19-06-2023

6. SEMI CONDUCTORS

* Free Electron Theory:-

→ According to Free electron theory, all the electrons are in the form of "cloud".

→ 'Drude' and 'Laurange' introduced this theory.

→ This theory couldnot explain 'Band Theory'.

* Sommerfeld Theory:-

→ This theory also couldnot explain the Band-Theory.

* Khronig Penny Theory:-

→ According to this theory, electrons are not flowing in the form of straight line.

Potential difference is varying.

* Blach's Theory:-

→ The scientist 'Blach', gave an equation.

"$\psi(x+a) = \psi(x)$."

→ Khronig penny model,

potential varies.

→ This is called "Periodic potential".

→ chronic penny model explained Band Theory clearly.

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→ Time ↑ $\xrightarrow{\text{conductor}}$ Resistance ↑

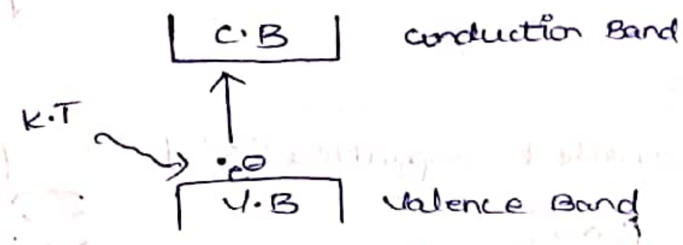
Time ↑ $\xrightarrow{\text{semi conductor}}$ Resistance ↓

→ Magnetic, Electric & Thermal properties are not explained by previous Theories.

→ chronic penny states that,

"electrons acquire Thermal energy and moves fastly due to high K.E and collide with eachother."

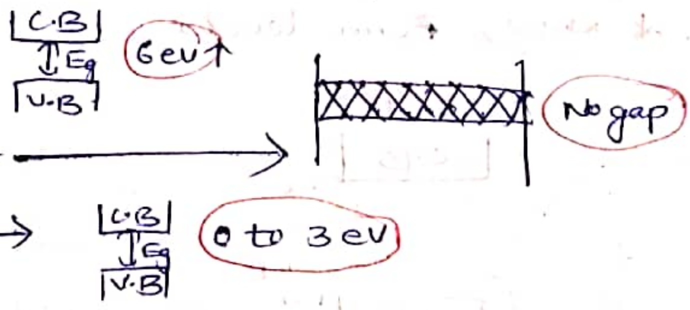
* Band Theory :-



→ The valence electrons acquire Thermal energy and moves from valence Band to conduction band and generates the conduction.

→ According to electric properties, matter is 3 types.

① Insulator ⟶
② ~~semi~~ conductor ⟶
③ semi conductor ⟶

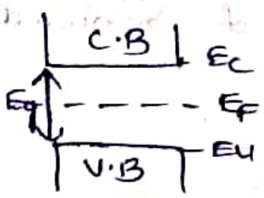


→ Semi conductor again classified into two types.

① Intrinsic [Pure] Ex :- Si, Ge, 4⁺ Tetra valence.

② Extrinsic

① Intrinsic :-



$\boxed{E_c - E_v = E_g}$

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

② Extrinsic :-

→ It is two types:

① P-type

② n-type

(i) P-type :-

→ Trivalent Impurities [3^{+}]

Ex :- Al, Ga, ___

(i) m :

→ In p-type, Holes are Majority carriers.

Electrons are Minority carriers.

(ii) n-type :-

→ Pentavalent impurities [5^{+}]

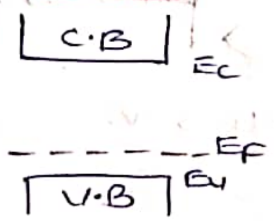
Ex :- P, As ______

→ e^{-} are Majority carriers

Holes are Minority carriers.

