Chapter 3 Semi conductors

Introduction

Electrical conductivity of a semi-conductor:

In metals only the electrons participate in the conduction phenomenon where as in semiconductors both electrons and holes are responsible for conduction phenomenon. The electrons and holes more in opposite directions because of their opposite charges, they add conductivity to the semi-conductor.

In metals, the conductivity is given by expression $\boxed{\sigma=\mu n e}$ "μ"is mobility, 'n'is electron Concentration and 'e' is charge of electron.

But in semi-conductors,contribution of () andholes re taken into account

i.e.,. Conductivity $\boxed{\sigma=ne\mu+pe\mu_p}$

Where,

 N = Electrons' concentration in conduction band
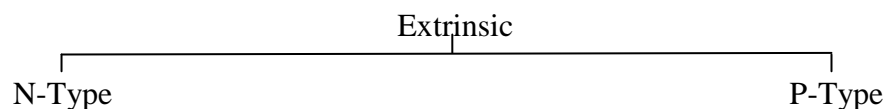
P =Holes concentration in valance bond

μ_n = Mobility of electron

μ_P = mobility of holes

 e = effective charge

Semi-conductors are of two types:

1. Intrinsic and 2) Extrinsic

Extrinsic

N-Type   P-Type

Intrinsic Semi conductors:

A semi conductor in which holes in the valance band and electrons in the conductions band are solely created by thermal excitations is called intrinsic semiconductors i.e.,.

A pure semi-conductor is considered as intrinsic semi conductor

The no. of electrons moving into the conduction band is equal to the no of holes created in the valence band

The Fermi Level lies exactly in the middle of forbidden energy gap.

The concentration of electrons and holes increases rapidly with temperature.

Intrinsic semi-conductors are not of practical use in view of their poor conductivity.

Carrier concentration in intrinsic semi-conductors

In the Conduction band, the level density D(E) at a energy E is given by the Expression.

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

The probability of an energy level filled with electrons is given by Fermi-Dirac function

$$F(E) = \frac{1}{1+\exp(\frac{E-EF}{KT})}$$

The no of E's 'n" filing into energy level between the energies E and E+dE is

$$\boxed{n-D(E)F(E)dE}$$

$$n= \frac{4\pi}{h^3}(2me)^{3/2} E^{1/2} \frac{1}{1+\exp(\frac{E-EF}{KT})} dE$$

In the Above expression, mass of the e" 'm" is replaced with effective mass me and factor '2' for the two possible spins of the electrons.

The number of electrons in the conduction band is obtained by making integration between the limits Ec to ∞.Since minimum energy in the conduction band is Ec and at the bottom of the conduction band we write E-Ec for E

$$n= \frac{4\pi}{h^3}(2me)^{3/2}\int$$

For all possible temperatures E-Ef >>>> KT

Hence $F(E) = \exp - (\frac{(E-Ef)}{KT}) = \exp(\frac{EF-E}{KT})$

Equation 1 becomes

$$n= \frac{4\pi}{h^3}(2me^v)^{3/2}\int (E-Ec)^{1/2}\exp(\frac{EF-E}{KT})dE$$

$$n= \frac{4\pi}{h^3}(2me^v)^{3/2} \exp(E_F/KT)\int (E-Ec)^{1/2}\exp(\frac{-E}{KT})dE$$

To solve this Integral Part

E-Ec =x

E=Ec+x

dE=dX

$$n= \frac{4\pi}{h^3}(2me^v)^{3/2} \exp(E_F/KT) \int_{\chi} \tfrac{1}{2}\exp -(\frac{Ec+x}{KT})dx$$

$$n = \frac{4\pi}{h^3} (2me^v)^{3}/^2 \exp\left(\frac{EF-Ec}{KT}\right) \int_\chi {}^{1\!/_2}\exp-\left(\frac{-x}{KT}\right)dx$$

Using gamma function, it can be shown that

$$\int_\chi {}^{1\!/_2}\exp-\left(\frac{-x}{KT}\right)dxd_\chi = (KT)^3/2\, \frac{\pi}{2}^{1\!/_2}$$

Hence ,n= n= $\frac{4\pi}{h^3} (2me^v)^{3}/^2 \exp\left(\frac{EF-Ec}{KT}\right) (KT)^3/2\, \frac{\pi}{2}^{1\!/_2}$

No of electrons per unit volume is given by

$$n = 2\left(\frac{2\pi me^v KT}{h^2}\right) \exp\left(\frac{Ef-Ec}{KT}\right)$$

Theexpression for no of holes in the valance bond is given by the expression

$$P = 2\left(\frac{2\pi mp^v KT}{h^2}\right) \exp\left(\frac{Ev-Ef}{KT}\right)$$

In Intrinsic semi conductor n=p then the Intrinsic carrier concentration is n=p=n;

$$ni^2 = 4\left(\frac{2\pi KT}{h^2}\right)^{3} (m_e^v\, m_{p^v})^{3/2} \exp\left(\frac{Ev-Ec}{KT}\right)$$

$$ni^2 = 4\left(\frac{2\pi KT}{h^2}\right)^{3} (m_e^v\, m_{p^v})^{3/2} \exp\left(\frac{-Eg}{KT}\right)$$

