_a + N_d}\right)$$

$$|E_M| = \sqrt{\frac{2q(V_0 - V)}{\epsilon}\left(\frac{N_a N_d}{N_a + N_d}\right)}$$

Q. The doping density of the p-n junction (silicon) $N_a = 10^{17}/cm^3$, $N_d = 8^{15}$. Determine V_{br} if critical electric field 3×10^5 V/cm. Avalanche breakdown takes place when max EF ~~density~~ intensity in the depletion region is critical electric field.

$\epsilon = \epsilon_0 \epsilon_r$
$8.85 \times 10^{-14} \times 11.7$

$$|E_M| = \sqrt{\frac{2q(V_0 - V)}{\epsilon}\left(\frac{N_a N_d}{N_a + N_d}\right)}$$

$$E_M^2 = \frac{2q(V_0 - V)}{\epsilon}\left(\frac{N_a N_d}{N_a + N_d}\right)$$

$$V_0 - V = \frac{\epsilon E_M^2}{2q}\left(\frac{N_a + N_d}{N_a N_d}\right)$$

$$= \frac{(3 \times 10^5)^2 (1.03 \times 10^{-12})(10^{17})}{2 \times 1.6 \times 10^{19} (8 \times 10^{22})}$$

$$V_0 - V = (9 \times 10^{10})$$

$$V_0 = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2}$$

$= 0.77$

$V_0 - V = 39.48$

$-V = 39 - 48 - V_0$

$-V_{br} = 39 - 48 - 0.77$

$V_{br} = -38.71V$

Q. Calculate intrinsic Carrier Conc. of GaAs at T = 300K and at 450K. Given $N_c = 4.7 \times 10^{17} /cm^3$ $N_v = 7 \times 10^{18} /cm^3$ at 300K $E_g = 1.42$ eV

$$n_i^2 = N_c N_v e^{\left(\frac{E_g}{KT}\right)}$$

$$n_i^2\Big|_{300} = 4.7 \times 10^{17} \times 7 \times 10^{18} e^{-\frac{1.42}{0.0259}}$$

$$= 32.9 \times 10^{34} \times e^{-54.82}$$

$$= 32.9 \times 10^{34} \times \cancel{6.42 \times 10^{23}}\ 1.55 \times 10^{-24}$$

$$= 50.995 \times 10^{10}$$

$$n_i^2 = 5.0995 \times 10^{12}$$

$$n_i = 2.26 \times 10^{6} /cm^3$$

$$KT\Big|_{450} = 0.0259 \times \frac{45}{30} = \cancel{0.0345}\ 0.03885$$

$$N_c\Big|_{450} = 7 \times 10^{18} \times \left(\frac{450}{300}\right)^{3/2}$$

$$= 7 \times 10^{18} \times (1.837) = 12.859 \times 10^{18}$$

$$n_i^2\Big|_{450} =$$

Q. Calculate diffusion current density for n type GaAs semiconductor at 300K. The $\bar{e}$ conc. varies linearly from 1×10^{18} to $7 \times 10^{17} /cm^3$ over a dist of 0.1 cm. $D_n = 225\ cm^2/sec$

$$J_n(\text{diff.}) = q D_n \frac{dn}{dx}$$

$$= 1.6 \times 10^{-19} \times 225 \times \frac{7 \times 10^{17} - 1 \times 10^{18}}{0.1}$$

$$= 3.6 \times 10^{-17} \times \left(\frac{3 \times 10^{17}}{0.1}\right)$$

$$= 108$$

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Q. Calculate the position of fermi level w in Si at 300 assuming effective mass $= 1.08\, m_0$, $m_p = 0.56\, m_0$

Q. Consider a p-type semiconductor in which hole mobility 200 /cm². If an EF of 2×10^3 V/cm exist in +x direction and hole density is given by $P(x) = 10^{18} \exp\left(\frac{-x}{L_p}\right)$ $L_p = 1\, \mu m$. Determine hole density at power of x.

$7.2 \times 10^4 \exp\left(\frac{-x}{L_p}\right)$

$$J_p = J_{p\,drift} + J_{p\,diff}$$
$$= p q \mu_p E - q D_p \frac{dp}{dx}$$

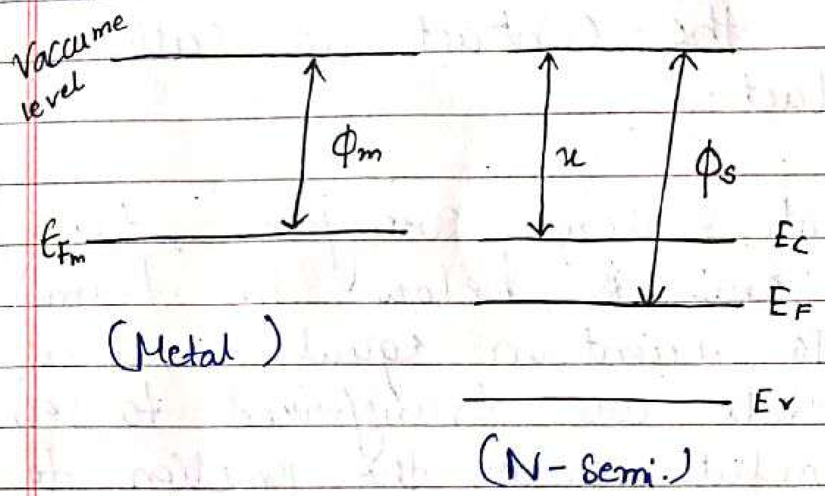
$$J_{p\,drift} = 10^{18} \times \exp\left(\frac{-x}{4}\right) \times 1.6 \times 10^{-19} \times 2 \times 10^3$$

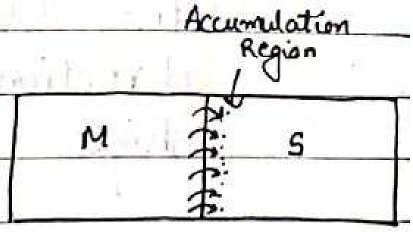
$$= 320 \times \exp\left(\frac{-x}{4}\right)$$

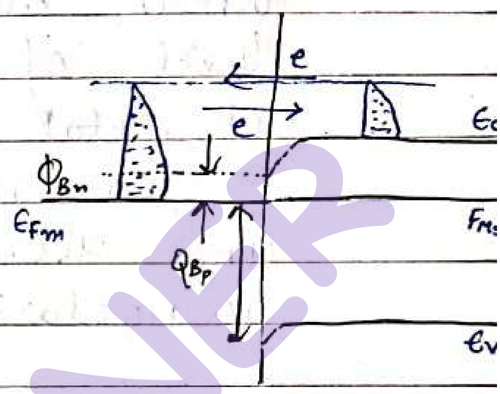
$$J_{p\,diff} = 1.6 \times 10^{-19} \times D_p \times \frac{dp}{dx}$$

$$D_p = \mu_p \frac{KT}{q}$$

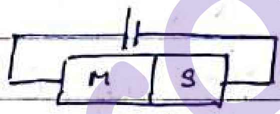
- Metal - Semiconductor Contact ($\phi_m < \phi_s$) Ohmic Contact



