5. Semiconductors.

Based on electrical conductivity, materials are devided into
- Conductors
- Insulators
- Semiconductors.

Semiconductor: At 0k, these elements are insulators where as at room temp they possess conductivity.

They are two types
1. Intrinsic
2. Extrinsic

Intrinsic Semiconductor

Pure Semi Conductors are called intrinsic Semi Conductor Eg Ge, Si

Extrinsic Semiconductor:

Adding impurities like III group (or) V group elements to pure semiconductor. This impure semiconductor is called extrinsic semiconductor.

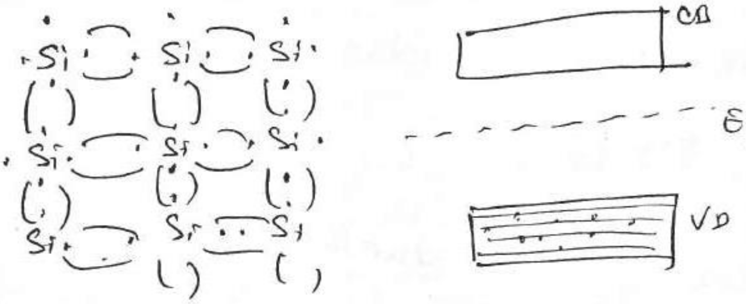
when adding III group element p-type semiconductor and adding V group elements n-type semiconductors are formed.

Intrinsic semiconductor

Pure semiconductor are known as intrinsic semiconductor. Frequently available are Ge, Si. belonging to IV group. Each semiconductor has four valence electrons in their outermost orbits, to get stability.

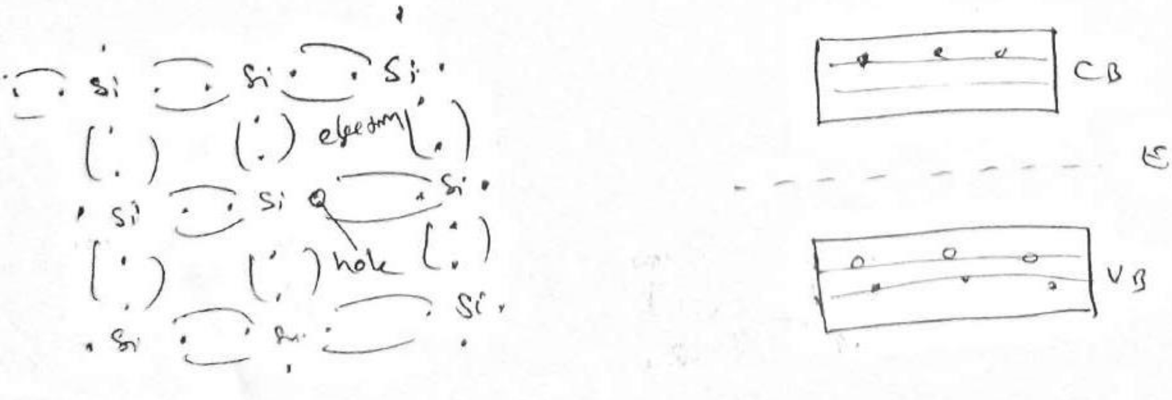
At 0K, all valence electrons are strongly bound to their atoms and are actively participating in the covelent bond formation. As a result it acts as a insulator.

At 0K



At T>0K: At room temp the valence electron acquires sufficient amount of thermal energy. As a result break of covalent bond takes place releasing free electrons. The free electrons create a vacance in its initial position in the crystal.

Free electrons acquiring of sufficient thermal energy, cross the energy gap and enter into the conduction band from valence band and occupi the energy levels in the conduction band



Carrier concentration of Intrinsic Semiconductor

9. In an intrinsic Semiconductor, each broken leads to generation of two carriers namely, an electron and hole. At any temp T, the no of electrons is equal to the no of holes.

