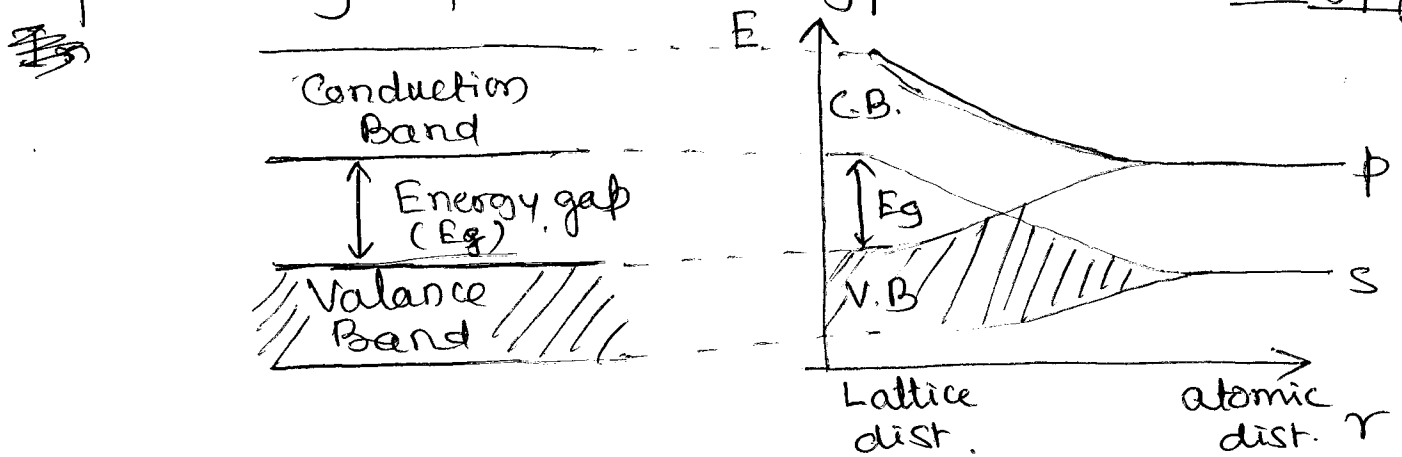# Semiconductors

Semiconductors are the materials whose conductivity lies between a metal (conductor) and insulator. The common commonly used semiconductors are Si, Ge, GaAs etc.

Conduction and Valance Band :

Atomic orbitals in a solid overlap and the energy levels gets broadened because of this overlap. The distance between individual energy levels are so small ($\lessgtr > 10^{-4}$ ev) that identifying them becomes difficult. This leads to the energy band concept. The bonding states which has $\bar{e}$s in them are called the valance shell band and the antibonding states are called as conduction band. These bands are separated by a forbidden energy state called 'energy gap'

In semiconductors the value of the energy gap is of the order of few eVs such that the thermal energy is able to elevate the $\bar{e}$s from valance to conduction band,

ex: Si $E_g = 1.12$ ev.   Compare it with C in diamond
     Ge $E_g = 0.67$ ev.   shape $E_g = 5.48$ ev.
     GaAs $E_g = 1.4$ ev   @ 300K.

At 0K the valance band of the semiconductor is completely filled and valanc conduction band is completely empty. Thus semiconductor is like an insulator at 0K as the temparature increases, more and more $\bar{e}$s occupy conduction band and become available for conduction. Thus conductivity in semiconductor increases with temparature

If a semiconductor is prestine (pure) ie, with out the impurities then such a semiconductors are known as intrinsic semiconductors. In this chapter we will be concerned about intrinsic semiconductors only.

There are 2 types of instrinsic semiconductors.
1) Direct   2) Indirect Bandgap semiconductors

1) <u>Direct Bandgap semiconductors</u>: If the lowest part of the conduction band lies exactly on top of the higest part of the valance band; such a semiconductor is known as direct bandgap semiconductor.

A recombination of e^- & holes in such semiconductors generates photons (light). Ex: <u>GaAs</u>.
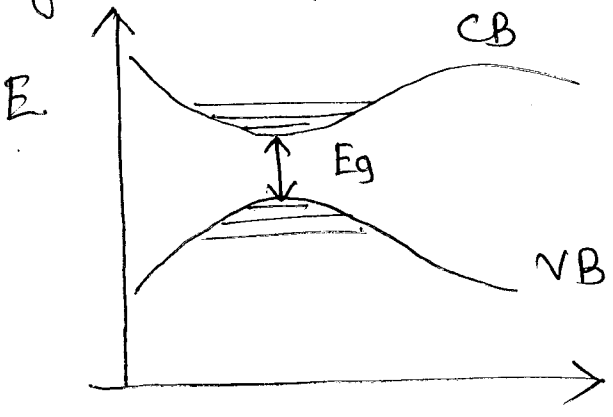
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2) <u>Indirect bandgap semiconductors</u>: If the lowest part of the conduction band is little displaced from the top of the valance band then such a semiconductor is called as an indirect bandgap semiconductor.