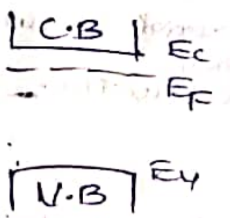
* Note :- Fermi levels

P-type :



Just above V.B.

n-type



Just below C.B

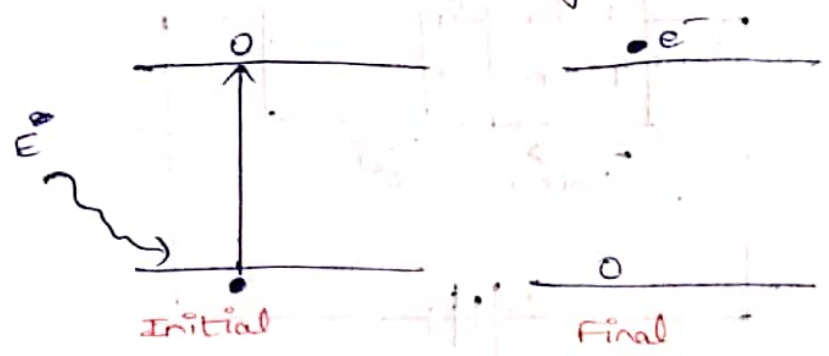
* Why we use semiconductors ?

→ To control the flow of current we use semiconductors.

→ We can change properties of semiconductors easily by doping.

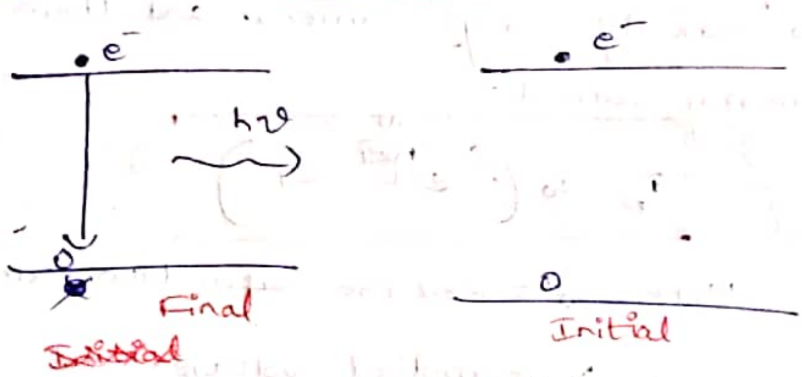
* Hole - $e^{\ominus}$ pair generation :-

→ when we give external energy to semiconductors then Hole - $e^{\ominus}$ pairs will be generated.



→ This principle is used in 'solars'.

* Hole - $e^{\ominus}$ pair Recombination :-



→ This principle is used in 'L.E.D'

* Diffusion :-

→ without any external field, The movement of particles from highest concentration level to lowest concentration level. is called 'Diffusion'.

* Drift :-

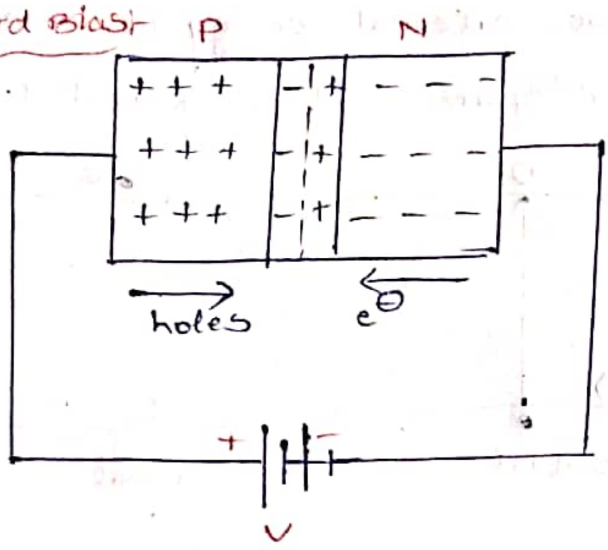
→ By using external force/ field, the movement of particles is called 'Drift.'

→ This velocity is called 'Drift velocity.'

$v_d \propto E$ $\quad$ $v_d = \mu E$. $\quad$ [μ = Mobility]

* P-N Junction Diode :-

* Forward Bias:-



→ At Depletion region / potential Barrier, there is no mobility.

→ In Forward Bias, current conduction is due to majority charge carriers. and there is no minority current.

$$\boxed{I_F = I_0 \left(e^{\frac{eV}{\eta KT}} - 1 \right)}$$

Here, I_0 = Reverse saturation current.

