Semiconductor Physics

Semiconductors -

- The materials having electrical conductivity lies in between conductors and insulators are the semiconductors.
- The pure semiconductors are called as intrinsic and impure (Doped) semiconductors are called as extrinsic semiconductors.
- When trivalent impurities (Aluminium, Boron etc) are added to pure semiconductors (Si/Ge) then p-type semiconductor is formed.
- When pentavalent impurities (Phosphorous, Arsenic) are added to pure semiconductors then n-type semiconductors are formed.
- Majority charge carriers in p-type → holes
- Majority charge carriers in n-type → electrons.

Classification of solids on the basis of band gap -

- Band gap - It is the energy difference between bottom of conduction band and top of the valence band.

or
- Band gap is the minimum energy required for an electron to move from valence band to conduction band.

(I) Solids can be classified as conductors, insulators and semiconductors on the basis of band gap.

(A) Conductors -

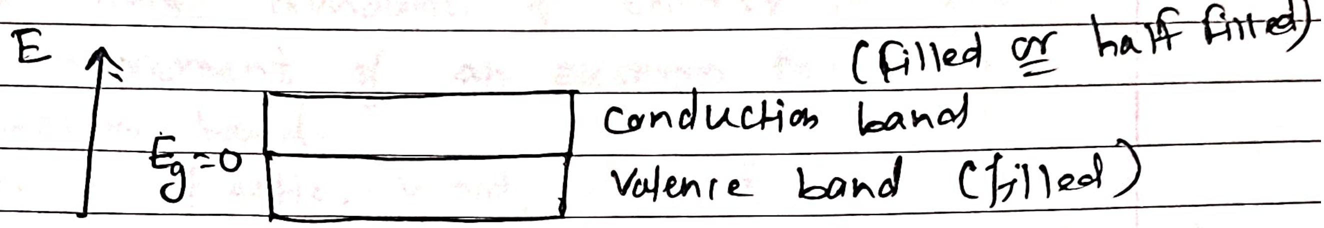
i) The materials which allows electricity to pass through them are conductors.

ii) Conductors contains free electrons.

iii) In conductors, conduction band and valence band are overlapped so, the band gap is zero.

iv) So, in conductors electron can easily jump from valence band to conduction band.

v) Ex:- Copper.

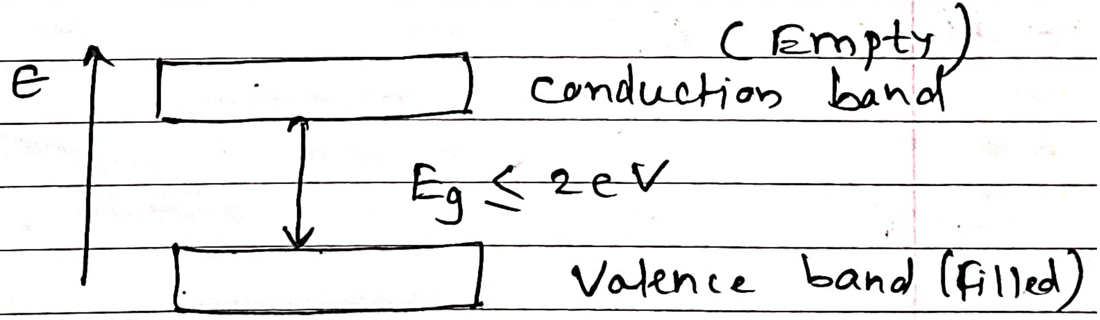


Ⓑ Semiconductors -

i) In semiconductors, the conduction band and valence bands are seperated from each other.

ii) The band gap in semiconductors is small (narrow) i.e. $E_g \leq 2$ eV

iii) So, small energy can results in current flowing through semiconductors.



iv) Ex - Si, Ge.

ⓒ Insulators

i) Insulators does not allow current to pass through them.

ii) They do not contain free electrons.