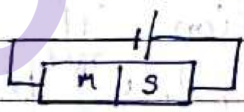




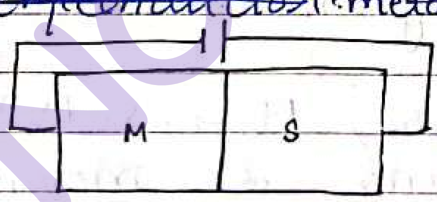
No Bias Condition,
$I = 0$

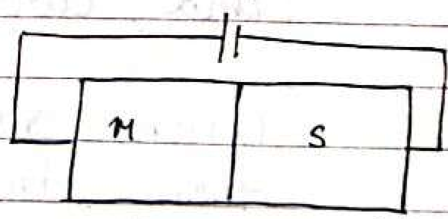
Forward Biased, 

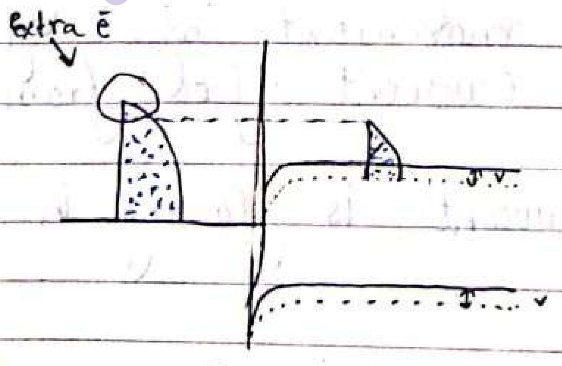
Band will move upward by V.
Current will flow from ~~Semiconductor~~ metal to ~~metal~~ semiconductor.

Reverse Biased 

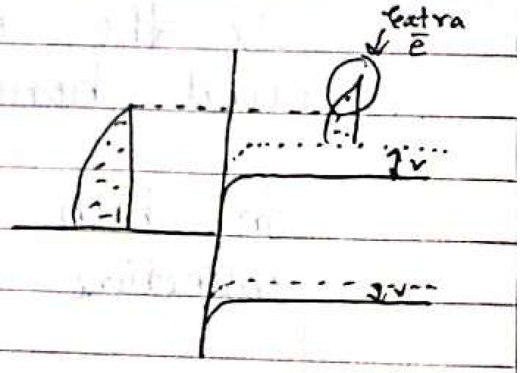
Band will move downward by V.
Current will flow from ~~semiconductor~~ metal to ~~Semiconductor~~ metal







Reverse



Forward

When metal & n-type Semi. is in contact where $\phi_m < \phi_s$ the current will flow in both the directions & the contact is called as ohmic contact.

When metal & semi. are joint, the fermi level of semi. is below the fermi level of metal. To maintain equal level at equil. $\bar{e}$ from metals are transferred to semicond and accumulate near the junction to form accumulation region.

In this process, band bending takes place as in the fig.

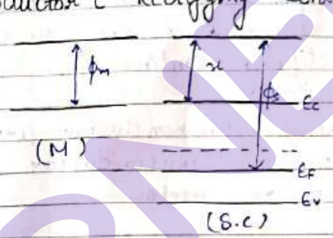
At equili. no. of $\bar{e}$ crossing the junction from $M \to S$ & $S \to M$ are almost same. so that the net current is 0.

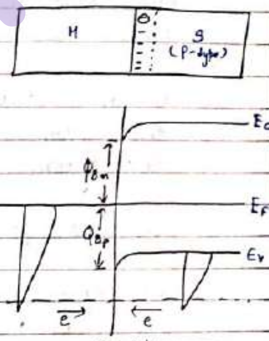
When junction is forward biased, $M \to +ve(V)$, $S \to -ve(V)$, the net potential increase and the band moves upward so that there is a effective movement from $S \to M$ and current flow from $M \to S$.

When reverse biased, $M \to -ve(V)$, $S \to +ve(V)$ then band bending is moving downward So the effective movement of $\bar{e}$ from $M \to S$ and hence the current flow from $S \to M$

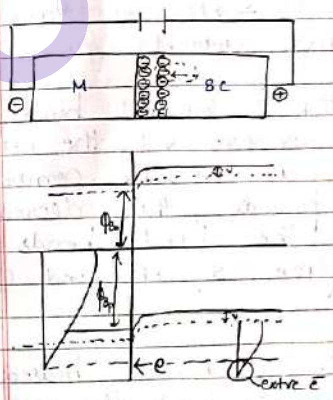
In both cases, current is flowing in both directions.

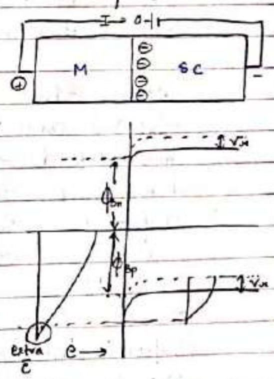
- Metal - Semiconductor Contact on p-type semi-conductor (Rectifying Contact) $\phi_m < \phi_s$





At equilibrium ⇒





Forward

Reverse

* Energy gap always remains the same.

When metal and p-type semiconductor is in contact where $\phi_m < \phi_s$, the current will flow in ~~both the~~ only one directions & the ~~th~~ contact is called as rectifying contact.

When metal and semiconductor are joint, the fermi level of semiconductor is below the fermi level of metal.

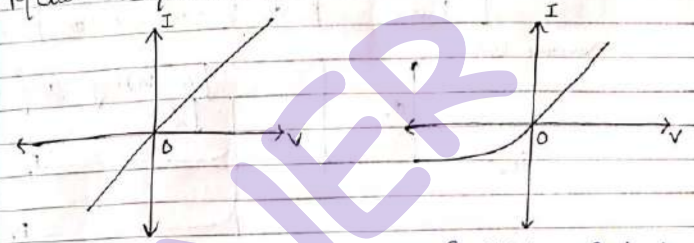
In this process, band bending takes place.

At equilibrium, no. of $\bar{e}$ crossing the junction from $M \rightarrow S$ and $S \rightarrow M$ are almost same so that the net current is 0.

When the junction is forward biased, M is -ive (v) and S.C is +ve (v), the net potential ~~increases~~ decreases as (+ve) ions combine with holes on the p-side, thus decreasing the depletion region. The band bends downwards $\bar{e}$ moves from $S \rightarrow M$ and current from $M \rightarrow S$.

When the junction is reverse biased, M is +ve (v) and S.C is -ve (v), the net potential increases as -ve ions accumulate. ~~on the~~ The band moves upward. The effective $\bar{e}$ moves from $M \rightarrow S$ and the current flows from $S \rightarrow M$.

- Metal-Semiconductor contact:



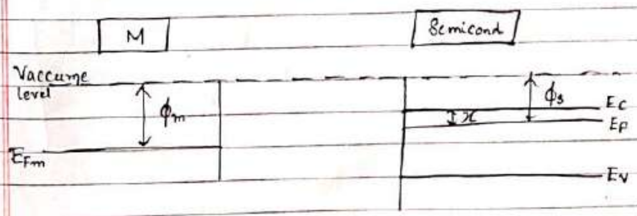
Ohmic Contact Rectifying Contact

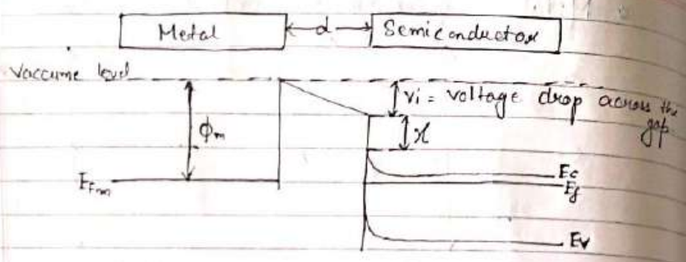
Metal semiconductor contact shows two types of characteristics:

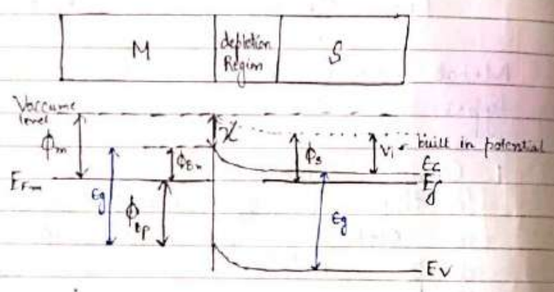
1. Ohmic contact
   In this type of contact current flows in both polarity with minimum voltage drop and the characteristics shown in the fig.

