Semicondutor

Doping

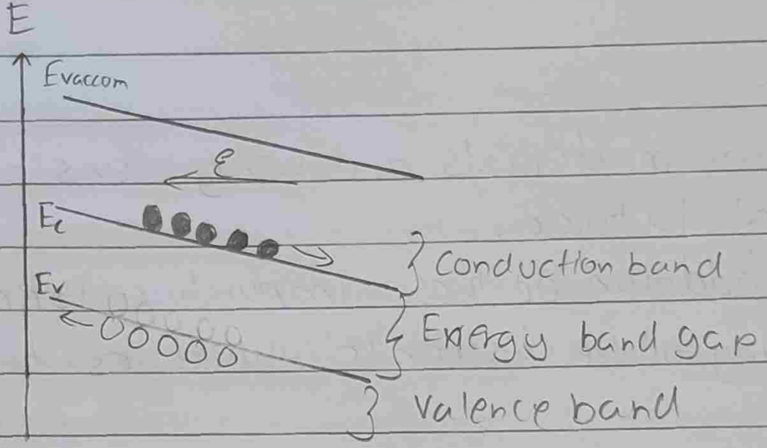
-> semiconductor materials are very sensitive to impurities in the crystal lattice.
-> The controlled addition od these impurities is known as doping
-> Allows the tuning od the electronic properties: technological applications.
-> Pure semiconductor are called 'intrinsic'.
-> Introduction od dopants -> 'extrinsic semiconductor'
-> Introduction od dopants.
i) New intra-band, energy level
ii) Generation od positive or negative charge carriers.
-> Band Gap values:
Conductors: VB & CB overlap
Semiconductors: ~1-3eV
Insulators: >5eV

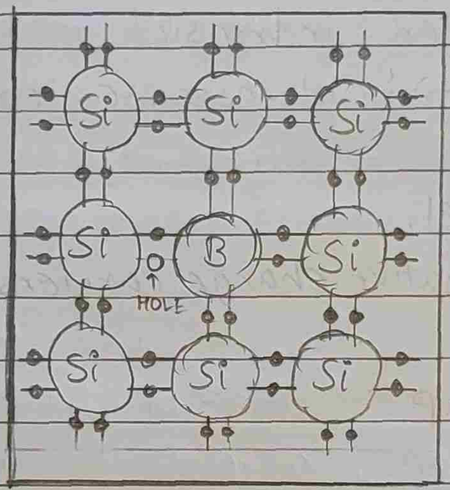
Extrinsic Semiconductors-

i) n-type: Pentavalent impurity - electrons as majority charge carriers (Donor atom)
ii) p-type: Trivalent impurity - holes as majority charge carriers (Acceptor atoms)

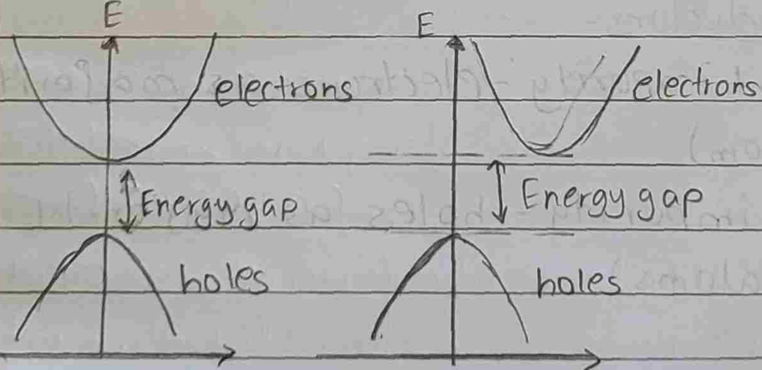
Concept od Holes

-> A hole can be seen as the "opposite" od an electron.
-> Holes have a positive charge
-> They are the absence od an electron in an atom
-> They are formed when electrons in atoms move out od the Valence band (VB) to the conduction band (CB).
-> Holes can move from atom to atom in semiconducting materials as electrons leave their positions.

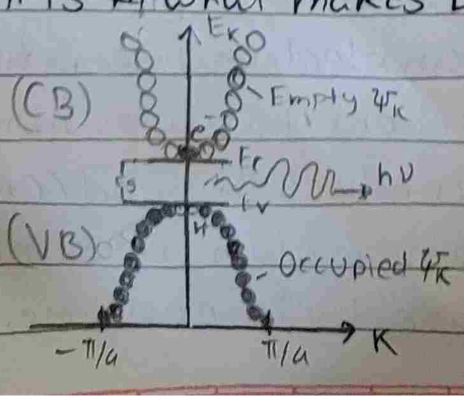


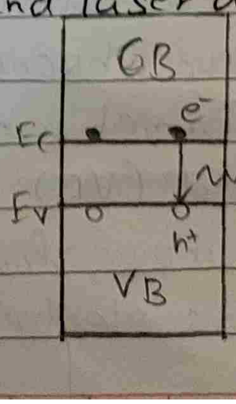


Band Gap



→ Direct gap is important in opto electronics as direct band gap materials have effient radiative absorption & emission which is what makes LEDs and laser diodes work





→ An E-k diagram shows charateristics of a particular semiconductor material.

→ It shows the relationship between the energy & momentum of available quantum mechanical states for electrons in the material.

Effective mass

→ The effective mass represents the effect of all the internal forces on the motion of the ~~e~~ electron in the CB.

→ **Assumption**: Mass of electron in solid is same as the mass of a free electron.

→ **Experimentally**: In some solids, electron mass is more while for some it is less than the free electron mass.