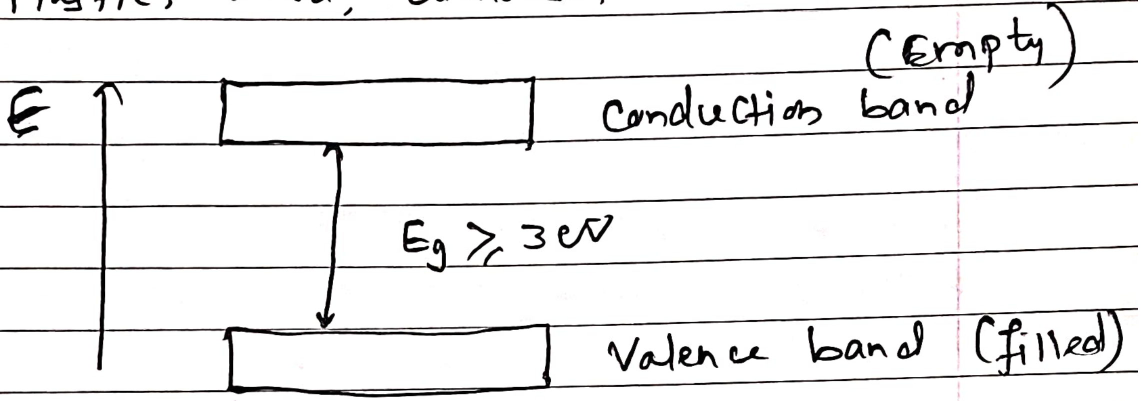
iii) In insulators. the conduction band and valence band are widely seperated form each other.

iv) The band gap is large (wide).

i.e. $E_g \geq 3\ eV$

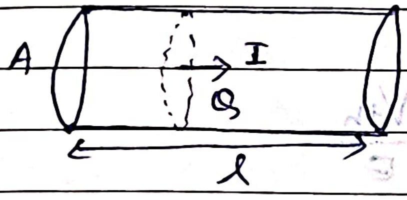
v) The large amount of energy is required for the movement of an electron form valence to conduction band.

vi) Eg:- Plastic, wood, dimond.



Conductivity of a semiconductor :-

Consider a semiconducting material of length 'l' & cross-sectional area 'A' carrying a current 'I'.



let, n = charge carrier density

V_d = Drift velocity

Now, the total charge passing through the given volume is,

$$Q = neAl$$

∴ current $= I = \frac{Q}{t} = \frac{neAl}{t}$

∴ $I = neAV_d$ $\left(\because \frac{l}{t} = V_d\right)$

So,

current due to electrons is,

$I_e = neAV_{de}$ —① (V_{de} = Drift velocity of electrons) (n = electron density)

and,

current due to holes is,

$I_h = peAV_{dh}$ —② (V_{dh} = Drift velocity of holes) (p = hole density)

∴ Total current is,

$$I = I_e + I_h$$

$$\therefore I = neAV_{de} + neAV_{dh}$$

∴ current density $= J = \frac{I}{A}$

$\therefore J = neV_{de} + peV_{dh}$

From, ~~And~~ microscopic form of ohm's law,

$J = \sigma E$, (σ = conductivity)

$\therefore \sigma = \frac{J}{E}$

$\therefore \sigma = \frac{neV_{de}}{E} + \frac{peV_{dh}}{E}$

Here, $\frac{V_{de}}{E} = \mu_e$ & $\frac{V_{dh}}{E} = \mu_h$,

μ_e & μ_h are mobilities of electron & hole

$$\therefore \boxed{\sigma = ne\mu_e + pe\mu_h}$$

Case-① - For intrinsic semiconductor,

$n = p = n_i$

$$\therefore \boxed{\sigma_i = n_i e(\mu_e + \mu_h)}$$

Case ② - For extrinsic semiconductor:-

ⓐ P-type semiconductor -

Here, $p >> n$,

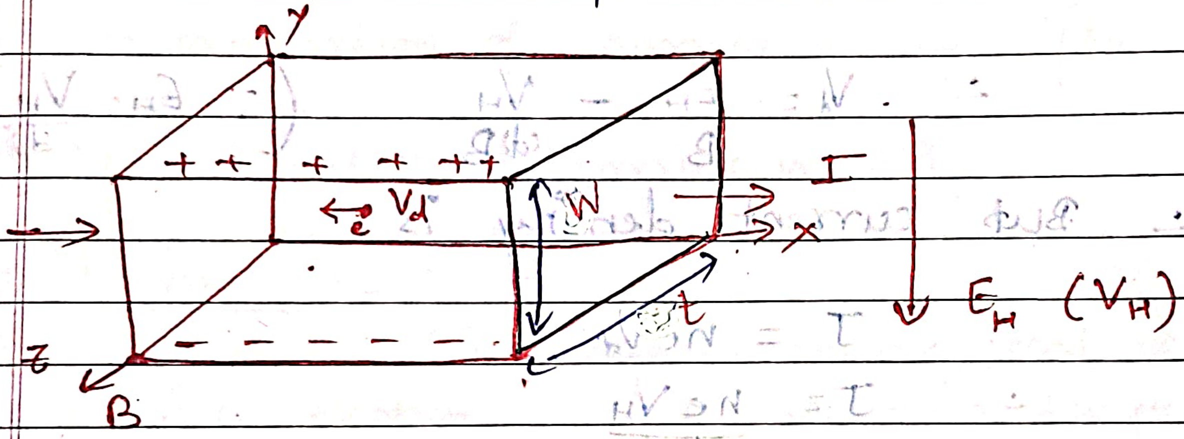
$\therefore \sigma_{p\text{-type}} = pe\mu_h$