2. Rectifying contact
   In this type, current flows only in 1 direction and blocks in other direction as shown in the fig.

- Metal semiconductor contact: $\phi_m > \phi_s$







$$\phi_{Bn} = \phi_m - \chi$$

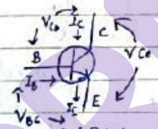
$$qV_{bi} = \phi_{Bn} - (E_c - E_f)$$

$$\phi_{Bp} = E_g - \phi_{Bn}$$

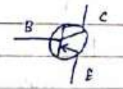
3. Transistor

– low power, high speed

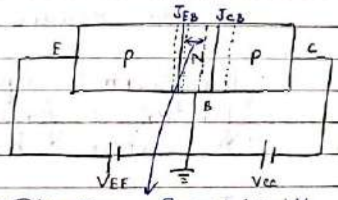
PNP



NPN



PNP



- Effective Base Width.
- Transfer of holes from low resistance to high resistance, hence named as transistor.

- Width of base is narrow and it is lightly doped so that 95 – 99.5% of the Carriers moves from emitter to collector.

- Forward bias : To move

Transistor is a 3-terminal device such as emitter, base & collector. From the emitter carriers are moving towards the base and reaches the collector.

Emitter is heavily doped, base is lightly doped and collector is lightly doped.

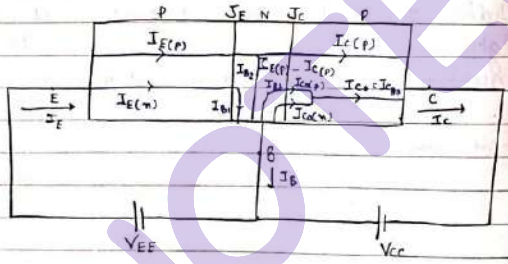
Base width is narrow compared to emitter or collector. Collector width is more than emitter to absorb heat or to reduce power per unit area.

For normal operation of transistor, EB junction is forward biased and CB junc is reverse biased.

Transistor are of 2 types.

1. NPN
2. PNP

- Operation of transistor / Current component of transistor.



$$I_E = I_C + I_B$$
$$I_E = I_{E(P)} + I_{E(n)} \simeq I_{E(P)} \quad (I_{E(n)} << I_{E(P)})$$

$$I_B = I_{B1} + I_{B2} - I_{B3}$$
$$I_{B3} = I_{Co} = I_{Co(P)} + I_{Co(n)}$$
$$I_C = I_{C(P)} + I_{Co}$$
$$I_{C(P)} = \alpha I_E$$
$$I_C = \alpha I_E + I_{Co}$$

- Emitter injection efficiency (γ)
Defined as the ratio of hole current injected from emitter diffused into the base to the total emitter current

$$\gamma = \frac{I_{E(P)}}{I_E}$$

- Base transport ratio (δ)
Defined as the ratio of hole current entering the collector from the base to the hole current entering the base from the emitter.

$$\delta = \frac{I_{C(P)}}{I_{E(P)}}$$

- CB Current Gain (α)
is defined as the ratio of output collector current to the input collector current

$$\alpha = \frac{I_{C(P)}}{I_E} = \gamma . \delta$$

$$\alpha = \frac{I_C}{I_E} \Rightarrow I_C = \alpha I_E + I_{Co}$$

$$I_C = \beta I_B + I_{CEO}$$

$$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO}$$

$\alpha < 1$
$(0.95 - 0.995)$

Q. Given a p-n-p transistor having following parameters: $I_{E(P)} = 2mA$

$I_{E(n)} = 0.01mA$

$I_{CP} = 1.98mA$

$I_{Cn} = 0.001mA$, Calculate: $\delta, \gamma, \alpha, \beta, I_B, I_{CEO}, I_{CBO}$

$$\gamma = \frac{I_{EP}}{I_{EP} + I_{EN}} = \frac{2}{2+0.01} = \frac{2}{2.01} = \underline{0.995}$$

$$\delta = \frac{I_{CP}}{I_{EP}} = \frac{1.98}{2} = \underline{0.99}$$

$$\alpha = \frac{I_{CP}}{I_E} = \frac{1.98}{2.01} = \underline{0.985}$$

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.985}{1-0.985} = \frac{0.985}{0.015}$$

$$= \underline{65.66}$$

$$I_B = \cancel{I_{B1} + I_{B2} - I_{B3}}$$

$$\cancel{= 0.01 + (2 - 1.98)} -$$

$$I_E = I_B + I_C$$

$$I_B = I_E - I_C$$

$$= 2.01 - 1.981 = 0.029$$

$$1.981 = \frac{0.985}{1-0.985} \times 0.029 + \frac{1}{1-0.985} \cdot I_{CBO}$$

$$1.981 = (65.66)0.029 + \frac{1}{0.015} \cdot I_{CBO}$$

$$1.981 = 1.9041 + 66.66 I_{CBO}$$

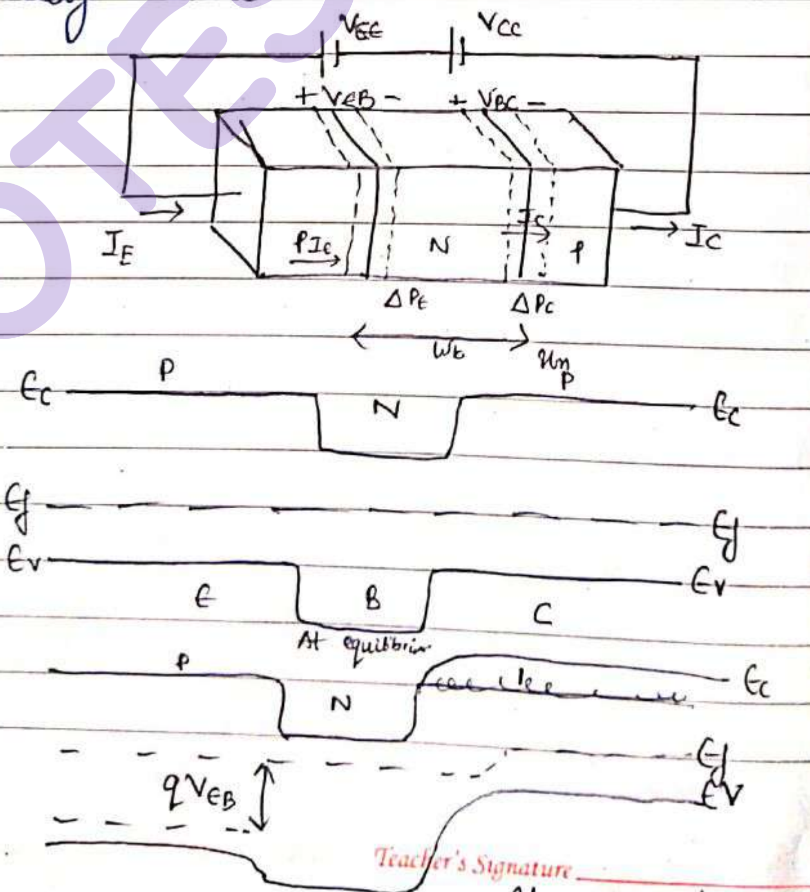
$$\frac{1.981 - 1.9041}{66.66} = I_{CBO}$$

$$I_{CBO} = \frac{0.077}{666.66} = \underline{1.15 \times 10^{-3}}$$

- Calculation of terminal current component for transistor.