For electron Concentration:-

Let 'n' be the no of electrons per unit volume in the energy range E and E+dE in the conduction band.

$$N(E)\,dE = g_e(E)\,dE\,f_e(E)$$

where $g(E)dE$ - no of available electron state between E and E+dE per unit volume of the material

$f_e(E)$ - probability that an electron occupies an electron state at E.

$$\therefore \quad n = \int_{E_c}^{E_{ct}} N(E)\,dE$$

$$= \int_{E_c}^{E_{ct}} g_e(E)\,dE\,f_e(E)$$

$$n = 2\left[\frac{2 m_e^* \pi k_B T}{h^2}\right]^{3/2} e^{-\left(\frac{E_c - E_F}{k_B T}\right)}$$

$$n = N_c\, e^{-(E_c - E_F)/k_B T}$$ where N_c - Psedo constant

For hole concentration

The number of holes per unit volume of semiconductor in the energy range E and $E+dE$ in the valence band is $p(E)dE$

$$p(E)dE = g_h(E)dE\, f_h(E)$$

p is the number of holes present in the valence band per unit volume of material is obtained integrating $p(E)dE$ with in the limits E_{V_b} and E_V

$$p = \int_{E_{V_b}}^{E_V} p(E)\,dE = \int_{E_{V_b}}^{E_V} g_h(E)\, f_h(E)\,dE$$

$$= 2\left[\frac{2 m_h^* \pi k_B T}{h^2}\right]^{3/2} e^{\frac{-(E_F - E_V)}{k_B T}}$$

$$p = N_V\, e^{(E_V - E_F)/k_B T}$$

For an intrinsic semiconductor

$$n = p = n_i$$

$$n_i^2 = np$$

$$= \left[N_c\, e^{(E_F - E_C)/k_B T}\right]\left[N_V\, e^{(E_V - E_F)/k_B T}\right]$$

$$= N_c N_V\, e^{(\cancel{E_F} - E_C + E_V - \cancel{E_F})/k_B T}$$

$$= N_c N_V\, e^{-(E_C - E_V)/k_B T}$$

$$\boxed{E_g = E_C - E_V}$$

$$= N_c N_V\, e^{-E_g/k_B T}$$

$$\boxed{n_i = (N_c N_V)^{1/2}\, e^{-E_g/2k_B T}}$$

Fermi energy level

$$n = p$$

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

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

$$= e^{(E_F - E_c - E_v + E_F)/k_BT}$$

$$= e^{[2E_F - (E_c + E_v)]/k_BT}$$

$$\log \frac{N_v}{N_c} = \frac{2E_F - (E_c + E_v)}{k_BT}$$

$$2E_F = k_BT \log \frac{N_v}{N_c} + (E_c + E_v)$$

$$E_F = \frac{1}{2} k_BT \log \frac{N_v}{N_c} + \frac{1}{2}(E_c + E_v)$$

$$\therefore E_F = \frac{E_c + E_v}{2} \quad \text{where } \frac{N_v}{N_c} = 1$$

Thus the fermi energy level in an intrinsic semiconductor lies in the middle (or) Centre of the energy gap. Fermi energy level is independent of temp

Energ

Intrinsic Conductivity

Consider an intrinsic semiconductor to which a potential diff V is applied. It gives an electric field E and the charge carriers are forced to drift.

The drift velocity acquired by the charge carrier is given by $V_d = \mu E$

μ is the mobility of charge carriers.