(b) n-type semiconductor :-

$$\boxed{\sigma_{n\text{-type}} = n e \mu_e}$$

Hall effect :-

When a conductor or a semiconductor carrying a current 'I' placed in a perpendicular (transverse) magnetic field 'B' then electric field is developed which is perpendicular to current and magnetic field.



let, I = current flowing along x-axis
B = m.f. along z axis
E_H = Hall field along y-axis
V_H = Hall voltage. , W = ~~thickness~~ width of material
V_d = Drift velocity of electrons. & $A = wt$

Magnetic field exert force on electron so, electrons move toward lower surface and lower surface acquires negative charge. So, upper surface acquires equal positive charge. This develops electric field and voltage.

∴ Force due to magnetic field,

$$F_m = eV_d B \quad \text{—①}$$

and,

Force due to electric field,

$$F_E = eE_H \quad \text{—②}$$

This electric force increases untill equillibrium condition reached.

∴ At equillibrium condition,

$$F_m = F_E$$

$$\therefore \cancel{e}V_d B = \cancel{e}E_H$$

$$\therefore V_d = \frac{E_H}{B} = \frac{V_H}{\omega B} \qquad \left(\because E_H = \frac{V_H}{\omega}\right)$$

∴ But current density is;

$$J = neV_d$$

$$\therefore J = \frac{neV_H}{\omega B}$$

$$\therefore V_H = \frac{JB\omega}{ne} = \frac{IBW}{neA} = \frac{IBW}{ne(tW)} = \frac{IB}{net}$$

Here,

the quantity $\frac{1}{ne} = \frac{V_H}{JB\omega}$ is called as Hall coefficient.

∴ Hall coefficient $= R_H = \frac{1}{ne} = \frac{V_H}{JB\omega}$

we know that,

$$J = neV_d \quad \text{and} \quad J = \sigma E$$

$$\therefore \quad neV_d = \sigma E$$

$$\therefore \quad \frac{V_d}{E} = \frac{\sigma}{ne} = \sigma R_H \qquad \left(R_H = \frac{1}{ne}\right)$$

$$\therefore \quad \boxed{\mu = \sigma R_H}$$

Where, 'μ' is called as mobility of carriers.

Applications of Hall effect –

(i) Determination of semiconductor type

(ii) Determination of carrier density $\left[R_H = \frac{1}{ne}, n = \frac{1}{R_He}\right]$

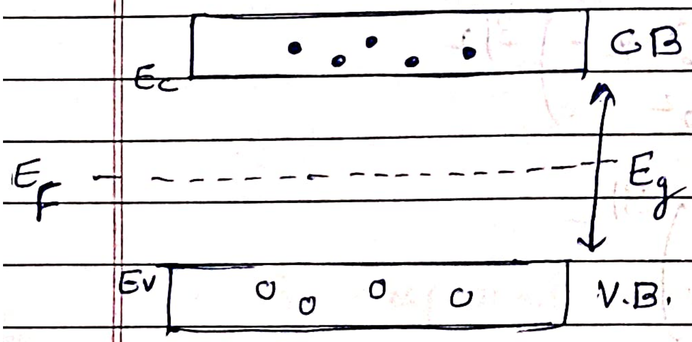
(iii) Determination of carrier mobility.

Fermi level :[In semiconductor]

"The average energy of charge carriers which are participating in conduction is called as Fermi energy."