→ **Effective mass**: Experimentally determined electron mass.

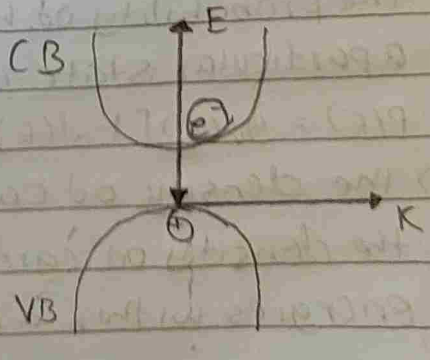
→ **Reason**: Interaction between the drifting electrons and the atoms in the solid.

→ **Sign of effective mass**: Determined from sign of curvature of the E-k curve.

→ The curvature of a graph at a min. point is a +ve quantity and while the curvature at the max. point is a −ve quantity.

→ Electron → +ve m^*

→ holes → −ve m^*



$$p = \frac{h}{\lambda} = \hbar k$$

$$E = E_c + \frac{\hbar^2 k^2}{2m^*} \quad \text{or} \quad E = E_v - \frac{\hbar^2 k^2}{2m^*}$$

$$\frac{d^2E}{dk^2} = \frac{\hbar^2}{m^*} \Rightarrow m^* = \frac{\hbar^2}{(d^2E/dk^2)}$$

Mobility

→ When an electric field is applied across a solid, it accelerates the electrons in the direction od applied field.

→ The moving electrons undergo repeated collision with the atoms and hence moves with a steady velocity known as drift velocity represented as V_d

→ $V_d \propto E \rightarrow V_d = \mu E$ where μ is the mobility od electrons.

→ Mobility: Measures how quickly an electron can move through a metal or semiconductor in presence od eletrical field.

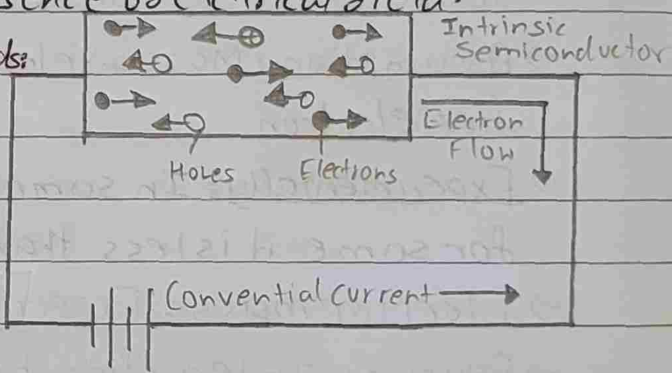
→ Semiconductor Mobility depends:

i) Defect concentration

ii) Temperature

→ μ_e (metal) $= 10^{-3}\ m^2/V_s$

→ μ_e (semiconductors) $= 10^{-1}\ m^2/V_s$



Carrier Concentration

→ The density od electron in a semiconductor → the density od available states and the probability that each od these states is occupied.

$n(E) = g_c(E) f(E)$

→ Holes corresponding to empty states in the valence band → the probability od having a hole equals the probability that a particular state is not filled.

$P(E) = g_v(E)[1 - f(E)]$ where $g_v(E)$ is the density od states in VB

→ The density od carriers is then obtained by integrating the density od carrier per unit energy over all possible energies within a band.

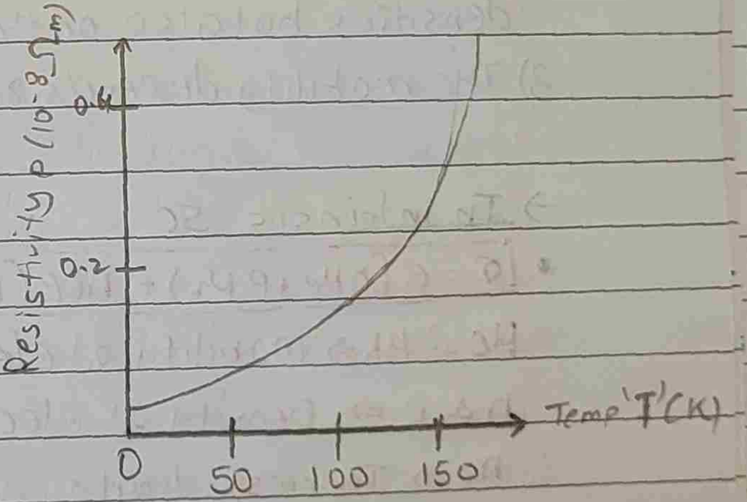
Conductivity

→ **In metal**

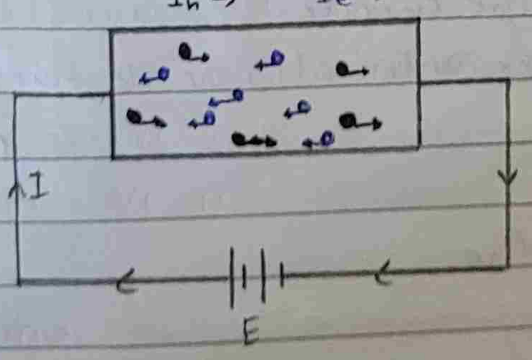
- Conductivity is attributed to free charge carriers in metals
- ~~At the~~ ↑ temp → ↑ vibration od the metal ions
- ↑ vibrations → causes frequent collisions between the ~~electr~~ electrons → drains out energy od the free electrons → restricts the movement od the delocalized electrons → V_d ↓ → resistivity od the metal ↑ → current ↓ → Conductivity od the material ↓
- $J = \sigma E$