V = applied voltage.

K = Boltzmann constant.

T = Temperature (kelvin).

η [Eta] → Ge → 1, Si → 2.

→ The depletion region width is decreases.

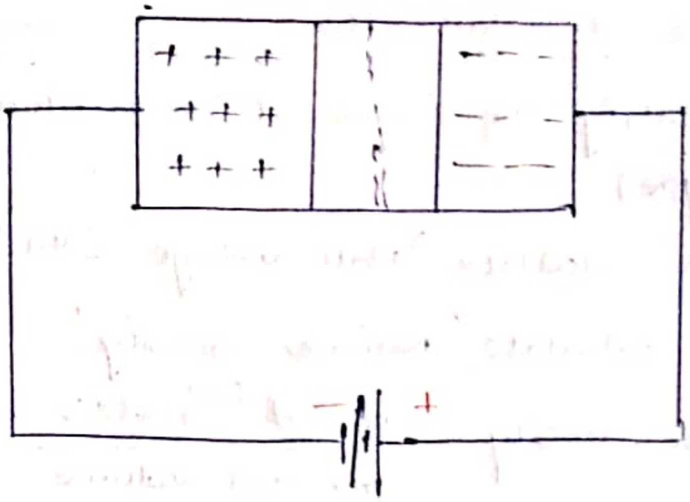
→ Resistance offered will be decreases [R_D] (Dynamic Resistance).

→ Dynamic Resistance in Forward Bias,

$R_F = 50\,\Omega - 500\,\Omega$

I is in mA.

* Reverse Bias :-



→ In 'Reverse Bias', current conduction is due to 'minority charge carriers.

→ The depletion region width is increases

→ Resistance offered by device is 'High'.

R :- 1 kΩ - 1 MΩ

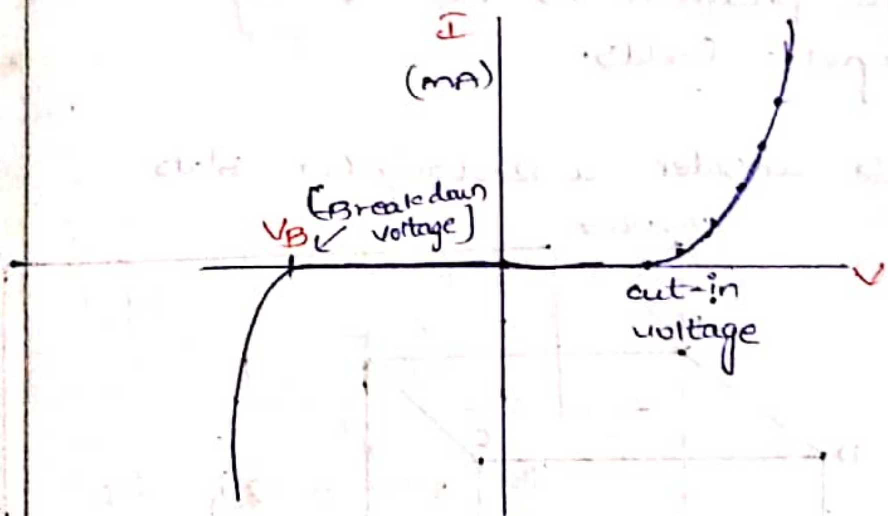
I :- μA / nA.

$$\boxed{I_R = I_0 \left(e^{\frac{-eV}{\eta kT}} - 1\right)}$$

Here, $e^{\frac{eV}{\eta kT}}$ is very large.

$\therefore \boxed{I_R = -I_0}$

Graph :-



Si ⇒ 0.7 V

Ge ⇒ 0.3 V

→ Huge amount of current will flows in Reverse Bias at Breakdown voltage.

* Hall Effect :-

* Significance of Hall Effect :-

(1) To identify the 'type of semiconductor' [p-type or n-type].

(2) We can calculate 'Hall voltage' [V_H].