Let 'n' be the concentration of electrons then the current density due to an electron

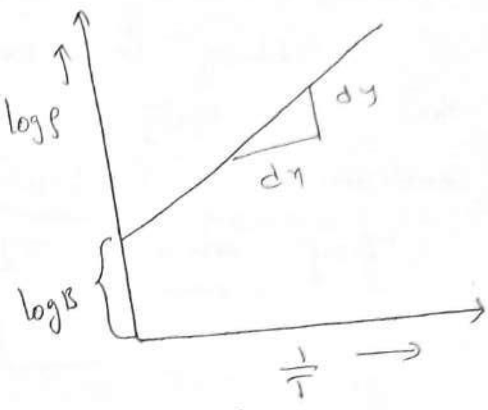
$$J_n = nev_d$$
$$= ne\mu_n E$$
$$J_p = pe\mu_p E$$
$$J = J_n + J_p = ne\mu_n E + pe\mu_p E$$
$$= eE(n\mu_n + p\mu_p)$$
$$= eE(n_i\mu_n + n_i\mu_p)$$
$$= n_i eE(\mu_n + \mu_p)$$
$$\sigma = J/E = \frac{n_i e\cancel{E}(\mu_n + \mu_p)}{\cancel{E}}$$
$$= n_i e(\mu_n + \mu_p)$$
$$= (N_c N_v)^{1/2} e^{-E_g/2k_BT} e(\mu_n + \mu_p)$$
$$\boxed{\sigma = A e^{-E_g/2k_BT}}$$

Energy band gap of Intrinsic Semiconductor

$$\sigma = A e^{-E_g/2k_BT}$$

$$\frac{1}{\sigma} = \frac{1}{A} e^{E_g/2k_BT}$$

$$\rho = B e^{E_g/2k_BT}$$



$$\log \rho = \log B + E_g/2k_BT$$

plot a graph b/w $\log \rho$ on y-axis and $\frac{1}{T}$ on x-axis slope gives

$$\frac{dy}{dx} = \frac{E_g}{2k_B}$$

$$\boxed{E_g = 2k_B\left(\frac{dy}{dx}\right)}$$

Extrinsic Semiconductor

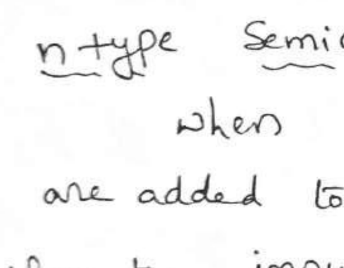
Adding impurities to intrinsic semiconductors, the conductivity of semiconductor increases. Those semiconductors are called extrinsic semiconductors.

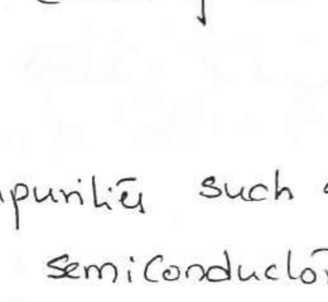
They are two types.

1. n-type semiconductors (adding V group elements)
2. p-type semiconductors (adding III group elements)

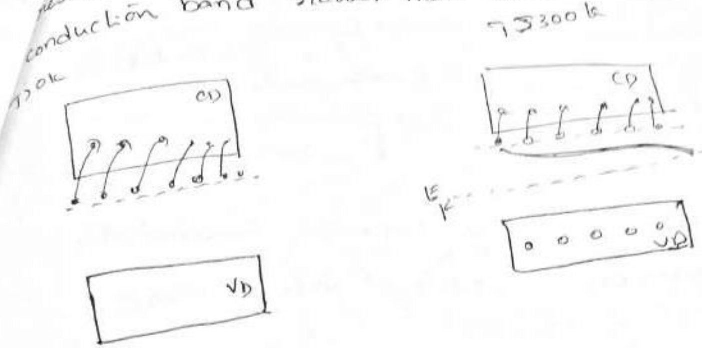
n type Semiconductor

when pentavalent impurities such as P(As, Pb) are added to an intrinsic semiconductor Si (or) Ge, then the impurity atoms interlock in the crystal lattice. Four electrons of 'p' will make covalent bonds and fifth electron is freely attached to 'Si'. Near to the conduction band, we have donar energy level (E_d). It acts as a donar