  $\rho = \frac{1}{\sigma}$
- The temperature dependance is given as:

  $\rho_t = \rho_0 [1 + \alpha (T - T_0)]$



→ **In semiconductor**



$I = I_e + ~~I_h~~ I_h$

$I_e = neAv_e$, $I_h = peAv_h$

$I = V/R$

$\frac{V}{R} = eA(nv_e + pv_h)$ OR $\frac{VA}{\rho l} = eA(nv_e + pv_h)$

$$\frac{E}{\rho} = e(nV_e + pV_h)$$

$$\mu = \frac{\text{drift velocity}}{\text{unit Electic field}}$$

$$\boxed{\frac{1}{\rho} = e(n\mu_e + p\mu_h)}$$

$$\boxed{\sigma = e(n\mu_e + p\mu_h)}$$

Note:

1) The electron mobility is higher than the hole mobility
2) The resistivity / conductivity depends not only on the electron & hole densities but also on their mobility.
3) The mobility depends relatively weakly on temperature.

→ In intrinsic SC

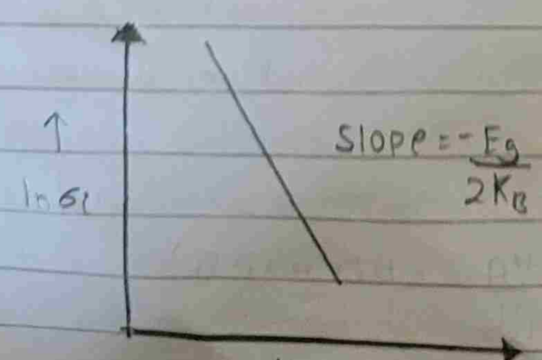
- $\boxed{\sigma = e(n\mu_e + p\mu_h) = n_i e(\mu_e + \mu_h)}$

  μ_e & μ_h ⇒ mobility of electron & holes

  n & p ⇒ Density of electron & holes

  n_i ⇒ Intrinsic density
- The electrons in the VB gain energy → moves to higher energy levels in the CB → becomes charge carrier
- Carrier Conc. depends exponentially on the band gap & is given as:

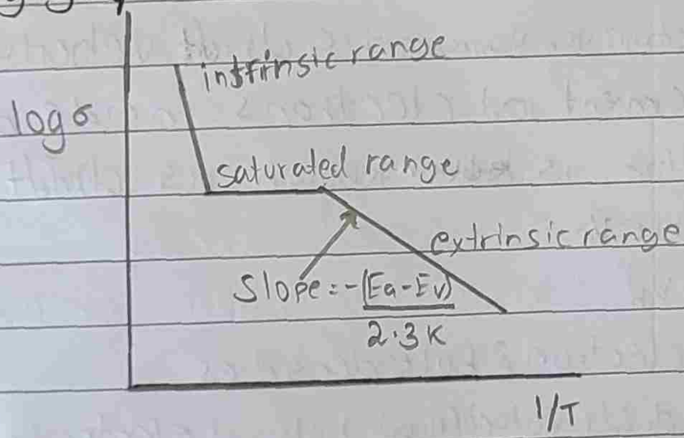
  $$n_i = \sqrt{N_c N_v}\, \exp\left[\frac{-E_g}{2K_B T}\right]$$
- Conductivity ∝ Temperature



$$\log_e \sigma = \frac{-E_g}{2KT} + \log_e B$$

→ Extrinsic SC

- Low Temp → frozen charge carrier → resistivity is ~~ext~~ extremely high
- Moderate ↑ in Temp → Rapid ~~d~~ ↓ in resistivity with ↑ of ionized charges
- At sufficiently high Temp → dopands are completely ionized → conductivity ↓ & resistivity ↑ again
- At still higher temp → resistivity ↓ sharply due to appreciable excitation of all carriers and crossing the energy gap.



- In doped semiconductor, majority carriers greatly outnumbers the minority carriers, so that the equation can be reduced to a single term involving the majority carrier.
- n-type

  $\sigma_n = n e \mu_e$
- p-type

  $\sigma_p =$ ~~$pe\mu_h$~~ $pe\mu_h$
- Conductivity is determined by two factors:

i) Conc. of free carriers available to conduct current.

ii) Their mobility.

In a semiconductor, both mobility & carrier concentration are temperature dependent

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Drift current

→ Absence of field: free electrons move in a conductor with random velocities and random directions.

→ Presence of field: the randomly moving electrons experience an electrical force in the direction of the field.

→ Electrons shift towards higher potential with their random motion.

→ The electrons will drift towards higher potential along with their random motions.

→ Electron have a net velocity towards the higher potential end of the conductor known as the drift velocity of electrons.

→ The drift movement of electrons inside an electrically stressed conductor, is ~~known~~ known as drift current.

→ $J_{(drift)\,electron} = -neV_e$

→ $J_{(drift)\,hole} = peV_h$

→ Where n, p are electron & hole densities

V_h, V_e are drift velocity of holes & electrons

→ -ve sign indicates that the electrons having -ve charge move in direction opposite to the applied field.