(3) We can calculate 'Number Density'.

$$\text{Number Density} = \frac{\text{no. of free particles}}{\text{per unit volume}}$$

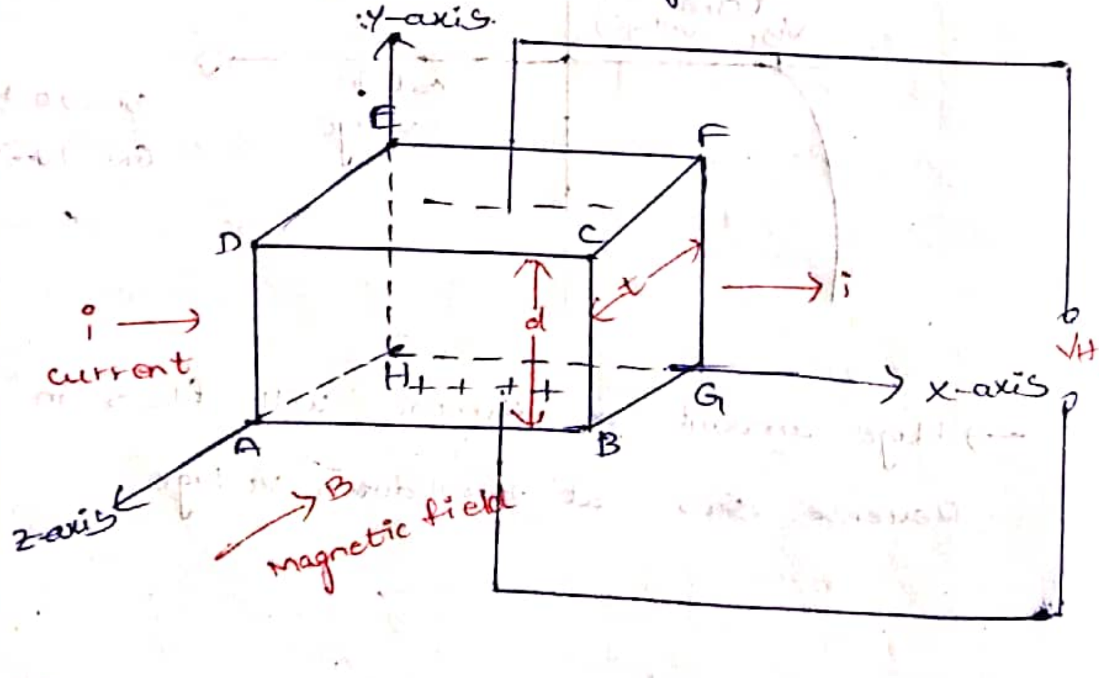
(4) We can calculate 'Mobility [μ]', 'conductivity [σ]', 'Resistivity [ρ]' etc——.

* Experiment :-

→ The process of getting voltage, when we pass current through the rectangular slab and applying magnetic field ⊥ar to current flow is called 'Hall Effect'.

→ 'Voltage' produced is ⊥ar to both current & magnetic fields.

→ Let us consider a Rectangular slab.



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→ Apply current to the side DEHA and magnetic field on [ABCD], [EFGH] $\perp$ar to current

Now, $\bar{F}_E = q\bar{E}$

$\bar{F}_B = q(\bar{v}_d \times \bar{B})$ [v_d = Drift velocity].

At equilibrium position,

$\vec{F}_E = \vec{F}_B$

$\Rightarrow \cancel{q}E = \cancel{q}(v_d \times B)$

$\Rightarrow E = v_d B$

$\therefore$ Hall Electric field, $\boxed{E_H = v_d B}$ → ①

We know, $J = \frac{I}{A}$ [J : current Density].

Also, $J = \frac{I}{A} = n e v_d$

$\Rightarrow v_d = \frac{J}{ne}$ → ②

From eq^n ① & ②

$\Rightarrow E_H = \frac{JB}{ne}$

$\Rightarrow E_H = \left(\frac{1}{ne}\right) JB$

$\Rightarrow \boxed{E_H = R_H JB}$ → ③   [$\because$ n : Number Density & e are constants]

$\therefore \boxed{R_H = \frac{1}{ne}}$

If 'R_H' is '+ve' then 'p-type'

If 'R_H' is '−ve' then 'N-type'