Here Ec-Ev=Eg (forbidden energy gap)

Hence $ni = 2\left(\frac{2\pi KT}{h^2}\right)^{3/2} (m_e^v\, m_{p^v})^{3\!/_4} \exp\left(\frac{-Eg}{KT}\right)$

Fermi Level: In Intrinsic semi conductor n=p and assuming the effective mass of e and hole to be same, i.e.,. $Me^v = Mp^v$

$$\exp\left(\frac{Ef-Ec}{KT}\right) = \exp\left(\frac{Ev-Ef}{KT}\right)$$

Ef-Ec=Ev-Ef

2Ef = Ev+Ec

$$E_f = \frac{Ev+Ec}{2}$$

Thus the Fermi level is located half way between the valance band and conduction band and its position is independent of the temperature.

Intrinsic semi conductor:

Impure semi conductors are called extrinsic semi-conductors .When pentavalent or trivalent impurities are added to Intrinsic (pure) semi-conductors, it becomes extrinsic semi-conductor. The phenomenon of adding impurities is called doping. The phenomenon of conductivity is increased by process of Doping.

N-Type semi – Conductors:

When pentavalent impurities like P. As, Sb is added to the intrinsic semi-conductors, resultant semi conductor is called N-Type semi-coductor.the concentration of free electrons is more when compared to concentration of holes carriers' concentration in N-type semi conductors:

In this type of semi conductor, there will be donor levels formed at an energy Ed

Nd represents no. of impurities per unit volume of semi conductor

At low temperature all donor levels are filled with electrons, with increase of temperature, more and more donor atoms gets ionized and the density of electrons in the conduction band increases

Density of electrons in the conduction band is given by

$$n = 2\left(\frac{2\pi me^v KT}{h^2}\right)^{3/2} \exp\left(\frac{Ef-Ec}{KT}\right) \rightarrow 1$$

The Fermi level (Ef) lies in between Ed & Ec

The density of empty donor levels is given by

$$Nd\ [\ 1-F(E_d)]\ \Xi\ N_d\ [\ 1-H\exp(\frac{Ed-Ec}{KT})$$

$$Nd\ [\ 1-F(E_d)]\ \Xi\ Nd\exp(\frac{Ed-Ec}{KT})$$

At low temperature, there are no excitations of the electrons from donor level to the conduction band. Hence, density of empty donors and the electron desity in conduction band should be same

i.e.,. $2\left(\frac{2\pi mp^v KT}{h^2}\right)^{3/2} \exp\left(\frac{Ef-Ec}{KT}\right) = N_d\exp\left(\frac{Ed-Ef}{KT}\right)$

Taking lon on both the sides& rearranging

$$\left(\frac{Ef-Ec}{KT}\right) - \left(\frac{Ed-Ef}{KT}\right) - \log Nd - \log 2\left(\frac{2\pi me^v KT}{h^2}\right)^{3/2}$$

$$Ef - Ec - Ed/KT = \log \left(\frac{Nd}{2\left(\frac{2\pi me^v KT}{h^2}\right)3/2}\right)$$

$$2Ef - (Ec+Ed)\; KT \log \left(\frac{Nd}{2\left(\frac{2\pi me^v KT}{h^2}\right)3/2}\right) \rightarrow 2$$

At absolute zero $Ef = \frac{Ec+Ed}{2}$

i.e.,. Fermi level lies exactly at the middle of donor lvel Ed and the bottom of the conduction band E

Substituting equation 2 in eqn. 1 & re-arranging,

$$N = (2^{Nd})\; \tfrac{1}{2} \left(\frac{2\pi me^v KT}{h^2}\right)^{3/4} \exp\left(\frac{Ed-Ec}{2KT}\right)$$

Hence the density of the electrons in the conduction band is proportional to the square root of the donor concentration

P-type semi conductors:

P-type semi-conductors are fabricated by addition of trivalent atoms like Al as impurity to the intrinsic semi-conductor

Hence, holes are majority charge carriers and free electrons are minority charge carriers.

Carrier concentration in P type semi-conductors

In this type of semi-conductor, there will be there will be acceptor levels formed at an enrgy Ea

Na represents no. of impurities per unit volume of semi-conductor.