→ Total drift current density:

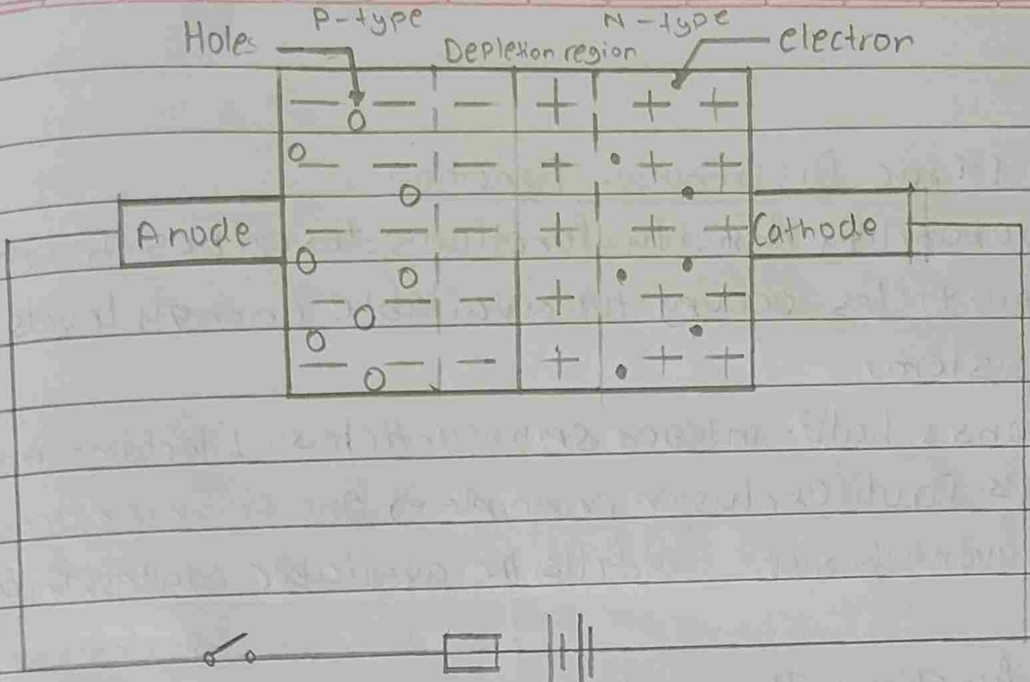
$J_{(drift)\,Total} = J_{(drift)\,hole} + J_{(drift)\,electron} = peV_h + neV_e$ —(1)

Diffusion current

→ In semiconducting material → Dopants are introduced to some region → even distribution of carriers takes place to maintain the uniformity → known as diffusion process

→ The movement of mobile charge carriers are responsible for the flow of diffusion current from one region to the other.

→ No source of energy is required for diffusion current.



→ Non-uniformity of charge (electron / holes) → gives the diffusion current (is independent of the electric field) → depends on the concentration gradient

→ Concentration of electron (n) & holes (p) varies with distance x

→ Diffusion current density of electron:-

$J_{(diff)\,el} = eD_n \frac{dn}{dx}$, ~~where D~~ Where D_n is diffusion coefficient for electrons.

dn/dn → conc. gradient of electrons

→ Diffusion current density for holes:-

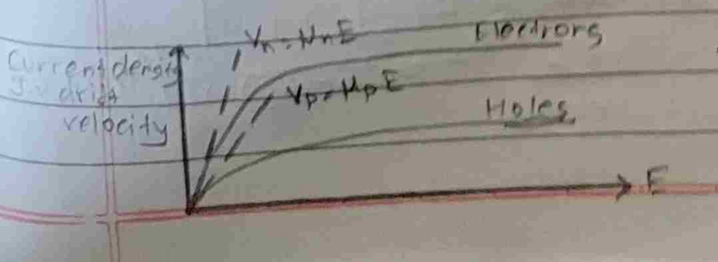
$J_{(diff)\,holes} = -pD_p \frac{dp}{dx}$, ~~where~~ Where D_p is diffusion coefficient for holes.

dp/dn → Conc. gradient of holes

→ $J_{(diff)\,Total} = eD_n \frac{dn}{dx} - pD_p \frac{dp}{dx}$ → ②

Total current dencity

$J_{Total} = peV_n + neV_e + eD_n \frac{dn}{dx} - pD_p \frac{de}{dx}$ from ① & ②



→ Figure shows the plot for the current density (J_{drift}) and absolute value of the drift velocity, over the Electric Field (E)

~~Ferm~~

Fermi Dirac Distribution Function

→ The probability density functions describes the probability that particles occupy the available energy levels in a given system.

→ Fermions: half-integer spin particles - Electrons are Fermions - obey's Pauli exclusion principle → One Fermion occupies a single quantum state → fills the available states in an energy band.

→ Fermi function: The probability that an energy level at energy 'E' in thermal equilibrium with a large system, is occupied by an electron

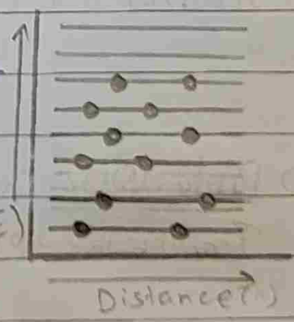
→ Fermi Dirac distribution function is given as:

$$f(E) = \frac{1}{1+\exp^{(E-E_F)/KT}}, \quad E_F \rightarrow \text{Fermi Energy}, \quad K \rightarrow \text{Boltzman Constant}$$

Fermi Level

1) In a conductor

Fermi function ~~f(E)~~ $f(E) = \frac{1}{1+\exp^{(E-E_F)/KT}}$



Case 1: At $T = 0K$; $E < E_F$

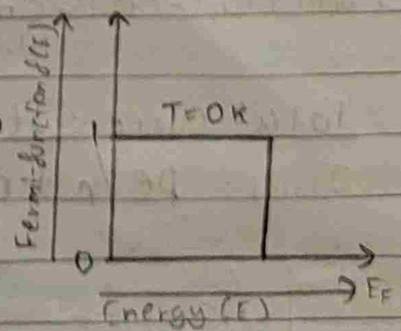
$$\therefore f(E) = \frac{1}{1+\exp^{-(E-E_F)/0}} = \frac{1}{1+e^{-\infty}} = 1$$