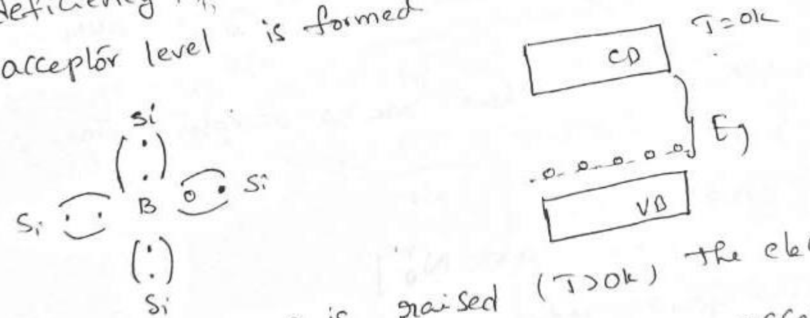


when the temp is increased (T > ~~300k~~ 0k) then the bound electrons becomes a free electron and enters into the conduction band. At high temp, breakage of covelent bond ~~be~~ releases ~~and~~ an electron and a hole. As a result concentration of electrons increases in the conduction band rather than holes.



P-type Semiconductor

When a small amount of trivalent impurity such as Boran (or Indium) is added to a pure Si, the boran settles one of Si atom's position. These three Boran atoms form a covalent bond with three 'Si' atoms, one bond is left over with the deficiency of an electron. Nearer the valence band acceptor level is formed



When temp is raised (T>0K) the electron from the valence band try to accupi the acceptor. As a result, holes becomes majority carriers and electron become minority carriers.

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$F = (\Delta n)$
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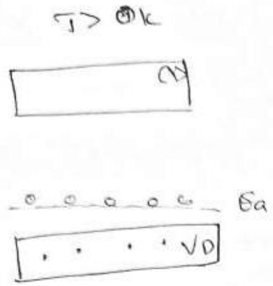
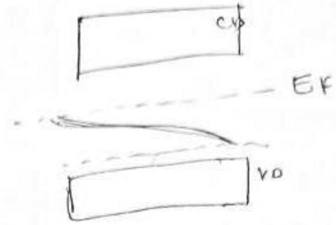
$T > 0K$





Carrier concentration in extrinsic Semiconductor (charge Densities in n & p type semiconductors),

The number of charge carriers present per unit volume of a semiconductor materials is called carrier concentration

The material will be electrically nutrel if,

$$n + N_A^- = p + N_D^+$$

The total negative charge due to conduction electrons and acceptor ions is equal to holes and donar ions in unit volume of material - Charge neutrality equation

In n-type material, there are no acceptor atoms.

So $N_A^- = 0$

$$n = p + N_D^+$$

$$n \approx N_D^+ \quad [p \ll N_D^+]$$

At room temp, the free electron concentration is almost equal to the donar atoms.

$$n_n \approx N_D$$

~~The~~

The hole Concentration in n-type

$$n_n P_n = n_i^2 \quad [\text{Law of mass action}]$$

$$P_n = \frac{n_i^2}{n_n}$$

$$= \frac{n_i^2}{N_D}$$

In p-type Semiconductor, there are no donor atoms

so $N_D^+ = 0$

$$n + N_A^- = P$$

$$N_A^- \approx P \quad [n \ll N_A]$$

At room temp $P_p \approx N_A$

The electron concentration in p-type material

is $n_n P_n = n_i^2$

$$n_n = \frac{n_i^2}{P_n}$$

$$= \frac{n_i^2}{N_A}$$

Law of Mass action

def : The product of majority and minority carrier concentration in an extrinsic semiconductor at a particular temp is equal to the square of intrinsic concentration at that temperature.

For intrinsic semiconductor

$$n = N_c \, e^{-(E_c - E_F)/K_B T}$$

$$p = N_v \, e^{-(E_F - E_v)/k_B T}$$

$$n_i = (N_c N_v)^{1/2} \, e^{-E_g/2k_B T}$$

The above relation shows that for any orbitary value of E_F, the product of n and p is a constant. — This is law of mass action

For n type $\quad n_n p_n = n_i^2$

p type $\quad n_p p_p = n_i^2$

The law suggests that the addition of impurities to an intrinsic semiconductor increases the conc of one type of carrier, which consequently becomes majority carrier and simultaneously decreases the conc of the other carrier, which as a result becomes the minority carrier.