We know, $E_H = \frac{V_H}{d}$ → ④   [$\because V = Ed$ $\Rightarrow E = \frac{V}{d}$]

From ③ & ④ equations,

$$\Rightarrow \frac{V_H}{d} = R_H J B$$

$$\Rightarrow V_H = R_H J B d.$$

$$\Rightarrow \boxed{V_H = \frac{JBd}{ne}} \longrightarrow ⑤$$

We know, $J = \frac{I}{A} = \frac{I}{dt}$ [From diagram, Height = d, width = t]

$$\Rightarrow V_H = \frac{IB\cancel{d}}{ne\cancel{d}t}$$

$$\Rightarrow V_H = \frac{IB}{net}$$

$$\therefore \boxed{V_H = \frac{IB}{net}} \text{ (or) } \boxed{V_H = \frac{R_H IB}{t}}$$ – Hall voltage

$$\therefore \boxed{R_H = \frac{V_H t}{IB}}$$ → Hall coefficient

From Hall voltage,

$$\boxed{n = \frac{IB}{V_H e t}}$$ → Number Density.

Mobility, $v_d \propto E_H \Rightarrow v_d = \mu E_H$

$$\therefore \boxed{\mu = \frac{v_d}{E_H}}$$ → Mobility ← $$\boxed{\mu = \frac{v_d}{R_H J B}}$$

Conductivity, we have $\sigma = ne\mu$.

$$\boxed{\sigma = \frac{ne\, v_d}{E_H}} \text{ (or) } \boxed{\sigma = \frac{ne\, v_d}{R_H J B}}$$

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

$$\boxed{\rho = \frac{E_H}{ne\, v_d}} \text{ (or) } \boxed{\rho = \frac{R_H J B}{ne\, v_d}}$$

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* Density of states :-

→ To calculate the 'density' of particle' in a particular state, we use a function called 'Density of states.'

→ According to 'Fermi-dirac theory', the degeneracy of spin of electrons is '2.'

→ consider a function,

$Z(E)$: [Energy density of states].

$$\Rightarrow Z(E)\,dE = \frac{1}{8}\,\frac{4\pi n^2\,dn}{V} \qquad \left[\begin{array}{l}\text{consider } \frac{1}{8}\text{th} \\ \text{part in 1D Box}\end{array}\right]$$

We know, degeneracy of e^- spin $= 2$.

$$\Rightarrow Z(E)\,dE = 2\cdot\frac{1}{8}\cdot\frac{4\pi n^2\,dn}{V} \longrightarrow ①$$

We know, '$E = \frac{n^2h^2}{8ml^2}$'.

$$\Rightarrow n^2 = \frac{8ml^2E}{h^2} \longrightarrow ②$$

Differentiate on Both sides.

$$\Rightarrow 2n\,dn = \frac{8ml^2}{h^2}\,dE$$

$$\Rightarrow dn = \frac{8ml^2}{h^2(2n)}\,dE$$

$$\Rightarrow dn = \frac{8ml^2}{2h^2\sqrt{\frac{8ml^2}{h^2}}\cdot\sqrt{E}}\,dE \qquad \left[\begin{array}{l}\because n^2 = \frac{8ml^2E}{h^2} \\ \Rightarrow n = \sqrt{\frac{8ml^2E}{h^2}}\end{array}\right]$$

$$\Rightarrow dn = \frac{1}{2}\cdot\left(\frac{8ml^2}{h^2}\right)^{1/2}(E)^{-1/2}\,dE \quad \left[\because \frac{x^2}{\sqrt{x}}\,dx = \sqrt{x}\right] \longrightarrow ③$$

Substitute eq^n ② & ③ in eq^n ① $\qquad [\because V = l^3]$

$$\Rightarrow Z(E)\,dE = 2\cdot\frac{1}{8}\cdot\frac{4\pi}{l^3}\cdot\frac{8ml^2E}{h^2}\cdot\frac{1}{2}\left(\frac{8ml^2}{h^2}\right)^{1/2}(E)^{-1/2}\,dE.$$

$$\Rightarrow Z(E)\,dE = \cancel{2}\cdot\frac{1}{\cancel{8}_4}\cdot\frac{4\pi}{l^3}\cdot\frac{\cancel{8}ml^2E}{h^2}\cdot\frac{1}{2\cancel{2}}\left(\frac{\cancel{8}ml^2}{h^2}\right)^{1/2} E^{-1/2}\,dE$$

$$\Rightarrow Z(E)\,dE = \frac{\pi}{2l^3}\left(\frac{8ml^2}{h^2}\right)^{3/2} E^{+1/2}\,dE$$