Assumptions to simplify calculation for PNP transistor.

1. Hole diffused from emitter to collector drift is negligible in base region.
2. The emitter current is madeup of entirely of holes. The collector saturation current is negligible.
3. The active part of the base and two junctions are of uniform cross sectional area and current flows in the base is essentially 1D from emitter to collector.
4. All the current and voltages are at steady state.



Teacher's Signature

At normal active mode

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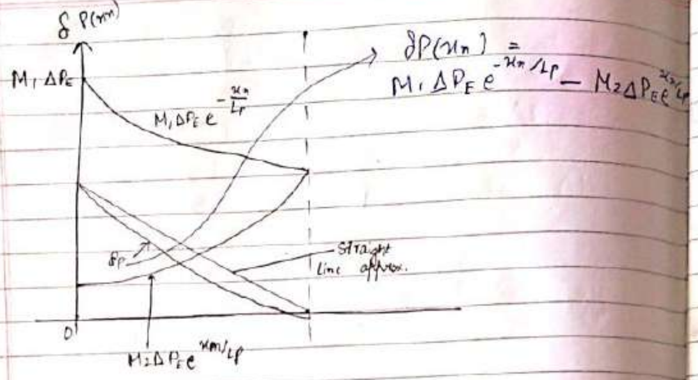

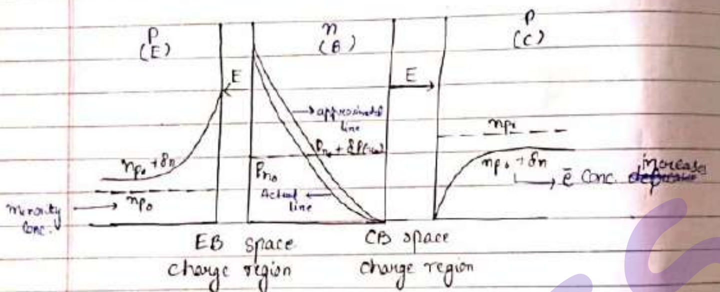

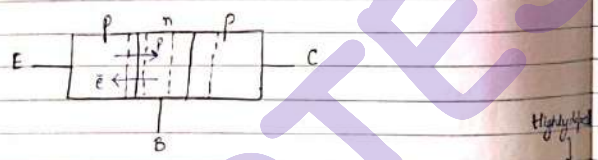

The minority carrier conc. ($\bar{e}$) in emitter (E) region) decay exponentially to 0 like in long diode. Similarly, conc. in Base and Collector region are shown.

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In the base region, hole conc. goes to 0 due to reverse bias CB junction (swept holes into collector region)

- Derivation of I_C, I_B and I_E

In the base region, near the depletion region, gradient of hole conc. gives the emitter current component.

$$I_p(x_n) = -qAD_p \frac{d\,\delta P(x_n)}{dx_n}$$

$$\frac{d[\delta P(x_n)]}{dx_n} = \frac{d(C_1 e^{x_n/L_p} + C_2 e^{-x_n/L_p})}{dx_n}$$

$$= \frac{C_1}{L_p} e^{x_n/L_p} - \frac{C_2}{L_p} e^{-x_n/L_p}$$

$$I_p|_{x_n} = -qAD_p \cdot \frac{1}{L_p}(C_1 e^{x_n/L_p} - C_2 e^{-x_n/L_p})$$

$$I_{E(p)} = I_p|_{x_n=0} = -qA\frac{D_p}{L_p}(C_1 - C_2)$$

$$= +qA\frac{D_p}{L_p}(C_2 - C_1) = qA\frac{D_p}{L_p}\left(\frac{\Delta P_E e^{W_b/L_p} - \Delta P_C}{e^{W_b/L_p} - e^{-W_b/L_p}} - \left(\frac{\Delta P_C - \Delta P_E e^{-W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}}\right)\right)$$

$$I_E = qA\frac{D_p}{L_p}\left(\frac{\Delta P_E(e^{W_b/L_p} + e^{-W_b/L_p}) - 2\Delta P_C}{e^{W_b/L_p} - e^{-W_b/L_p}}\right)$$

$$I_E = qA\frac{D_p}{L_p}\left(\frac{\Delta P_E(e^{W_b/L_p} + e^{-W_b/L_p})}{e^{W_b/L_p} - e^{-W_b/L_p}}\right) - \left(\frac{2\Delta P_C}{e^{W_b/L_p} - e^{-W_b/L_p}}\right)$$

$$I_E = qA\frac{D_p}{L_p}\left[\Delta P_E \cdot \coth\left(\frac{W_b}{L_p}\right) - \Delta P_C \operatorname{cosech}\left(\frac{W_b}{L_p}\right)\right]$$

$$\left[\frac{e^x + e^{-x}}{e^x - e^{-x}} = \coth x\right], \left[\frac{2}{e^x - e^{-x}} = \operatorname{cosech} x\right]$$

Teacher's Signature

Teacher's Signature

$$I_C = I_p(x_n = W_b)$$

$$= qA\frac{D_p}{L_p}\left[C_1 e^{\frac{W_b}{L_p}} - C_2 e^{-\frac{W_b}{L_p}}\right]$$

$$= \frac{qAD_p}{L_p}\left[\left(\frac{\Delta P_c - \Delta P_E e^{-\frac{W_b}{L_p}}}{e^{W_b/L_p} - e^{-W_b/L_p}}\right)e^{\frac{W_b}{L_p}} - \left(\frac{\Delta P_E e^{+\frac{W_b}{L_p}} - \Delta P_c}{e^{W_b/L_p} - e^{-W_b/L_p}}\right)\right]$$

$$= \frac{qAD_p}{L_p}\left[\frac{\Delta P_c e^{W_b/L_p} - \Delta P_E - \Delta P_E + \Delta P_c e^{-W_b/L_p}}{e^{\frac{W_b}{L_p}} - e^{-\frac{W_b}{L_p}}}\right]$$

$$I_C = \frac{qAD_p}{L_p}\left[\Delta P_E \operatorname{Cosech}\left(\frac{W_b}{L_p}\right) - \Delta P_c \operatorname{Coth}\left(\frac{W_b}{L_p}\right)\right]$$

$$I_B = I_E - I_C$$

$$= \frac{qAD_p}{L_p}\left[\Delta P_c \operatorname{Cosech}\left(\frac{W_b}{L_p}\right) - \Delta P_E \operatorname{Coth}\left(\frac{W_b}{L_p}\right) - \Delta P_E \operatorname{Cosech}\left(\frac{W_b}{L_p}\right) + \Delta P_c \operatorname{Coth}\left(\frac{W_b}{L_p}\right)\right]$$

$$I_B = \frac{qAD_p}{L_p}(\Delta P_E + \Delta P_c)\left[\tanh\left(\frac{W_b}{2L_p}\right)\right]$$

12.9.19

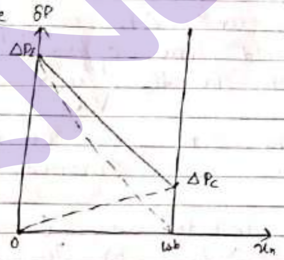
The equations derived above is valid for symmetrical transistor. For real transistor, it may deviate.