(I) Fermi level in intrinsic semiconductor :– (at 0K

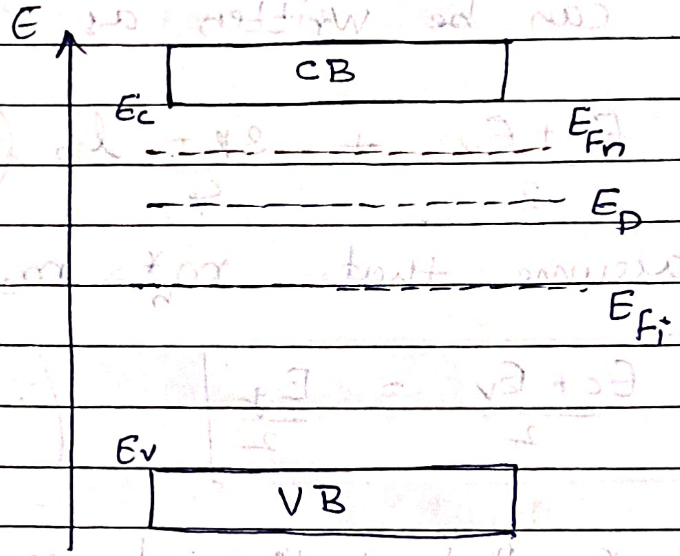
let,
n = electron density in CB
p = hole density in VB
N_c = effective density of states in C.B.
N_v = effective density of states in V.B.



{ E_F in intrinsic semiconductor lies at Centre of CB and VB }

Position of Fermi level of extrinsic semiconductors at T=0K and T>0K →

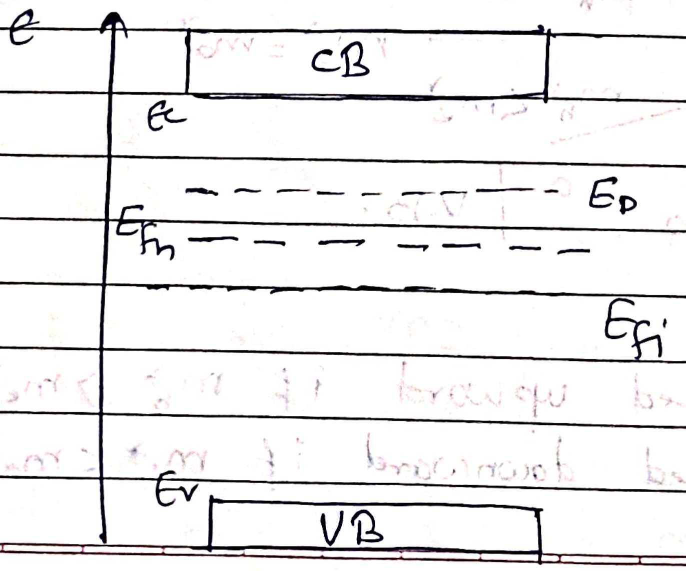
(A) (I) Fermi level of n type semiconductor at T=0K



→ Here, E_{F_i} = Fermi level of intrinsic semiconductor
E_D = Donor level
E_{Fn} = Fermi level of n-type semiconductor.

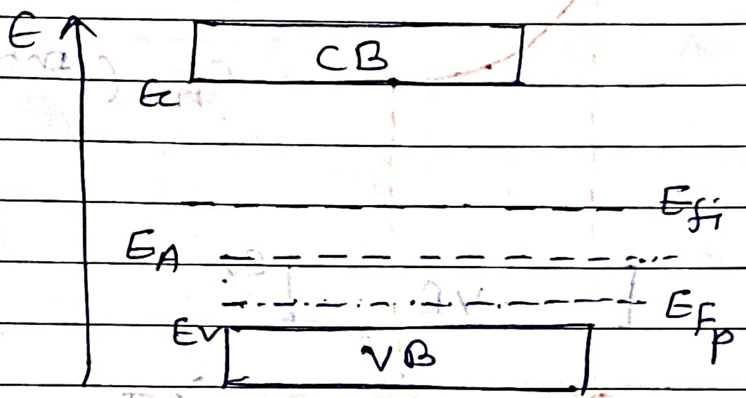
- Donor level forms just below the conduction band.
- Fermi level of n-type forms between the E_c & E_D.