All Levels below E_F is occupied

Case 2: At $T = 0K$; $E > E_F$

$$\therefore f(E) = \frac{1}{1+\exp^{(E-E_F)/0}} = \frac{1}{1+e^{\infty}} = 0$$

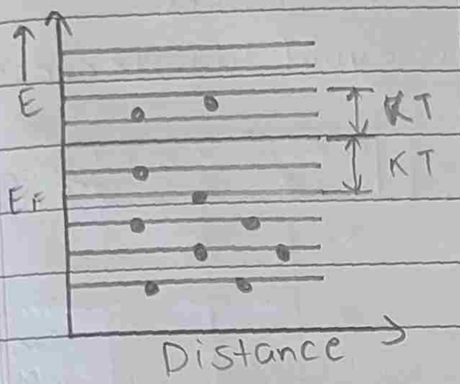
All levels above E_F are vacant

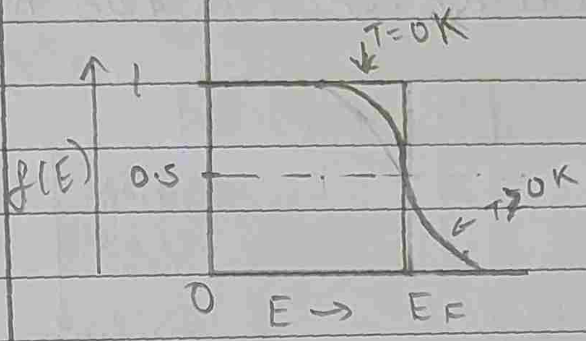


Case 3: $T > 0K$; $E = E_F$

$\therefore f(E) = \dfrac{1}{1 + e^{(0/KT)}} = \dfrac{1}{1+1} = 0.5$

The probability od occupancy at any temp $T > 0K$ is 50%.





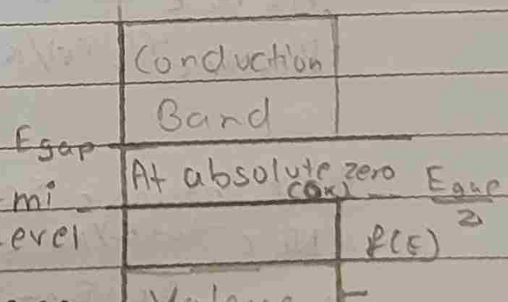
→ Fermi energy: Average energy possessed by electrons participating in conduction at temperature above 0K

→ Fermi velocity: (V_F): It is the velocity od the electrons in the highest occupied states in metals at zero temperature

$V_F = \sqrt{2E_F/m}$

What is fermi Level?

→ The highest energy level that an electron occupies at the absolute zero (0K) Temperature is Known as Fermi Level



Fermi Level

→ The fermi level lies between the VB & CB.

At T = 0 K, the electrons are all in the lowest energy state → Fermi level can be considered as the sea od Fermions (or electrons) above which no electrons exist.

→ The Fermi level changes as the T ↑ or electron are added to or withdrawn from the solid

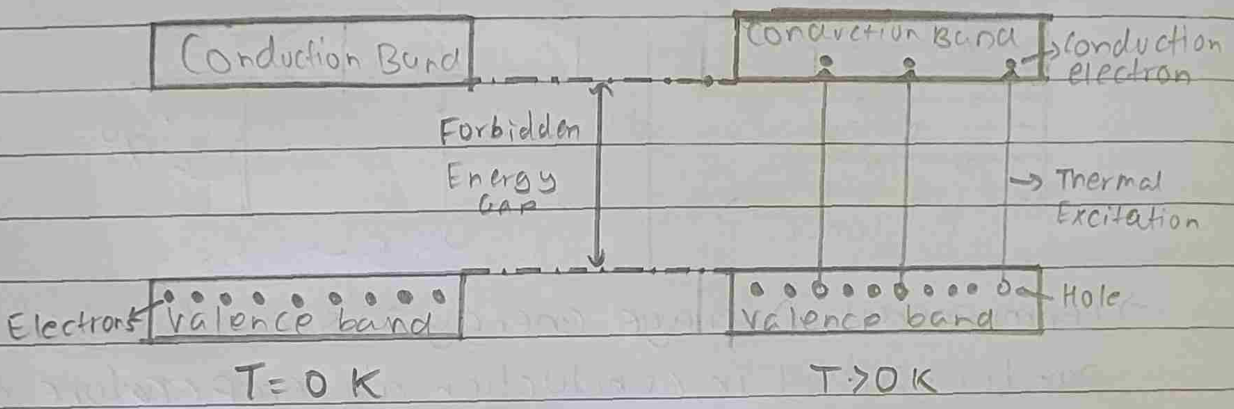
2) In Intrinsc SC

→ At T = 0 K, the valence band will be full of electrons → impossible to cross the energy barrier → acts as an insulator.

→ At T > 0K → the electron movement ~~moven~~ from the VB to the CB increases

→ Create holes in the VB in place of electrons.