If the role of emitter & collector is inter-changed then complicated equations may come. The derivations are based on normal active mode i.e. EB junction – forward biased, CB junction – reverse biased.

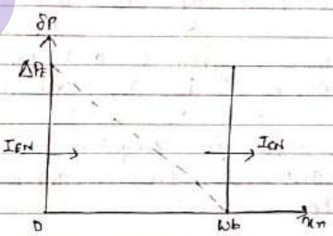
But in some cases, particularly switching, the normal active mode is violated and injection of hole and collection of hole properties across the 2 junctions play vital role.

A generalised approach is developed for a transistor operation as a diode couple model valid for all combination of EC bias.

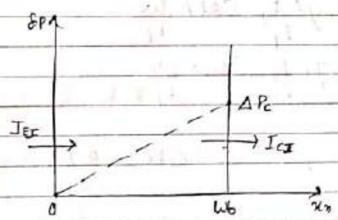
Couple diode Model / Eber Mole Model



Generalised Saturation mode (both are forward biased)



Normal mode (left to right)



Inverted ~~Reverse~~ mode (right to left)

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If the collector junction of transistor is forward biased we cannot neglect ΔP_c

If both the junctions are forward biased then ΔP_E and ΔP_c are positive and the straight line approx. for ΔP_E and ΔP_c are shown in the figure.

The straight line can be broken into 2 parts: Normal and Inverted mode.

The holes injected by E and collected by C are represented by I_{EN} and I_{CN} (Normal mode)

The holes injected from C and collected at E are represented by I_{EI} and I_{CI} (Inverted mode)

I_{EI} and I_{CI} will be negative since hole flow is opposite to our original definition of I_E and I_C.

Assuming, $a = \frac{qAD_p}{L_p} \coth \frac{W_b}{L_p}$

$b = \frac{qAD_p}{L_p} \text{Cosech} \frac{W_b}{L_p}$

$I_{EN} = a \Delta P_E$
$I_{CN} = b \Delta P_E$ $\quad (\because \Delta P_c = 0)$

$I_{EI} = -b \Delta P_c$
$I_{CI} = -a \Delta P_c$ $\quad (\because \Delta P_E = 0)$

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$I_E = I_{EN} + I_{EI} = a \Delta P_E - b \Delta P_c$
$= A(e^{qV_{EB}/KT} - 1) - B(e^{qV_{CB}/KT} - 1)$

where $A = aP_{n_0}$, $B = bP_{n_0}$

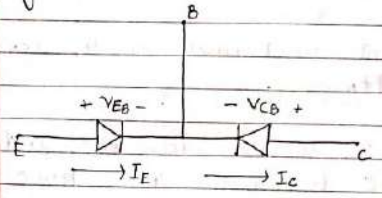
$I_C = I_{CN} + I_{CI} = b\Delta P_E - a \Delta P_c$
$I_C = B(e^{qV_{EB}/KT} - 1) - A(e^{qV_{CB}/KT} - 1)$

I_E an I_C are same as the previously derived current equation for symmetrical transistor. By replacing A and B we will have same equation as in the previous case.

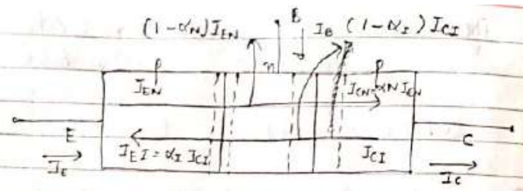
Eber-Mole model is valid for symmetrical as well as asymmetrical transistor.

Asymmetrical Transistor

13.9.19



$I_{EN} = I_{ES}(e^{qV_{EB}/KT} - 1)$ $\quad$ $I_{CI} = -I_{CS}(e^{qV_{CB}/KT} -$



$$I_E = I_{EN} + I_{EI} = I_{ES}(e^{\frac{qV_{EB}}{KT}} - 1) - \alpha_I I_{CS}(e^{\frac{qV_{CB}}{KT}} - 1) \quad \text{—(1)}$$

$$I_C = I_{CN} + I_{CI} = \alpha_N I_{ES}(e^{\frac{qV_{EB}}{KT}} - 1) - I_{CS}(e^{\frac{qV_{CB}}{KT}} - 1) \quad \text{—(2)}$$

Considering a asymmetrical transistor, we want to relate 4 components of current such as 2 normal component (I_{EN}, I_{CN}) and 2 inverting component (I_{EI}, I_{CI})

Emitter current for normal mode: $I_{EN} = I_{ES}(e^{\frac{qV_{EB}}{KT}} - 1)$ like diode eq.

Collector current in normal mode: $I_{CN} = \alpha_N I_{EN}$

When the transistor is inverted active mode i.e. e-c terminals are interchanged, the inverted component $I_{CI} = -I_{CS}(e^{\frac{qV_{CB}}{KT}} - 1)$
'−' sign indicates → actual current is opposite to assumed current. Similarly $I_{EI} = \alpha_I I_{CS}$ and total emitter & collector current can be found at the terminals by adding each components.

These equations are derived by J. Jeber and J.J moll. Thus called as Eber-Moll equation

We know the conc. of minority carrier

$$\Delta P_E = P_{n_0}(e^{\frac{qV_{EB}}{KT}} - 1)$$

$$\frac{\Delta P_E}{P_{n_0}} = e^{\frac{qV_{EB}}{KT}} - 1 \quad \text{—(3)}$$

Similarly, $\Delta P_C = P_{n_0}(e^{\frac{qV_{CB}}{KT}} - 1)$

$$\therefore \frac{\Delta P_C}{P_{n_0}} = e^{\frac{qV_{CB}}{KT}} - 1 \quad \text{—(4)}$$

Replacing 3 and 4 in 1 and 2,

$$I_E = I_{ES}\left(\frac{\Delta P_E}{P_{n_0}}\right) - \alpha_I I_{CS}\left(\frac{\Delta P_C}{P_{n_0}}\right)$$

$$I_C = \alpha_N I_{ES}\left(\frac{\Delta P_E}{P_{n_0}}\right) - I_{CS}\left(\frac{\Delta P_C}{P_{n_0}}\right)$$