(II) Fermi level of n-type semiconductor at T>0K



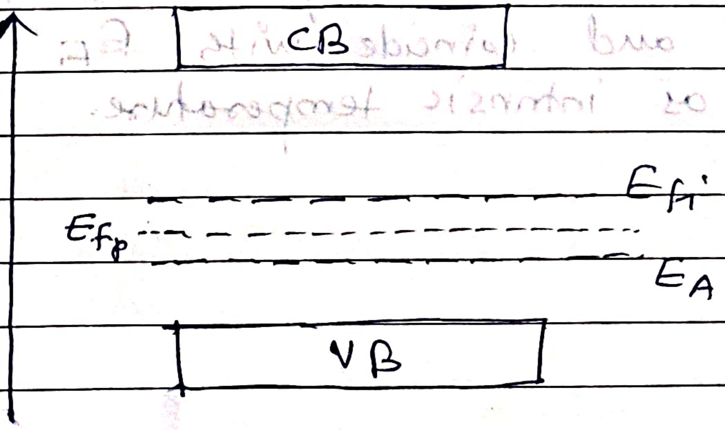
- As temperature increases, electrons from level E_D jumps to conduction band. So, number of electrons in 'E_D' decreases.
- Therefore Fermi level 'E_{Fn}' shifts downward at $T>0K$.

Ⓑ (I) Fermi level of p-type semiconductor at $T=0K$.



- Here, E_A = Acceptor level
E_{Fp} = Fermi level of p-type semiconductor.
- Acceptor level forms above the valence band.
- Fermi level of p-type forms between E_v and E_A.

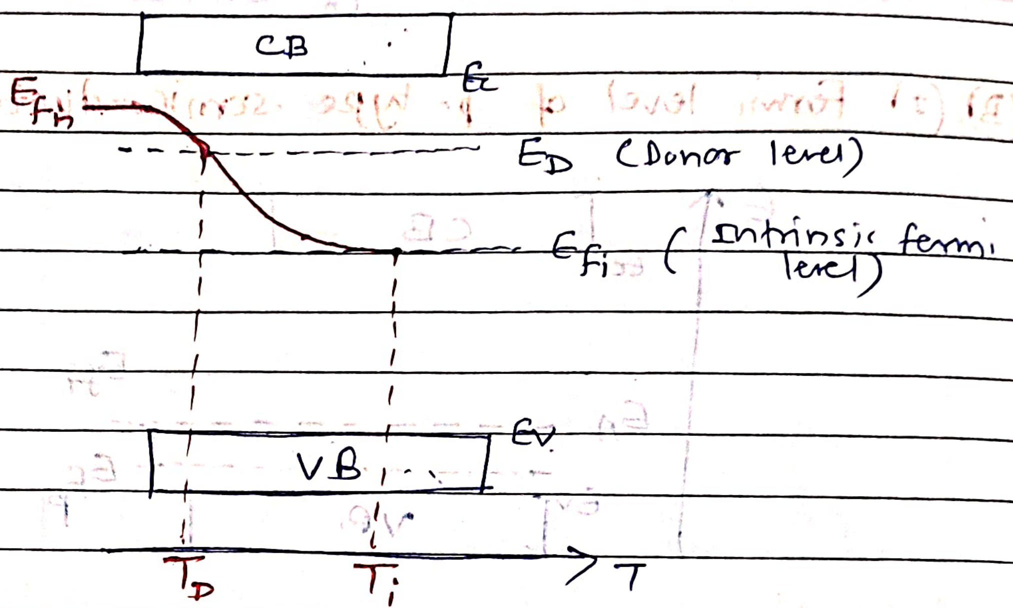
(II) Fermi level of p-type semiconductor at $T>0K$



- As temperature increases, electrons from valence band jumps to accepter level and Fermi level shifts upward.

Variation in fermi level with temperature :-

(I) n-type semiconductor :-



- As temperature increases, electrons from level E_D jumps to conduction band.
- So, level 'E_D' gets depleted from free electrons.
- Therefore, 'E_{fn}' shifts downward and coincides with level 'E_D' at temperature 'T_D' called as depletion temperature.
- Further increase in temperature, 'E_{fn}' shifts downward and coincide with 'E_{fi}' at temperature 'T_i' called as intrinsic temperature.