Fermi energy level (Extrinsic)

n-type : when a pentavalent impurity is added to the crystal it creates an extra electrons without any new holes. This impurity introduces a new energy level into the energy band.

The density of electrons in conduction band is approximately equal to donor atoms density.

$$n \approx N_d$$

$$2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{3/2} e^{(E_F - E_C)/k_B T} = N_d$$

$$N_c \, e^{(E_F - E_C)/k_B T} = N_d$$

$$\frac{N_c}{N_d} = e^{(E_C - E_F)/k_B T}$$

$$\log \frac{N_c}{N_d} = \frac{(E_C - E_F)}{k_B T}$$

$$E_C - E_F = k_B T \log \frac{N_c}{N_d}$$

$$\boxed{E_F = E_C - k_B T \log \frac{N_c}{N_d}}$$

In n-type semiconductor, fermilevel lies just below the conduction band.

P-type when trivalent Impurity is added to the semiconductor, the concentration of electrons in the conduction band

The density of holes in the valency band is approximately equal to a acceptor atoms density

$$P \approx N_a$$

$$2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{3/2} e^{\frac{(E_V - E_F)}{k_B T}} = N_a$$

$$\frac{N_V}{N_a} = e^{(E_F - E_V)/k_B T}$$

$$\log \frac{N_V}{N_a} = (E_F - E_V)/k_B T$$

$$(E_F - E_V) = k_B T \log \frac{N_V}{N_a}$$

$$\boxed{E_F = E_V + k_B T \log \frac{N_V}{N_a}}$$

In p-type semiconductor fermi level lies just above the valence band.

Effects of temp on E_F

when temperature increases, the n-type and p-type semiconductor changes to intrinsic ~~semico~~ semiconductor.

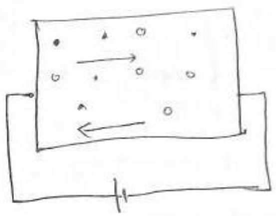
Dri
Dri
te
P

Drift & Diffusion [Conductivity Mechanism]

Drift when we give an external electric field, the charge carriers are force to move in a perticular direction constituting electric current. This phenomena is known as the drift.

V_d is the drift velocity.

Let 'n' is the electrons



Current density $J = neV_d$

$$\sigma = J/E = \frac{neV_d}{E}$$

$$\boxed{V_d = \mu_n E}$$

$$\sigma = \frac{ne\mu_n E}{E}$$

$$= ne\mu_n$$

Current density due to electrons $J_n = ne\mu_n E$

" " " holes $J_p = pe\mu_p E$

Total Current density $J = J_n + J_p$

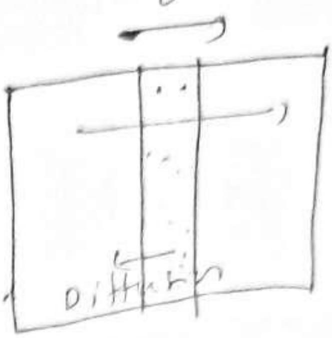
$$= ne\mu_n E + pe\mu_p E$$

$$= eE(n\mu_n + p\mu_p)$$

Conductivity due to drift

$$\boxed{\sigma = e(n\mu_n + p\mu_p)}$$

Diffusion



Due to non-uniform carrier concentration in a semiconductor, the carriers move from high conc to low conc. This process is known as diffusion of charge carriers.