For asymmetrical transistor, using reciprocity theorem, we have

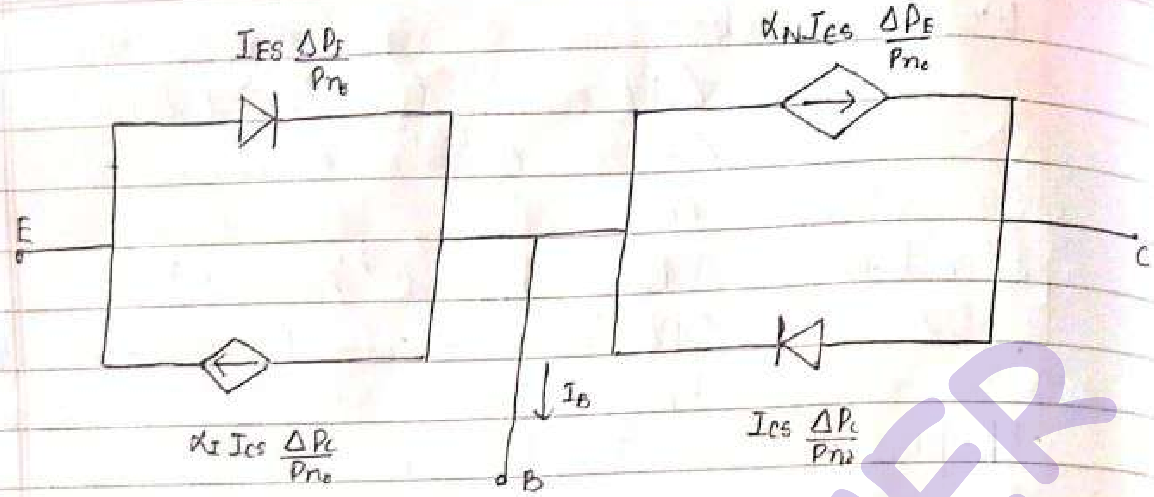
$$\alpha_N I_{ES} = \alpha_I I_{CS} \longrightarrow \left(I_{CS} = \frac{\alpha_N}{\alpha_I} I_{ES}\right)$$

$$I_E = I_{ES}\left(\frac{\Delta P_E}{P_{n_0}}\right) - \cancel{\alpha_I} \times \frac{\alpha_N}{\cancel{\alpha_I}} I_{ES}\left(\frac{\Delta P_C}{P_{n_0}}\right)$$

$$= \frac{I_{ES}}{P_{n_0}}(\Delta P_E - \alpha_N \Delta P_C)$$

$$I_C = \cancel{\alpha_N} \cdot I_{CS} \times \frac{\alpha_I}{\cancel{\alpha_N}}\left(\frac{\Delta P_E}{P_{n_0}}\right) - I_{CS}\left(\frac{\Delta P_C}{P_{n_0}}\right)$$

$$= \frac{I_{CS}}{P_{n_0}}(\alpha_I \Delta P_E - \Delta P_C)$$

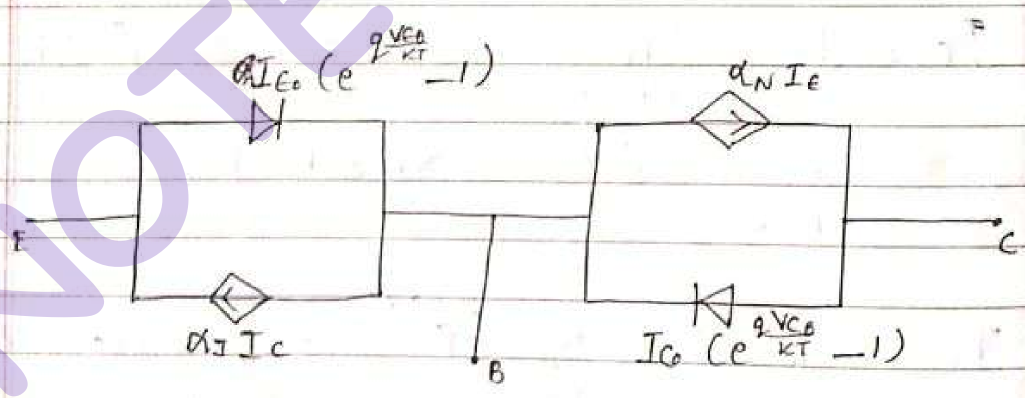


To simplify the above model, multiple eq (1) by α_N and substract from the eq (2)

$$\alpha_N I_E = \alpha_N\left(I_{ES}\left(e^{\frac{qV_{EB}}{KT}}\right) - \alpha_I I_{CS}\left(e^{\frac{qV_{CB}}{KT}} - 1\right)\right)$$

$$I_C - \alpha_N I_E = \cancel{\alpha_N I_{ES}\left(e^{\frac{qV_{EB}}{KT}} - 1\right)} - \cancel{\alpha_N I_{ES}\left(e^{\frac{qV_{EB}}{KT}} - 1\right)} - I_{CS}\left(e^{\frac{qV_{CB}}{KT}} - 1\right) + \alpha_N \alpha_I I_{CS}\left(e^{\frac{qV_{CB}}{KT}} - 1\right)$$

$$= \alpha_N \alpha_I I_{CS}\left(e^{\frac{qV_{CB}}{KT}} - 1\right) - I_{CS}\left(e^{\frac{qV_{CB}}{KT}} - 1\right)$$



$$I_{E_0} = I_{ES}(1 - \alpha_N \alpha_I)$$
$$I_{C_0} = I_{CS}(1 - \alpha_N \alpha_I)$$

$$x_{no} = \frac{W N_a}{N_a + N_d}$$

$$W = \sqrt{\frac{2\epsilon V_0}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)}$$

$$x_{no} = \sqrt{\frac{2\epsilon V_0}{q}\left(\frac{N_a + N_d}{N_a N_d}\right) \cdot \frac{N_a^2}{(N_a + N_d)^2}}$$

$$x_{no} = \sqrt{\frac{2\epsilon V_0 N_a}{q N_d (N_a + N_d)}}$$

$V_0 \rightarrow V_0 + V_{CB}$

$N_a >> N_d$

$$l = \sqrt{\frac{2\epsilon (V_0 + V_{CB}) N_a}{q N_d (N_a + N_d)}} = \sqrt{\frac{2\epsilon (V_0 + V_{CB}) N_a}{q N_a \cdot N_d}}$$

$V_0 << V_{CB}$

$$l = \sqrt{\frac{2\epsilon V_{CB}}{q N_d}}$$

$$l \propto \sqrt{V_{CB}}$$

→ Punch through:
In the reverse bias, CB junction if V_{CB} increases far enough, it is possible to decrease effective base width to the extent that the collector depletion region will essentially fill the entire base and the process is called punch through.

In this punch through condition, holes are directly swept from $E \rightarrow C$ and the transistor action is lost. This is one type of breakdown avoided in the circuit. In most of the cases avalanche breakdown occurs at collector junction before punch through.

Q. A silicon n-p-n transistor has n_{AB} $= 10^{17}/cm^3$ and $N_{DC} = 10^{16}/cm^3$, $l = W_b = 0.25\,\mu m$ at 300K. Find the punch through voltage. Find avg value of EF intensity at punch through where $l = W_B$ = penetration length in base region. 53

$$l = \sqrt{\frac{2\epsilon (V_{PT}) N_a}{q N_d (N_a + N_d)}} \qquad \epsilon = \epsilon_0 \epsilon_r$$

$$0.25 \times 10^{-6} = \sqrt{\frac{2 \times 8.85 \times 10^{-12} \times \epsilon_r \times V_{PT} \times 10^{17}}{1.6 \times 10^{-19} \times 10^{16} (10^{17} + 10^{16})}}$$

$$(0.25 \times 10^{-6})^2 = \frac{2 \times 8.85 \times 10^{-12} \times 11.7 \times V_{PT} \times 10^{17}}{1.6 \times 10^{-19} \times 10^{16} (10^{17} + 10^{16})}$$

$$V_{PT} = \frac{(0.25 \times 10^{-6})^2 \times 1.6 \times 10^{-19} \times 10^{16} (10^{17} + 10^{16})}{2 \times 8.85 \times 10^{-12} \times 11.7 \times 10^{17}}$$

$$= \frac{6.25 \times 10^{-14} \times 1.6 \times 10^{-19} \times 10^{16} (1.1 \times 10^{17})}{16170 \times 10^5 \times 11.7}$$

$$= \frac{10 \times 10^{-33} \times 1.1 \times 10^{33}}{189189 \times 10^5} = 11$$

→ Avalanche Breakdown in transistor
In most of the transistor Avalanche multiplication occurs before punch through. The collector current increases sharply at a well defined breakdown voltage (BV_{CBO}) for CB configuration.
Similarly, for CE configuration the break down voltage is BV_{CEO}.
The current in Rev. biased i.e CB junction is multiplied by a factor M near the breakdown because of Avalanche process.