→ The electron concentration 'n' is equal to hole concentration 'p'



→ Let 'n' be no. of electrons in the SC ~~conduction~~ band.
'p' " " " holes " " Valence "

At T > 0 K

$n = N_c e^{-(E_c-E_F)/KT}$ Where N_c = Effective density of states in the CB

$P = N_v e^{-(E_F-E_v)/KT}$ Where N_v " " " " " VB

→ For intrinsic SC ~~$N_c = N_v$~~ $\boxed{n = P}$ — 1

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

$\frac{N_c}{N_v} = e^{(E_c+E_v-2E_F)/KT}$

~~$\frac{N_v}{N_c} = e^{[}$~~

$\frac{N_v}{N_c} = e^{[2E_F-(E_c+E_v)]/KT}$ — 2

$\frac{N_v}{N_c} = \frac{\cancel{2}\left(\frac{2\pi m_n^* KT}{h^2}\right)^{3/2}}{\cancel{2}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2}} = \left[\frac{m_n^*}{m_e^*}\right]^{3/2} \sim 1$ — 3

$\because m_e^* \approx m_n^*$

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From ② & ③

$$e^{[2E_F-(E_C+E_V)]/KT} = 1$$

∴ Taking log on both side

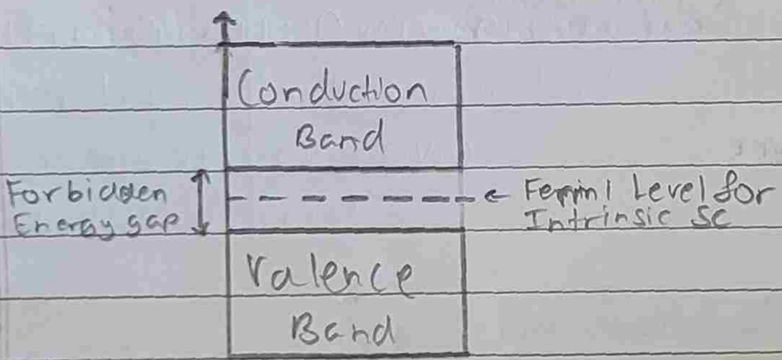
$$\frac{2E_F-(E_C+E_V)}{KT} = 0$$

~~2EF~~

$$2E_F - (E_C+E_V) = 0$$

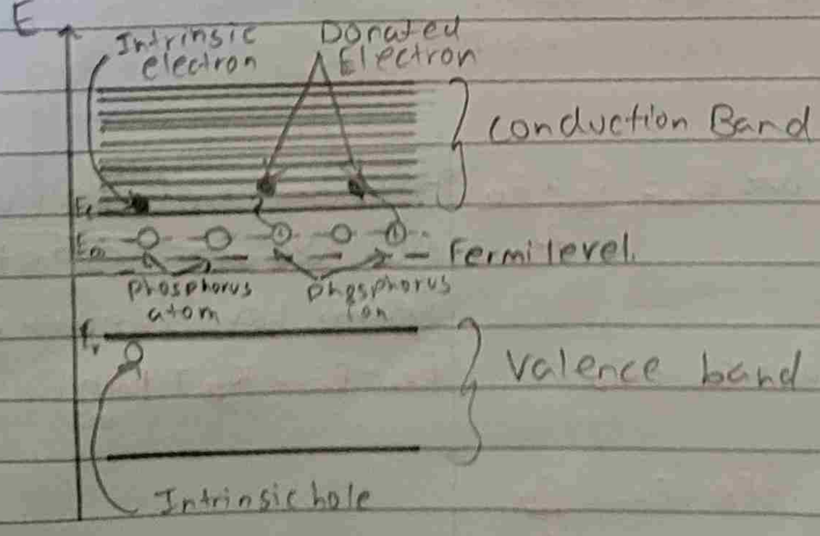
$$\boxed{E_F = \frac{E_C+E_V}{2}}$$

∴ The fermi energy for intrinsic SC is halfway between Valence & conduction band

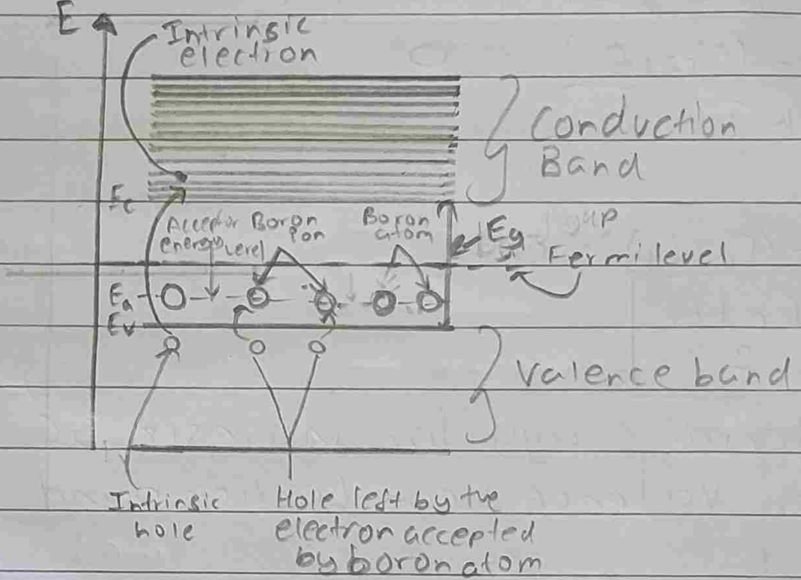


3) <u>In Extrinsic SC</u>

→ <u>N-type</u> : Pentavalent impurity ⇒ electron as majority charge carriers ⇒ donor impurities