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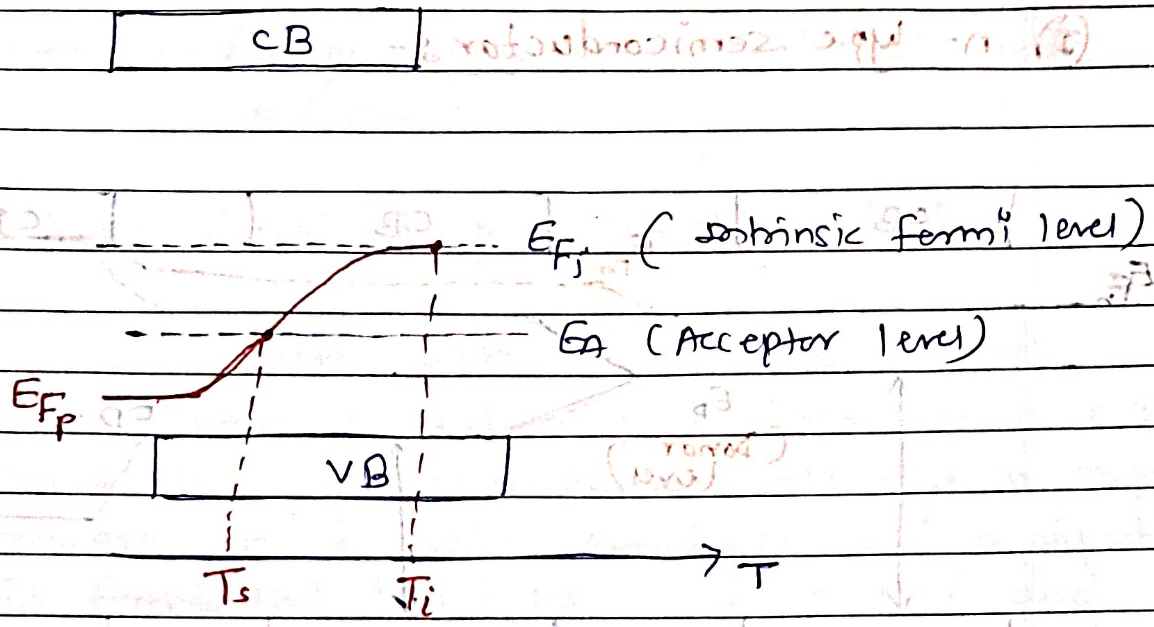
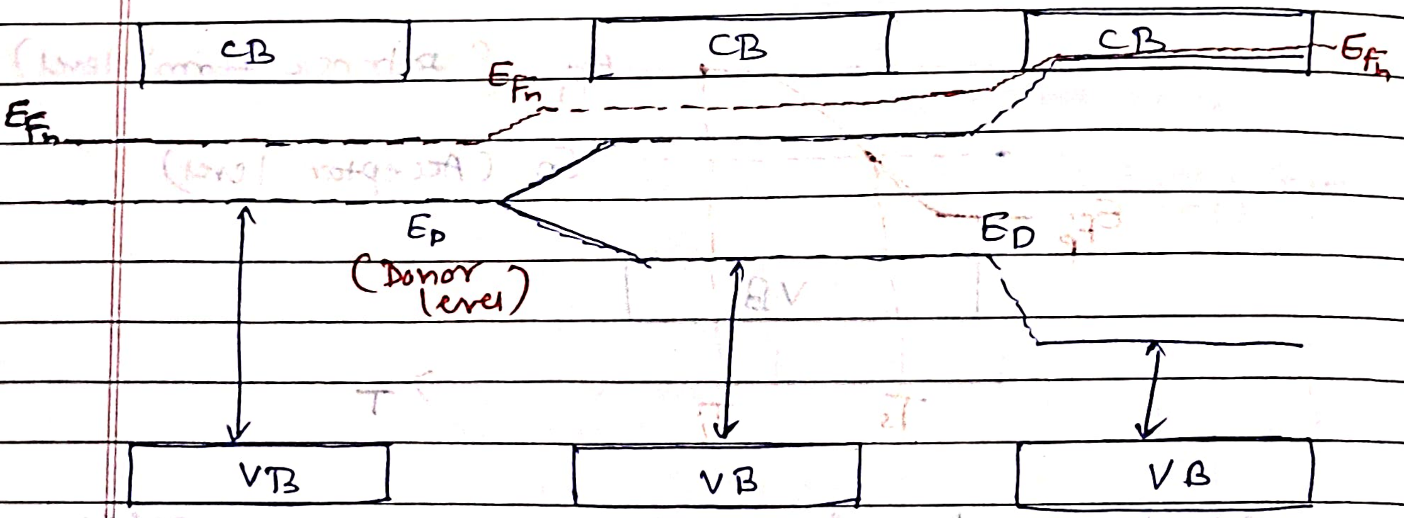
(II) p-type semiconductor :-



- As temperature increases, more electrons shifts from Valence band to acceptor level.
- So, level 'E_{F_p}' shifts upward and coincides with 'E_A' at temperature 'T_s' called as saturation temperature.
- Further increase in temperature, 'E_{F_p}' shifts upward and coincides with 'E_{F_i}' at temperature 'T_i' called as intrinsic temperature.