Let Δn be the excess electron concentration

According Fick's law

The rate of diffusion of electrons $\propto -\frac{\partial}{\partial x}(\Delta n)$

$$= -D_n \frac{\partial}{\partial x}(\Delta n)$$

where D_n is the diffusion coefficient of electron

current density $J_n = -e\left[-D_n \frac{\partial}{\partial x}(\Delta n)\right]$

$$= eD_n \frac{\partial}{\partial x}(\Delta n)$$

Current density due to holes $J_p = e\left[-D_p \frac{\partial}{\partial x}(\Delta p)\right]$

$$= -eD_p \frac{\partial}{\partial x}(\Delta p)$$

Total current density due to diffusion

$$J = J_n + J_p$$

$$= eD_n \frac{\partial}{\partial x}(\Delta n) - eD_p \frac{\partial}{\partial x}(\Delta p)$$

current density due to driftfusion

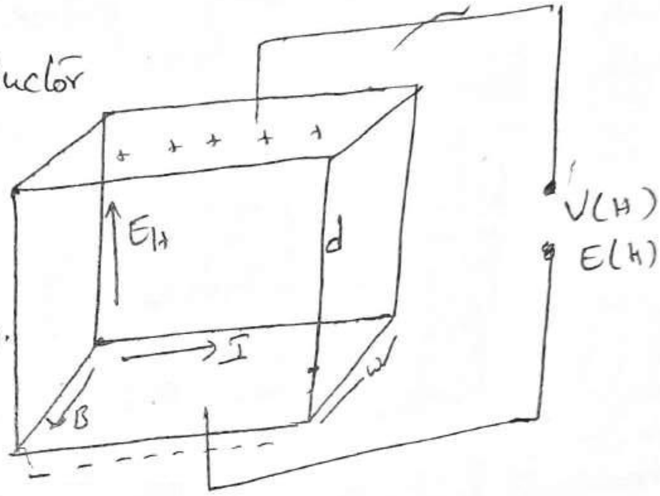
$$J_n = J_n(\text{drift}) + J_n(\text{diffusion})$$

$$J_n = ne\mu_n E + eD_n \frac{\partial}{\partial x}(\Delta n)$$

$$J_p = pe\mu_p E - eD_p \frac{\partial}{\partial x}(\Delta p)$$

Hall effect Imp

def : When a current carrying semiconductor is subjected to a transverse magnetic field, then a potential Difference is developed in a direction perpendicular to both current and applied magnetic field.



Consider a semiconductor slab of thickness 'd' and width 'w'. Current is flowing along X-direction. Magnetic field along Y-direction. The charge carriers inside the semiconductor experiences a force due to magnetic field, the electrons will be move to bottom of the semiconductor and the (+)ve charge on upper surface. Thus the potential difference and electric field developed along z-direction.

Let E_H be the Hall electric field

The force on electron due to $E_H = eE_H$

The force due to magnetic field $= Bev$

At Steady ~~stay~~ state $eE_H = Bev$

$$E_H = BV$$

V_H is Hall voltage, $E_H = \frac{V_H}{d}$

App

$$\frac{V_H}{d} = Bv$$

$$V_H = B(v)d$$

current density $J = nev$

$$\Rightarrow v = \frac{J}{ne}$$

$$V_H = BVd$$

$$= B\frac{J}{ne}d$$

$$V_H = B[v]d$$

$$\Rightarrow \frac{B[J]d}{ne}$$

$$V_H = \frac{BId}{Ane} \quad [\because J = I/A]$$

$$= \frac{BI\cancel{d}}{\cancel{d}wne} \quad [\because A = dw]$$

$$\boxed{V_H = \frac{BI}{new}}$$

Hall coefficient $R_H = \frac{1}{ne}$

$$\therefore V_H = R_H \frac{BI}{w}$$

$$\boxed{R_H = \frac{V_H w}{BI}}$$

The Conductivity in a semiconductor due to electrons

$\sigma = ne\mu$

$\mu = \sigma/ne = R_H \sigma$

Applications:

1. Knowing R_H and σ we know μ
2. Determine sign of R_H, we can say that n type when (-)ve sign and p-type when (+)ve sign.