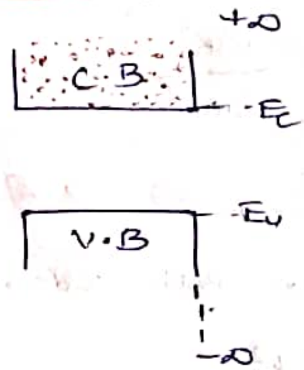
$$\Rightarrow Z(E)\,dE = \frac{\pi}{2}\left(\frac{8m}{h^2}\right)^{3/2} E^{+1/2}\,dE.$$

$$\Rightarrow Z(E)\,dE = \frac{8\pi}{2h^3}(2m)^{3/2} E^{+1/2}\,dE.$$

$$\Rightarrow Z(E)\,dE = \frac{4\pi}{h^3}(2m)^{3/2} E^{1/2}\,dE$$

$\therefore$ $\boxed{Z(E)\,dE = \frac{4\pi}{h^3}(2m)^{3/2} E^{1/2}\,dE}$ is the general function of energy density of states. ⟶ (4)

* carrier concentration in conduction Band :-



⟶ According to Fermi-Dirac Function,

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

We know, $Z(E)\,dE = \frac{4\pi}{h^3}(2m_e)^{3/2}(E-E_c)^{1/2}\,dE$

$$n_e = \int_{E_c}^{+\infty} Z(E)\cdot F(E)\,dE.$$

$$\Rightarrow n_e = \int_{E_c}^{+\infty} \frac{4\pi}{h^3}(2m_e)^{3/2}(E-E_c)^{1/2}\cdot\left(\frac{1}{1+e^{\left(\frac{E-E_F}{KT}\right)}}\right)dE.$$

Let $E - E_F >> kT$,

$$\Rightarrow n_e = \int_{E_c}^{+\infty} \frac{4\pi}{h^3}(2m_e)^{3/2}\cdot(E-E_c)^{1/2}\cdot\frac{1}{e^{(E-E_F)/kT}}\,dE$$

$$\Rightarrow n_e = \int_{E_c}^{+\infty} \frac{4\pi}{h^3}(2m_e)^{3/2}\cdot(E-E_c)^{1/2}\, e^{-\left(\frac{E-E_F}{kT}\right)}\,dE.$$

$$\Rightarrow n_e = \frac{4\pi}{h^3}(2m_e)^{3/2}\int_{E_c}^{+\infty}(E-E_c)^{1/2}\cdot e^{-\left(\frac{E-E_F}{kT}\right)}\,dE.$$

$$\Rightarrow n_e = \frac{4\pi}{h^3}(2m_e)^{3/2}\cdot e^{\left(\frac{E_F-E_c}{kT}\right)}(kT)^{3/2}\cdot\frac{\sqrt{\pi}}{2}$$

$$\therefore \boxed{n_e = 2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}\cdot e^{\left(\frac{E_F-E_c}{kT}\right)}}$$ is the number/total number of electrons.

similarly,

$$\therefore \boxed{n_h = 2\left(\frac{2\pi m_h kT}{h^2}\right)^{3/2}\cdot e^{\frac{E_v-E_F}{kT}}}$$ is the total no. of holes (or) carrier concentration in valence Band.