Variation in Fermi level with impurity concentration :-

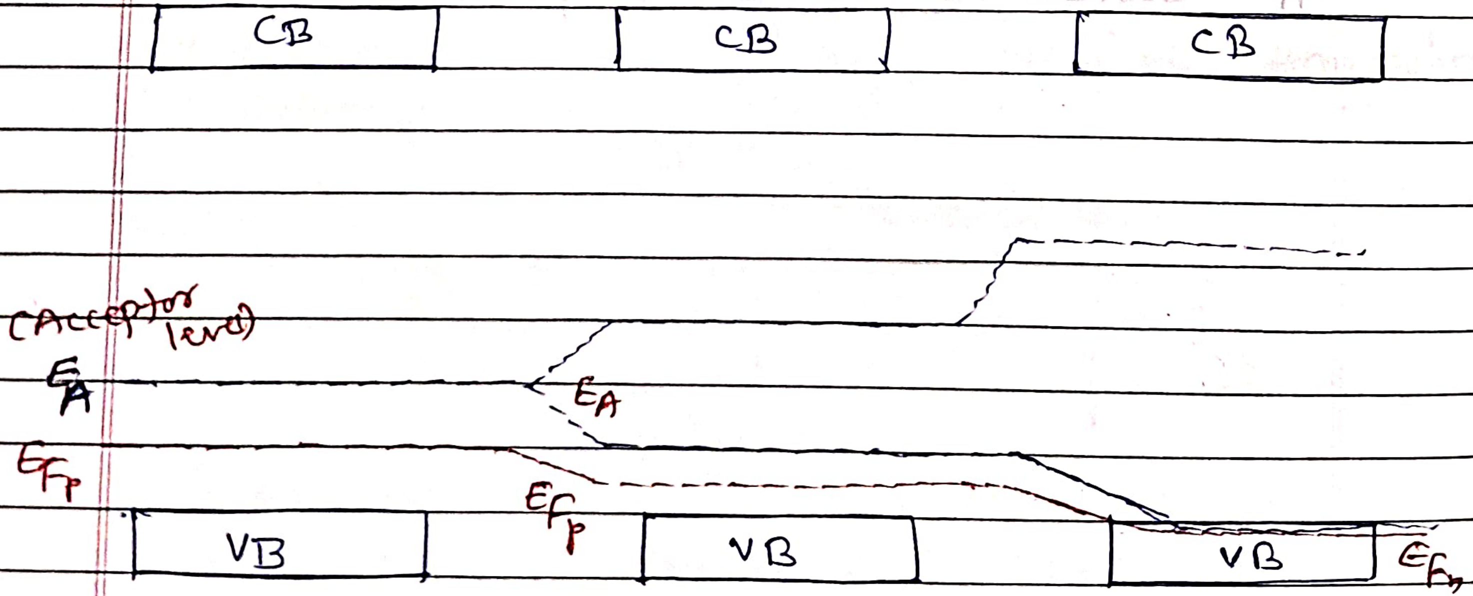
(I) n-type semiconductor :-



Light doping   Medium doping   Heavy doping

- As impurity concentration increases, the width of donor level (E_D) increases and Fermi level shifts upward and finally moves into the conduction band.

(II) p-type semiconductor :-



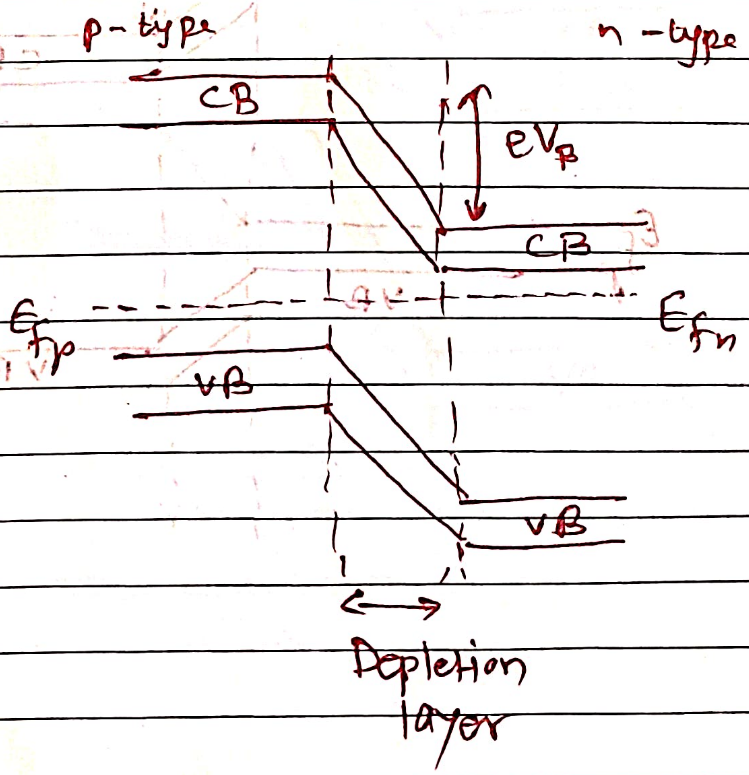
- As impurity concentration increases, the width of acceptor level [E_A] increases & fermi level shifts downward & finally moves into valence band.