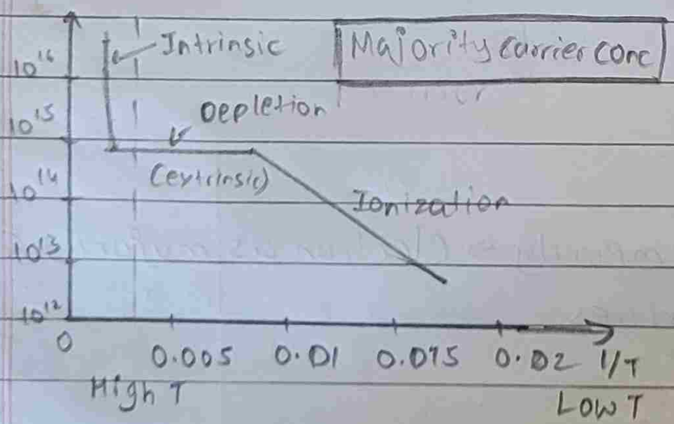


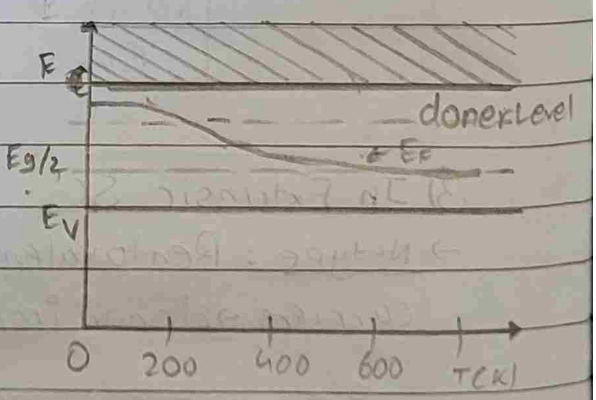
→ P-type: Trivalent impurity → holes as majority charge carriers → acceptor impurities.



Effect of Temperature

1) E_F of N-type





→ Region I:

Ionization region: $E_{Fn} = \frac{E_c + E_D}{2}$

→ Region II:

Depletion region: $E_{Fn} = E_D$

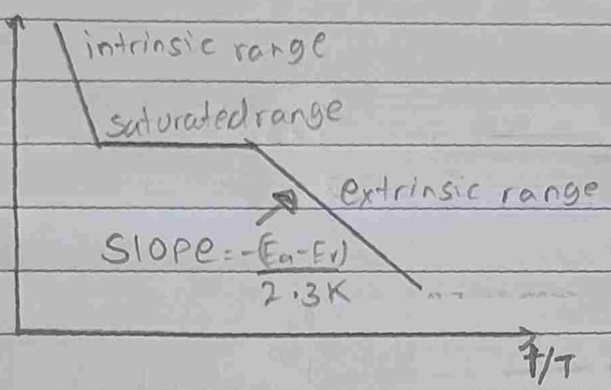
→ Region III:

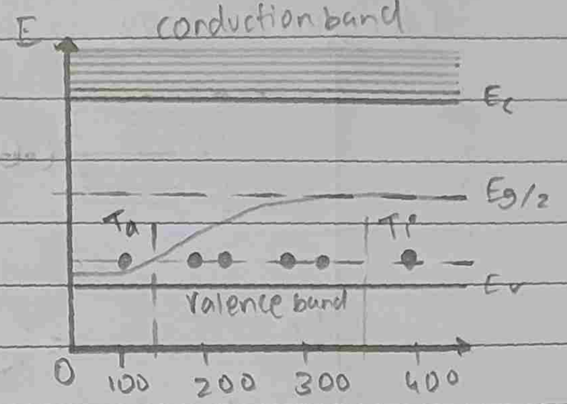
Intrinsic region: $E_{Fn} = E_{Fi} = \frac{E_g}{2}$

→ Fermi level position in n-type SC with respect to intrinsic Fermi Level is given as:

$E_{Fn} - E_{Fi} = K_B T \ln\left(\frac{n}{n_i}\right)$

2) E_F od P-type





→ Region I

Ionization region : $E_{F_P} = \frac{E_V + E_A}{2}$

→ Region II

Depletion region : $E_{F_P} = E_A$

→ Region III

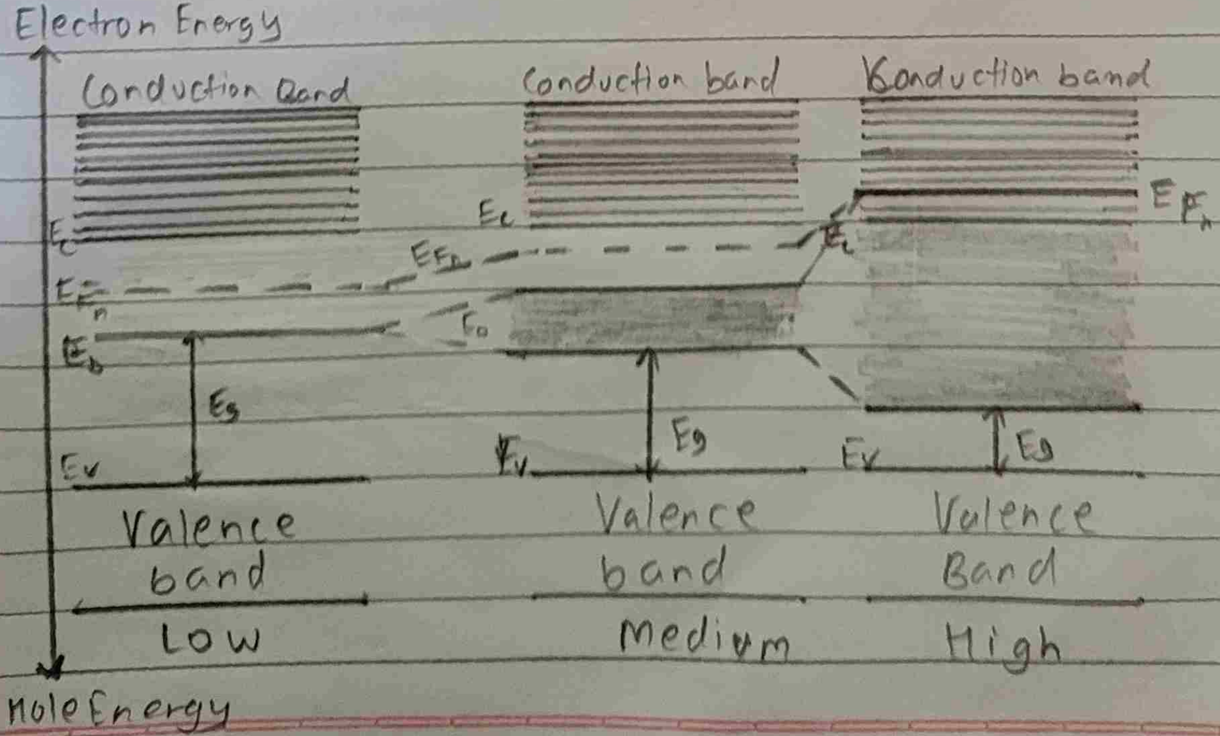
Intrinsic region : $E_{F_P} = E_{F_i} = E_g/2$

→ Fermi level position in P-type semiconductor with respect to intrinsic fermi level is given as:

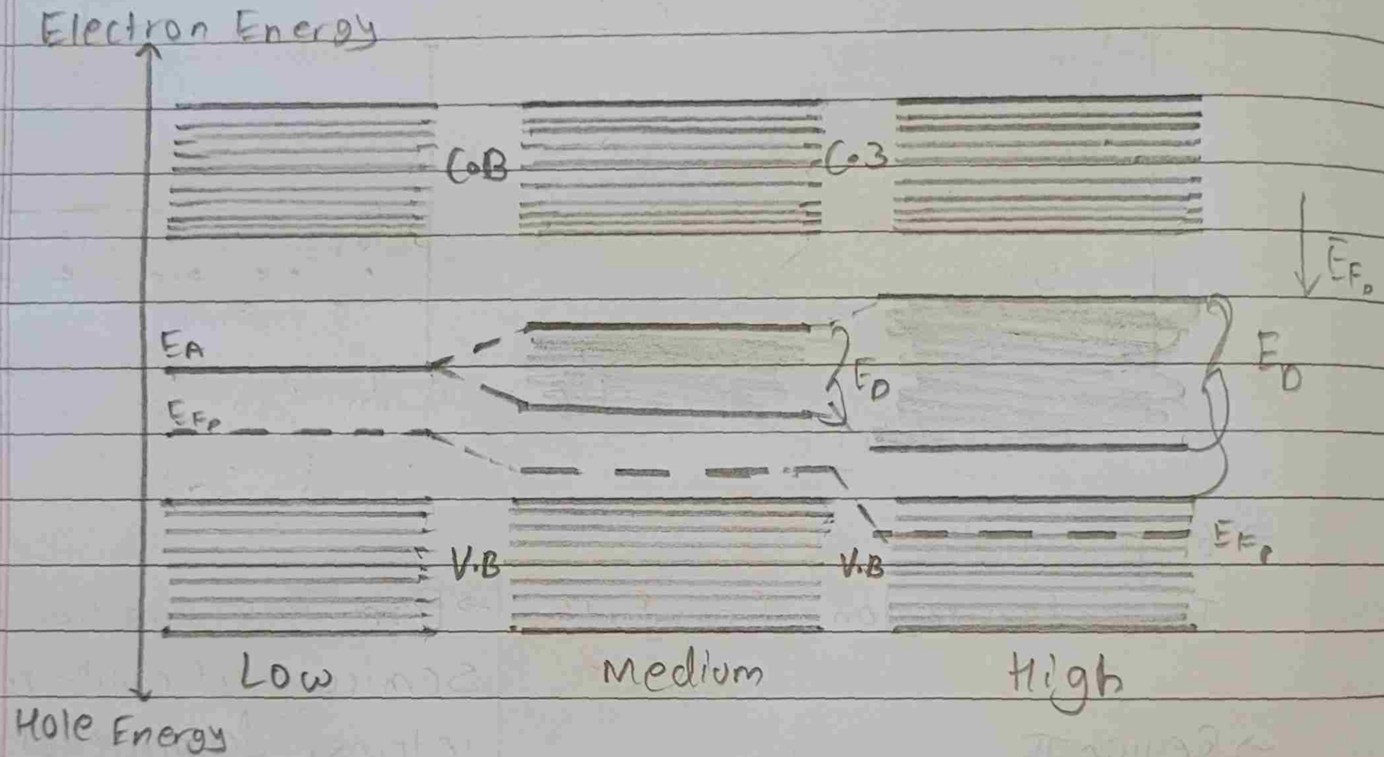
$E_{F_P} - E_{F_i} = -K_B T \ln\left(\frac{P}{n_i}\right)$

Effect od Impurity concentration

1) E_F od N-type



2) E_F of P-type


Electron Energy
C.B
C.B
E_{F_p}
E_A
E_{F_p}
E_D
E_D
V.B
V.B
E_{F_p}
Low
Medium
High
Hole Energy