* Position of Fermi Levels :-

ⓐ Intrinsic Semi conductors :-

→ Here, number density of $e^{\ominus}$ $[n_e]$ = Number density of holes $[n_h]$.

$$\Rightarrow 2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}\cdot e^{\left(\frac{E_F-E_c}{kT}\right)} = 2\left(\frac{2\pi m_h kT}{h^2}\right)^{3/2}\cdot e^{\left(\frac{E_v-E_F}{kT}\right)}$$

$$\Rightarrow \left(\frac{m_e}{m_h}\right)^{3/2} = e^{\left(\frac{E_v-E_F}{kT}\right)-\left(\frac{E_F-E_c}{kT}\right)}.$$

Apply logarithm on both sides.

$$\Rightarrow \ln\left(\frac{m_e}{m_h}\right)^{3/2} = \left(\frac{E_v - E_F}{KT}\right) - \left(\frac{E_F - E_c}{KT}\right)$$

$$\Rightarrow \frac{3}{2}\ln\left(\frac{m_e}{m_h}\right) = \frac{E_v - E_F - E_F + E_c}{KT}$$

$$\Rightarrow \frac{3}{2}\ln\left(\frac{m_e}{m_h}\right) = \frac{E_v + E_c - 2E_F}{KT}$$

$$\Rightarrow \frac{3}{2}K \cdot T \ln\left(\frac{m_e}{m_h}\right) = E_v + E_c - 2E_F$$

$$\Rightarrow 2E_F = E_v + E_c - \frac{3}{2}KT\ln\left(\frac{m_e}{m_h}\right).$$

$$\Rightarrow E_F = \frac{E_v + E_c}{2} - \frac{3}{4}KT\ln\left(\frac{m_e}{m_h}\right).$$

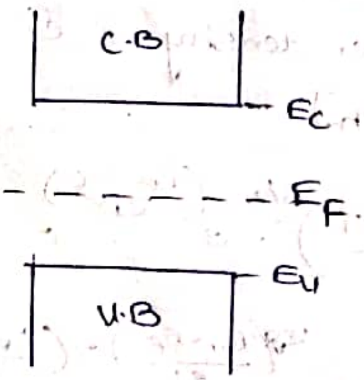
$$\therefore \boxed{E_F = \frac{E_v + E_c}{2} + \frac{3}{4}KT\ln\left(\frac{m_h}{m_e}\right).}$$

Here, Fermi level depends on Temperature.

when $m_h = m_e$.

$$\Rightarrow E_F = \frac{E_v + E_c}{2} + 0 \qquad [\because \ln 1 = 0].$$

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



Here $[E_q = E_F]$

E_q = equilibrium

(B) Extrinsic Semiconductors :-

(i) n-type :-

We know that,

$$n_d = n_e = 2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{\left(\frac{E_F - E_c}{kT}\right)} \quad [\because \text{Donor}]$$

Let $n_c = 2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}$

$$\Rightarrow n_d = n_c \cdot e^{\left(\frac{E_F - E_c}{kT}\right)}$$

$$\Rightarrow \frac{n_d}{n_c} = e^{\frac{E_F - E_c}{kT}}$$

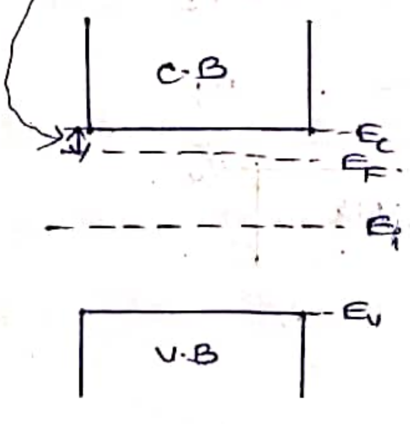
Apply logarithm

$$\Rightarrow \ln\left(\frac{n_d}{n_c}\right) = \frac{E_F - E_c}{kT}$$

$$\Rightarrow kT \ln\left(\frac{n_d}{n_c}\right) = E_F - E_c$$

$$\Rightarrow E_F = kT \ln\left(\frac{n_d}{n_c}\right) + E_c$$

$$\therefore \boxed{E_F = E_c - kT \underbrace{\ln\left(\frac{n_c}{n_d}\right)}_{\text{very less value}}}$$ "Fermi level in n-type"



Region b/w E_F & E_i is called 'Forbidden level'

(ii) P-type :-

We know that,

$$n_a = n_h = 2\left(\frac{2\pi m_h KT}{h^2}\right)^{3/2} e^{\frac{E_v - E_F}{KT}}$$

[∵ Holes are Acceptors so, 'n_a'].