Energy band picture of p-n junction diode :-

When p-n junction is formed, the electrons from n-region moves into the p-region and holes from p-region moves into the n-region. This process of diffusion continues and a depletion layer is formed and Fermi levels of n-type and p-type are at the same level. (equilibrium condition)

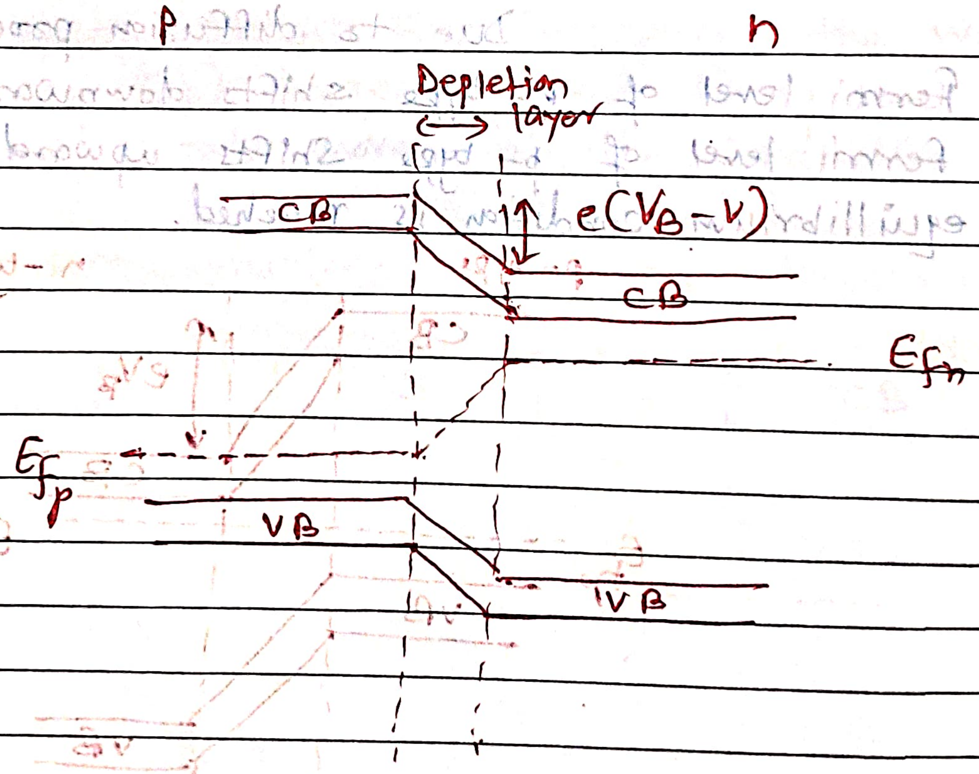
(I) Zero biased :-

Due to diffusion process, the fermi level of n-type shifts downward and fermi level of p-type shifts upward until equillibrium condition is reached.



(II) Forward biased :-

- Diode is said to be forward biased when positive terminal of battery is connected to the p-side and negative terminal of battery is connected to n-side.
- Due to forward biasing, fermi level of n-side shifts upward because negative terminal of battery supplies electrons to n-region
- The fermi level of p-side shifts downward because positive terminal of battery attracts (pulls) electrons from p-side.
- width of depletion layer decreases, so, barrier potential decreases.



(III) Reverse biased:-

- Diode is said to be reverse biased when positive terminal of battery is connected to the n-side and negative terminal of battery is connected to the p-side.
- Due to reverse biasing, fermi level of n-side shifts downward because positive terminal of battery pulls electrons from n-region.
- The fermi level of p-side shifts upwards because negative terminal of battery supplies electrons to p-region.
- Width of depletion layer increases.