The recombination in such semiconductor requires a photon and hence heat is generated as a result of the recombination. Ex. Si, Ge.
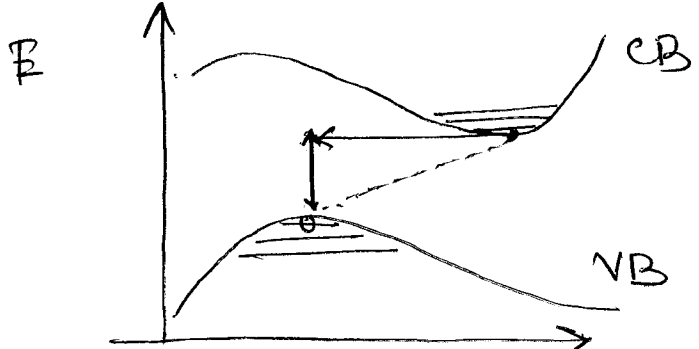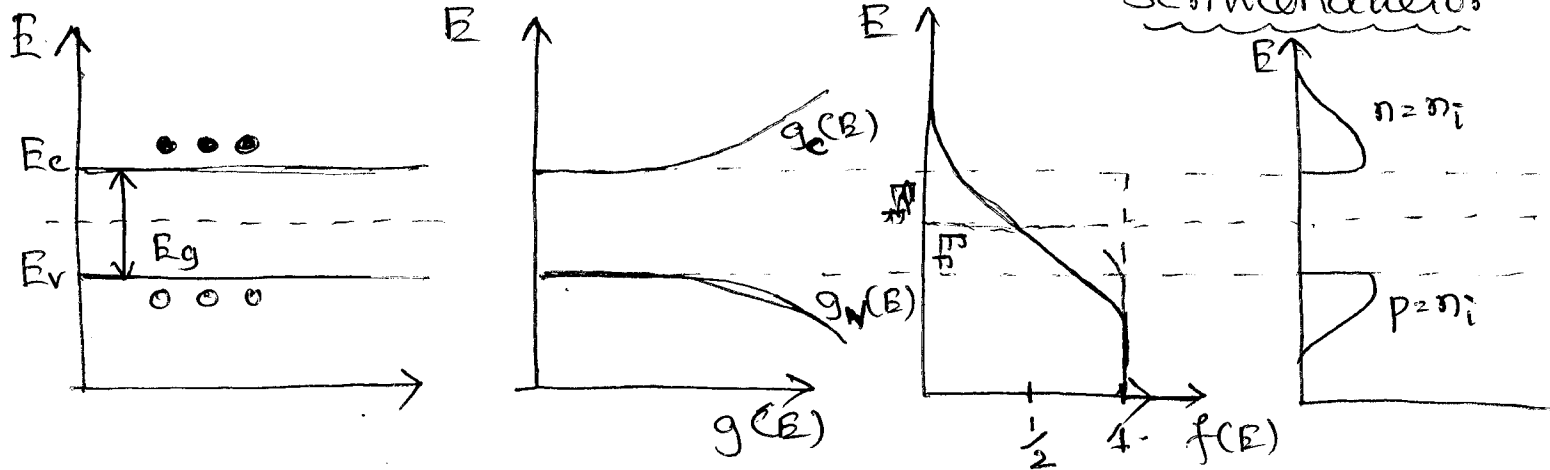
Concentration of $\bar{e}$ in conduction band can be found by.

$$n_e = \int_{E_c}^{\overset{top\ of}{CB}} f(E) \cdot g_c(E)\, dE.$$

But $g_c(E) = \dfrac{\pi}{2}\left[\dfrac{8m_e^*}{h^2}\right]^{3/2} (E-E_c)^{1/2}$ for $E > E_c$

$\therefore\ n_e = \displaystyle\int_{E_c}^{\infty} \dfrac{\pi}{2}\left[\dfrac{8m_e^*}{h^2}\right]^{3/2} \dfrac{(E-E_c)^{1/2}}{1+\exp\left\{\frac{(E-E_F)}{kT}\right\}}\, dE.$

which after integration gives,

$$n_e = 2\left[\dfrac{2\pi m_e^* kT}{h^2}\right]^{3/2} e^{-(E_c-E_F)/kT}$$

$$\boxed{n_e = N_c\, e^{-(E_c-E_F)/kT}}$$

or

where $N_c = 2\left[\dfrac{2\pi m_e^* kT}{h^2}\right]^{3/2}$

Similarly, concentration of holes in valance band can be determined by. $n_h = \displaystyle\int_{\substack{Bottom\ of\\ VB}}^{E_v} \left[1 - f(E)\right] g_v(E)\, dE.$

$g_v = \dfrac{\pi}{2}\left[\dfrac{8m_h^*}{h^2}\right]^{3/2} (E_v - E)^{1/2}$ for $E < E_v$.