~~Unit~~

Direct and Indirect bandgap Semiconductors.

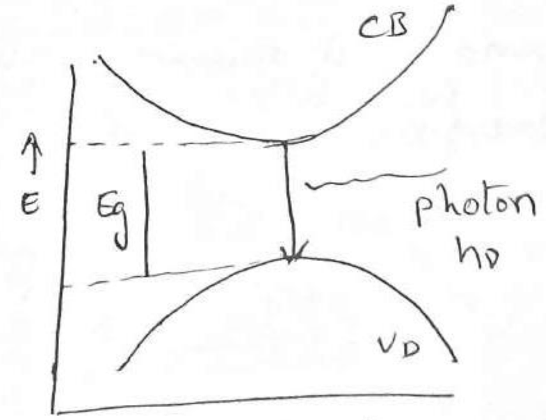
Based on the structure of energy bands, semiconductors are classified into

(i) Direct bandgap Semiconductors
(2) Indirect bandgap Semiconductors

1). Direct bandgap Semiconductors:

The electrons and holes present in a semiconductor possess energies. They possess K.E and momentum. we plotted a graph between Energy (E) verses momentum (or) wave vector.

The energy gap of the semiconductor is equal to the energy difference between minimum energy of conduction band and maximum energy of the valency band.

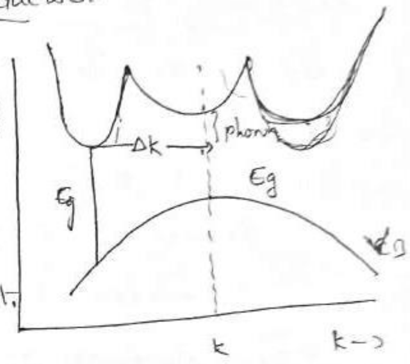


Can be determind.

If the maximum energy of valence band is exactly below the maximum energy of conduction band and have the same k value. The electron transition between these bands causes emission (or absorption of a photon.

Eg: GaAs

Indirect bandgap semiconductor:



As shown fig, the k value corresponds to the maximum energy of valence band and the minimum energy of conduction band are different. And also between these k values, there exists large probability of transition. When transition takes place between the minimum of conduction band and maximum valence band, the difference in energy is generated in the form of phonons is equal to Δk.

$$E_g = h\nu + E_{ph}$$

Eg: Ge, Si.

• Eienstein's Equation:

Einstein Showed the direct relation between the mobility (μ) and diffusion coefficient (D) of the Semiconductor

In equilibrium, the drift & diffusion currents due to excess concentration are equal. So, for electrons

$$(\Delta n) e \mu_n E = D_n e \frac{\partial}{\partial n}(\Delta n)$$

The force on excess electrons (Δn) to restore equilibrium is given by $F = (\Delta n) e E$

$$= \frac{D_n}{\mu_n} e \frac{\partial}{\partial x}(\Delta n) \quad \text{—(1)}$$

At temp TK, the force on excess electrons to maintain equilibrium depends on thermal energy of excess electrons $k_B T$ times the Concentration gradient $\frac{\partial}{\partial x}(\Delta n)$

$$F = k_B T \frac{\partial}{\partial n}(\Delta n) \quad \text{—(2)}$$

From (1) and (2)

$$\frac{D_n}{\mu_n} e \frac{\partial}{\partial n}(\Delta n) = k_B T \frac{\partial}{\partial n}(\Delta n)$$

$$\frac{D_n}{\mu_n} = \frac{k_B T}{e} \quad \text{—(3)}$$

for holes

$$\frac{D_p}{\mu_p} = \frac{k_B T}{e} \quad \text{—(4)}$$

from (3) and (4)

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p}$$

$$\boxed{\frac{D_n}{D_p} = \frac{\mu_n}{\mu_p}}$$

using above Eqn the diffusion coefficient of electrons and holes can be determined.