Let, $n_v = 2\left(\frac{2\pi m_h KT}{h^2}\right)^{3/2}$.

$$\Rightarrow n_a = n_v \cdot e^{E_v - E_F/KT}.$$

$$\Rightarrow \frac{n_a}{n_v} = e^{\frac{E_v - E_F}{KT}}.$$

Applying logarithm

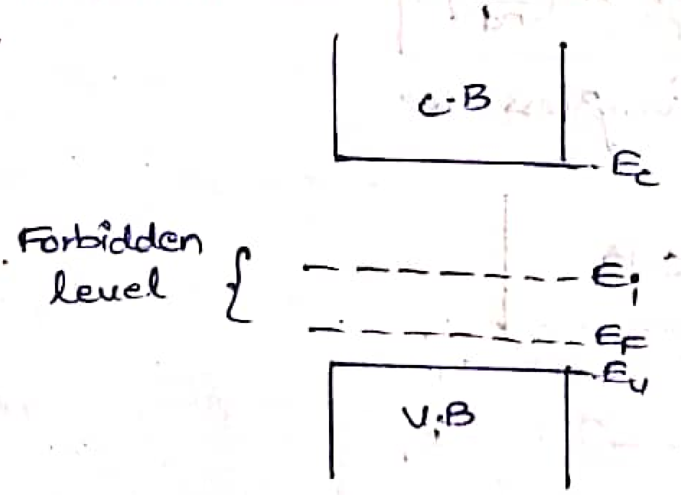
$$\Rightarrow \ln\left(\frac{n_a}{n_v}\right) = \frac{E_v - E_F}{KT}$$

$$\Rightarrow KT \ln\left(\frac{n_a}{n_v}\right) = E_v - E_F$$

$$\Rightarrow E_F = E_v - KT \ln\left(\frac{n_a}{n_v}\right)$$

$$\therefore \boxed{E_F = E_v + KT \ln\left(\frac{n_v}{n_a}\right)}$$

"Fermi level in p-type"



* Effective Mass:-

→ According to quantum mechanics, the mass of electron at rest and at motion will be varied/ changed.

→ Phase velocity is more than group velocity.

$$v = \frac{d\omega}{dK}.$$

$$\Rightarrow v = \frac{d\omega}{dK}\,\frac{\hbar}{\hbar} = \frac{1}{\hbar}\,\frac{(d\hbar\omega)}{dK}.$$

$$\Rightarrow v = \frac{1}{\hbar}\,\frac{dE}{dK} \longrightarrow (1) \qquad [\because E = \hbar\omega]$$

We have. $\frac{dP}{dt} = m\frac{dv}{dt}$

$$\Rightarrow \frac{d(\hbar k)}{dt} = m\,\frac{dv}{dt} \qquad [\because P = \hbar K \;\&\; E = \hbar\omega].$$

$$\Rightarrow \hbar\,\frac{dk}{dt} = m\,\frac{dv}{dt}$$

$$\Rightarrow \frac{\hbar}{m}\,\frac{dk}{dt} = \frac{dv}{dt} \longrightarrow (2)$$

$$\Rightarrow \frac{\hbar}{m}\,\frac{dk}{dt} = \frac{d}{dt}\left[\frac{1}{\hbar}\,\frac{dE}{dk}\right] \qquad [\because \text{From } (1)].$$

Multiply & divide with 'dk'.

$$\Rightarrow \frac{\hbar}{m}\,\frac{\cancel{dk}}{\cancel{dt}} = \frac{1}{\hbar}\,\frac{d}{dK}\left(\frac{dE}{dE}\right)\cdot\frac{\cancel{dk}}{\cancel{dt}}$$

$$\Rightarrow \frac{\hbar^2}{m} = \frac{d}{dK}\left(\frac{dE}{dK}\right).$$

$$\Rightarrow \frac{\hbar^2}{m} = \frac{d^2E}{dK^2}.$$

$$\Rightarrow m = \frac{\hbar^2}{\left(\frac{d^2E}{dK^2}\right)}.$$

$\therefore$ Effective mass of $e^{\ominus}$, $\boxed{m^* = \frac{\hbar^2}{\left(\frac{d^2E}{dK^2}\right)}}$.