$\therefore\ n_h = \displaystyle\int_{-\infty}^{E_v} \dfrac{\pi}{2}\left[\dfrac{8m_h^*}{h^2}\right]^{3/2} \cdot (E_v - E)^{1/2}\, e^{-(E_F - E)/kT}\, dE.$

Integration gives,

$$n_h = 2\left[\dfrac{2\pi m_h^* kT}{h^2}\right]^{3/2} e^{-(E_F - E_v)/kT}$$

or $\boxed{n_h = N_v\, e^{-(E_F - E_v)/kT}}$

where $N_v = 2\left[\dfrac{2\pi m_e^* kT}{h^2}\right]^{3/2}$

Expression for Fermi energy in intrinsic semiconductor

For intrinsic semiconductor the concentration of e^- s and holes are equal.

i.e, $n_e = n_p$

i.e, $N_c \, e^{-(E_c - E_f)/kT} = N_v \, e^{-(E_f - E_v)/kT}$

or $e^{-(E_c - E_f)/kT} = \left(\dfrac{N_v}{N_c}\right) e^{-(E_f - E_v)/kT}$

Taking '$\ln$' on both sides, we have,

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

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

rearranging and simplifying, we get,

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

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

But $\left(\dfrac{N_v}{N_c}\right) = \left(\dfrac{m_h^*}{m_e^*}\right)^{3/2}$ and $\ln x^a = a \ln x$.

Thus

$$\boxed{E_f = \left(\frac{E_c + E_v}{2}\right) + \frac{3kT}{4} \ln\left(\frac{m_h^*}{m_e^*}\right)}$$

For small 'kT' $m_e^* = m_h^*$ for intrinsic semiconductor. Therefore 2nd term in the above equation is negligible

$\therefore E_f = \dfrac{E_c + E_v}{2}$

by adding and subtracting $\dfrac{E_v}{2}$

or $E_f = \dfrac{E_c + E_v + E_v - E_v}{2}$

$\therefore E_f = \dfrac{E_c - E_v}{2} + E_v$.

But $\dfrac{E_c - E_v}{2} = E_g$.

$$\boxed{\therefore E_f = \frac{E_g}{2} + E_v}$$

If we consider top of the valance band E_v as zero then

$$\boxed{E_f = \frac{E_g}{2}}$$

Conductivity of Semiconducting Materials:

Current density J can be deffined as "current /unit cross-sectional area"

i.e, $J = \dfrac{I}{A}$.

The microscopic origin of current I can be understood by considering a long conductor with cross-sectional area 'A'

$I = n e v_d A$ where 'n' → no. of free $\bar{e}$, e → charge on $\bar{e}$ and v_d → drift velocity of the $\bar{e}$s.

In semiconductors as the temp. increases, some of the $\bar{e}$s from valance band move to conduction band and ~~then the~~ the vacancy in valance band is called as 'holes'

∴ The expression for current for $\bar{e}$s and holes can be written as,

$$I_e = n_e \bar{e} V_e A \quad \text{and} \quad I_h = n_h \bar{e} V_h A.$$

∴ $J = \dfrac{(I_e + I_h)}{A} = e(n_e V_e + n_h V_h)$

We know that $J = \sigma E$ where σ is the conductivity and E is the applied electric field.

∴ $\sigma E = e(n_e V_e + n_h V_h)$

or $\sigma = e\left(n_e \dfrac{V_e}{E} + n_h \dfrac{V_h}{E}\right)$

Mobility $\mu = \dfrac{V_d}{E}$ drift velocity acquired by $\bar{e}$s per unit E-field.

∴ $\sigma = e\left[n_e \mu_e + n_h \mu_h\right]$ where $\mu_e = \dfrac{V_e}{E}$ & $\mu_h = \dfrac{V_h}{E}$.

For intrinsic semiconductor $n_e = n_h = n_i$ → density of intrinsic charge carrier.

∴ $\boxed{\sigma = n_i e (\mu_e + \mu_h)}$

Law of mass action in semiconductors.

For an instrinsic semiconductor, we know that

$n_e = n_p = n_i$ where n_i is the intrinsic concentration of charges.

$$n_e \cdot n_p = n_i \cdot n_i = n_i^2$$

$$= \left[N_c \, e^{-(E_c - E_F)/kT} \right] \cdot \left[N_v \, e^{-(E_F - E_v)/kT} \right]$$

$$= (N_c N_v) \, e^{-(E_c - E_v)/kT}$$

$$= (N_c N_v) \, e^{-E_g/kT} \qquad \left(\because \; E_c - E_v = E_g \text{ the energy gap} \right)$$

$$\therefore \; n_i = (N_c N_v)^{1/2} \, e^{-E_g/2kT}$$

Statement : Addition of impurities to an intrinsic semiconductor increases the concentration of one type of carriers which consequently becomes majority carrier. and simultaneously decreases the concentration of the other carrier. which results into a minority carrier,

Significance of the law : Since n_i is constant, increase of one type of charge by doping etc. increases the concentration of that type and the other type of carrier decrease below the intrinsic value. The product of majority and minority charge carrier is constant. ~~in an~~ e even in an extrinsic semiconductor and it is independent of the amount of donor or accepter impurity concentration. This helps in estimating the minority charge carrier concentration,