Teacher's Signature

Teacher's Signature

The Collector Current :

$$I_C = M(\alpha I_E + I_{CBo})$$

$$M = \frac{1}{\left[1 - \left(\frac{V_{BC}}{BV_{CBo}}\right)^n\right]}$$

Q. An n-p-n Silicon BJT at 300K has a heavy Collector doping and $N_a = 10^{16}\ cm^{-3}$ Given $W_b = 1\ \mu m$. Determine

(A) Breakdown voltage for active region in the Cv mode where Breakdown field in Silicon is 3×10^5 Volt / cm.

(B) Find punch through voltage

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4. MOSFET

Metal Oxide

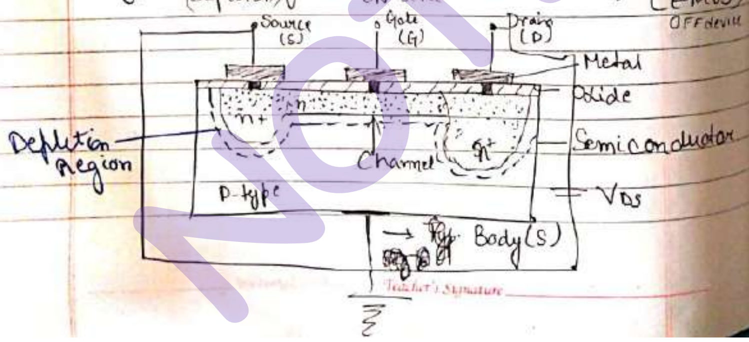
Mosfet
In most of the electronic devices particularly in digital circuits, metal-insulator-semiconductor (mis) transistors are used.

In this device, channel current is controlled by a voltage applied at the gate which is isolated from the channel by an insulating layer and is also called as IGFET (insulating gate field effective transistor)

Most of the devices use metal or heavily doped poly silicon for gate electrode. SiO_2 is used as oxide or insulator and Si as a substrate semiconductor. Hence the name is metal oxide semiconductor FET.

M are used in very large scale integration (VLSI) due to small size and low power consumption.

2 types: D type (D-MOS) (Depletion) ON device, Enhancement type (E-MOS) OFF device



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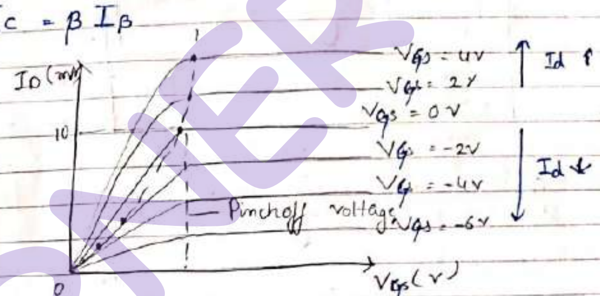
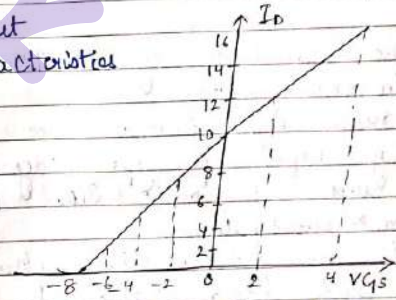
* Also known as MOSFET Capacitor.
Current controlled device.

$I_C = \beta I_B$



Output Characteristics



Transfer characteristics

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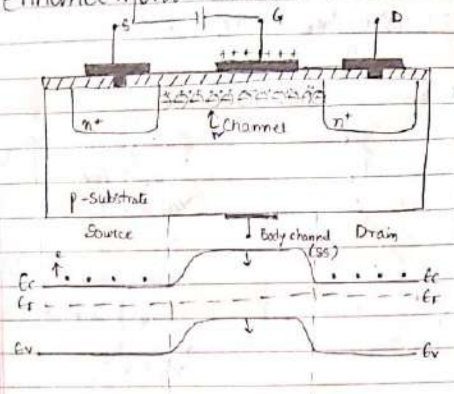
- Enhancement MOSFET



The basic structure of E-MOSFET is shown in the figure.
The n+ drain and source are seperated by lightly doped p-type region.
A thin layer of oxide (SiO_2) is seperating gate from substrate.
There is no pre-existing channel b/w source and drain as in D-MOSFET.
The energy band dia. for E-MOS shows fermi level is flat at equilibrium and it is near to the conduction band for n-type source & drain and near to the valance band near p-type drain. Hence there is a potential barrier across source & substrate, and substrate and drain as in p-n junction diode.

When +ve volt is applied to gate relative to the substrate then +ve charges will accumulate on the gate material.

In response to that -ve charges are induced below the insulating layer by the formation of thin layer of mobile e^- layer.

The induced e^- from the channel of the FET and allow the current flow from source to drain.

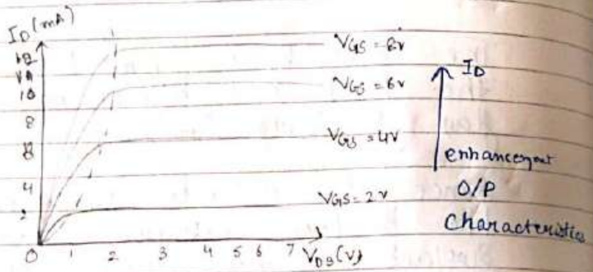
Since the e^- are induced statically, the p-type substrate near the surface becomes less p-type. Thus, the conduction band moves down and e^- from the more easily to the drain.

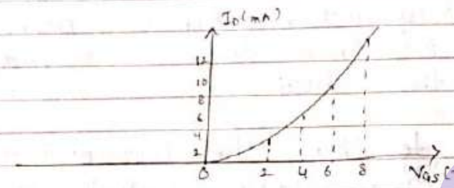
Due to this, the barrier reduced and min gate voltage which is required to create virtual channel b/w source and drain is called as threshold voltage (V_T)

Here gate controls the P Barrier and I to flow from Source to Drain. High quality insulating material is required to reduce leakage I or off state current.

This type of E-MOS are called as n-channel E MOSFET because e^- are formed or accumulate in the channel. These are also called as normally off devices i.e with 0 gate voltage even if we apply V_{DS}, transistor will be off and no current will flow.

whereas D-MOS is known as normally on devices due to existing channel and current flows at 0 gate voltage.





Transfer characteristics

27.9.19

Q. A silicon sample is doped with 10^{17} boron atoms cm^{-3}. What is the $\bar{e}$ conc at 300K and find the conductivity of sample if $\mu_p = 250\, cm^2 V^{-1} s^{-1}$ and $n_i = 1.5 \times 10^{10}\, cm^{-3}$

$N_a \cdot N_d = n_i^2$

$N_a = \frac{(1.5 \times 10^{10})^2}{10^{17}}$

$= 2.25 \times 10^{20} \times 10^{-17}$

$= 2.25 \times 10^{3}$

Q2. Silicon p-n junction diode has $n_a = 10^{17}\, cm^{-3}$ and $n_d = 10^{14}\, cm^{-3}$. What is built in potential.

$V_0 = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$

$= 0.0259 \ln\left(\frac{10^{17} \times 10^{14}}{(1.5 \times 10^{10})^2}\right)$

$= 0.635 V$

Q3. Justify the name MOSFET and how they act as parallel plate capacitor?

Q4. Determine the probability of occupancy of a state located at $0.0259V$ above E_f at 300K.

Q5 Calculate thermal equilibrium hole concentration in Si at 300K assuming fermi level is 0.27eV above the valence band energy. $N_v = 1.04 \times 10^{19}$ at 300K.

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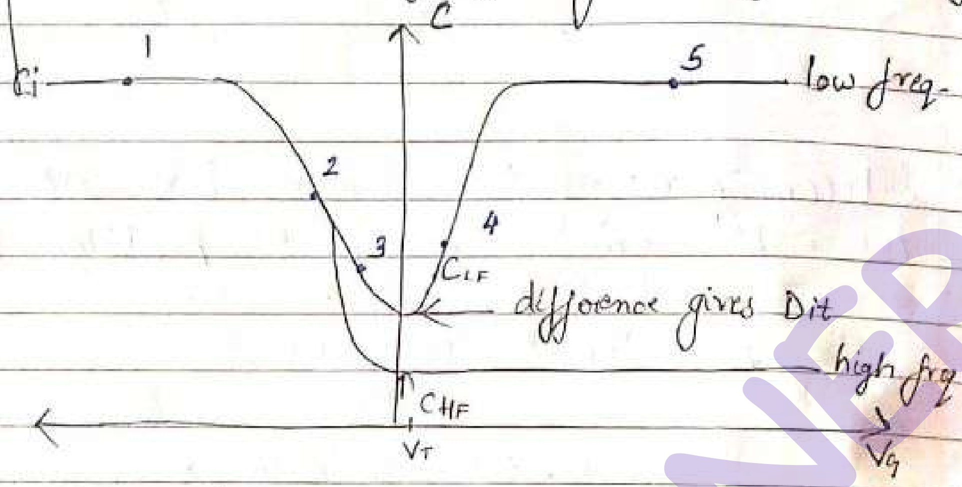
Q. Draw the V-C graph for high & low frequency



→ For low freq. operation i.e gate bias is changed slowly so that there is time for the minority carriers to be generated in the bulk (substrate) and drift across the substrate through depletion region to reach inversion layer or go back to the substrate and recombine.

From ϕ_s Vs Q_s graph, inversion charge increases exponantially with increase in ϕ_s. Hence for low freq. MOS series capacitance in strong inversion is Ci which is indicated at point 5

→ For high frequency, if the V_G increases rapidly, the charge in the inversion layer cannot change in response to the variation. Hence, it will not contribute to strong signal capacitance.
Due to this, capacitance is minimum corresponding to minimum depletion width.

Q. An n^+ polysilicon gate n channel MOS transistor is made on p-type silicon substrate with $n_a = 5 \times 10^{15}\ cm^{-3}$. The SiO_2 thickness is $100 Å$ in the gate region and the effective interface charge $(Q_i) = 4 \times 10^{10}\ qC/cm^3$. Find C_i and C_{min} on the CV characteristics and find W_m, flat bend voltage (V_{FB}) and threshold voltage (V_t), given $\phi_{ms} = -0.95$

$$V_t = \underbrace{\phi_{ms} - \frac{Q_i}{C_i}}_{V_{FB}} - \frac{Q_d}{C_i} + 2\phi_F$$

$$\cancel{C_i = \frac{\epsilon}{Q_i} = \frac{3.9\epsilon_0}{4 \times 10^{10}} = 0.975 \times 10^{-10}\epsilon_0 = 0.0862}$$

$$\cancel{Q_d = -qN_aW_M}$$

$$\cancel{W_m = 2\sqrt{\frac{\epsilon_s \phi_F}{qN_a}} = 2\sqrt{11.8\epsilon_0}}$$

$$Q_d\ \cancel{W_m} = -2\sqrt{\epsilon_s N_a q \phi_F}$$

$$= -2\sqrt{11.8 \times 5 \times 10^{15} \times 1.6 \times 10^{-19} \times 8.85 \times 10^{-14}}$$

$$= \cancel{0} -3.315 \times 10^{-7} \times 0.329$$

$$\phi_F = \frac{KT}{q} \ln \frac{N_a}{N_i} = 0.0259 \ln \frac{5 \times 10^{15}}{1.5}$$

$$= 0.329$$

$$C_i = \frac{\epsilon}{d} = \frac{8.85 \times 10^{-14} \times 3.9}{100 \times 10^{-7}} = 3.45 \times 10^{-4}\ F/cm^2$$

$$W_m = 2\sqrt{\frac{\epsilon_s \phi_F}{qN_a}} = 2\sqrt{\frac{11.8 \times 8.85 \times 10^{-14} \times 0.329}{1.6 \times 10^{-19} \times 5 \times 10^{15}}}$$

$$= 2\sqrt{\frac{3.435 \times 10^{15}}{8 \times 10^{-4}}} = 0.415 \times 10^{-6}\ m$$

$\cancel{\phi_F}$

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$$V_t = -0.95 - \frac{4 \times 10^{10}}{3.45 \times 10^{-7}} - \frac{3.32 \times 10^{-8}}{3.45 \times 10^{-7}} + 2(0.329)$$

$$= -0.95 - 1159.42 -$$

$$= -0.215\ V$$

Q. Consider a Si n-channel MOSFET which has n^+ poly silicon gate and has following const.

$N_a = 5 \times 10^{16}\ cm^{-3}$

$Q_i = 5 \times 10^{10}\ qC/cm^2$

Thickness of oxide (T_{ox}) = $300\ \mathring{A}$ $= 300 \times 10^{-7}$ $= 3 \times 10^{-5}$

$\mu_{n\,effective} = 500\ cm^2/Vsec$

$L = 50\ \mu m$

$n_i = 1 \times 10^{10}\ cm^3$

$\varepsilon_{ox} = 3.9\ \varepsilon_0$

$\varepsilon_{Si} = 11.8\ \varepsilon_0$

$qE_g = 1.12\ eV$

$\phi_{ms} = -0.96\ V$, Find V_{FB}, V_T,

$$C_i = \frac{\varepsilon}{d} = \frac{3.9 \times 8.85 \times 10^{-14}}{3 \times 10^{-5}} = \frac{3.4515 \times 10^{-13}}{3 \times 10^{-5}}$$

$$= \cancel{10.35}\ 11.5 \times 10^{-8}$$

$$\phi_F = \frac{KT}{q} \ln \frac{N_a}{N_i} = 0.0259 \times \ln \left(\frac{5 \times 10^{6}}{1 \times 10^{10}} \right)$$

$$= \cancel{0.4V}\ 0.0259 \times -7.60$$

$$= 0.4V$$

$$V_{FB} = \phi_{ms} - Q_i = -0.96 - 5 \times 10^{10} \times 0.0695$$