At low temperatures, all the acceptor levels are empty

With increase of temperature, acceptor atoms gets integrated i.e.,. the electrons moves from valance band and occupy the vacant sites in the acceptor energy levels, there by leaving holes in the valence band

Density of holes in the valance band is given by

$$P = 2 \left(\frac{2\pi mp^v KT}{h^2}\right)^{3/2} \exp\left(\frac{Ev-Ef}{KT}\right)$$

Since Ef lies below the acceptor levels, the density of ionized acceptors is given by

$$N_a F (E_a) = N_a \exp\left(\frac{Ef-Ea}{KT}\right)$$

Hence, density of holes in the valance band is equal to the density of ionized acceptors.

$$2\left(\frac{2\pi mp^{v}KT}{h^2}\right)^{3/2} \exp\left(\frac{Ev-Ef}{KT}\right) = N_a\exp\left(\frac{Ef-Ea}{KT}\right)$$

Ie.,. $2\dfrac{Ev-Ef-Ef+Ea}{KT} = \dfrac{Na}{2\left(\frac{2\pi mp^{v}KT}{h^2}\right)3/2}$

Taking log, $\dfrac{Ev+Ea-2Ef}{KT} = \log \dfrac{Na}{2\left(\frac{2\pi mp^{v}KT}{h^2}\right)3/2} \rightarrow 2$

At 0° K, $E_f = \dfrac{Ev+Ea}{2}$

i.e.,. at 0 o K, Fermi level lies exactly at the middle of the acceptor level and in the top of the valance bond

Sub. eqn. 2 in eqn. 1 & re-arranging

$P = (2Na)\;\tfrac{1}{2}\left(\dfrac{2\pi mp*KT}{h^2}\right)^{3/4} \exp\left(\dfrac{Ev-Ea}{KT}\right)$

Thus the density of the holes in the valance band is proportional to the square root of the acceptor concentration

Equation of Continuity:

In the equilibrium, all the processes are balanced and there will not be any external force.

The Fermi level is constant throughout the volume of the solid.

Under equilibrium, there exists a steady state, in which the condition of the system does not change

In non-equilibrium conditions, the Fermi level will be varying through the volume of the solid. The Fermi level will not be exactly in the middle of the forbidden band. Hence, the electrons from the valance band can easily pass to the conduction band.

So the generation of charges will not be equal to the rate of recombination and there will be a net change in the concentration of excess electrons or holes.

The Condition will be changing with time.

The divergence of current density gives time rate of change of concentration of electrons or holes.

Number of electrons or holes generated =divergence of current density.

When electron concentration causes current

$\dfrac{djn}{dx} = \dfrac{-dn}{dt}$

This is one dimensional equation of continuity which is written as

$\Delta J + \frac{d\rho}{dt} = 0$

J = Current density

ρ= charge density =Ne for electrons, 'n' is concentration of electrons.

$\frac{d\rho}{dt} = \frac{1}{e} \Delta Jn$

For electrons

$\frac{1}{e} \Delta Jn - \frac{dn}{dt} = 0$

For holes

$\frac{1}{e} \Delta Jp - \frac{dp}{dt} = 0$

Under equilibrium conditions the rate of generation of charges will be equal to the rate of recombination. But for non-equilibrium conditions, there is a net rate of change of generation

For Electrons $\frac{dn}{dt} = Gn-Rn + \frac{1}{e} \Delta Jn$

For holes $\quad \frac{dp}{dt} = Gp-Rp + \frac{1}{e} \Delta Jp$

Gn, Gp =rate of generation of electrons/holes

Rn, Rp = rate of recombination of electrons/holes

Recombination rate Rn of electrons is

$Rn = \frac{n-no}{Tn}$

n_o=Equilibrium concentration of electrons

n=Concentration of electrons.

Tn =Electron life time

$\frac{dn}{dt} = Gn- \frac{n-no}{Tn} + \frac{1}{e} \Delta Jn$

Electron current density Jn is sum of diffusion and drift currents due to electron is given by

$Jn = n\mu_n eE + D_ne(\frac{dn}{dx})$

Here the first term gives drift current of electrons with mobility Mu() due to application of the electric field

Second term gives diffusion current due to the concentration gradient of electrons, d^2

$$\frac{dn}{dt} = Gn - \frac{n-no}{Tn} + n\mu_n\frac{dE}{dx} + D_n e \frac{d^2 n}{dx^2}$$

For holes

$$\frac{dp}{dt} = Gp - \frac{p-po}{Tp} + p\mu_p\frac{dE}{dx} + D_p e \frac{d^2 p}{dx^2}$$

Continuity equation is used to calculate the excess density of electrons and holes in time and space. This is the basic equation in describing the semi-conductors

Hall-Effect

When a material carrying current is subjected to a magnetic field I a direction perpendicular to direction of current, an electric field is developed across the material in a direction perpendicular to both the direction of magnetic field and current direction. "this phenomenon is called "Hall-effect"

Explanation: Consider a semi-conductor, and a current passes along the X-axis and a magnetic field Bz is applied along the Z-direction, a field Ey is called the Hall field which is developed in the Y-direction

In P-tpe semi-conductor, holes move with the velocity "V" in the "+"ve X-direction. As they move across the semi conductor the holes experience a transverse force B() ev due to the magnetic field. This force drives the holes down on to face1, as shown in the figure. As a result, the lower face becomes +vely charged and –ve charge on the upper surface creating the hall field in the Y-direction.the Hall field exerts an upward force on holes equal to E().n the steady sate, two forces just balance and as a result, no further increase of + ve charge occurs on Face1.

If N type semi conductor, the majority charge carriers are electrons experiences a force in the downward direction and face1 gets – vely charged. As a result, Hall field will be in the Y – direction

Demonstration:

Consider a rectangular slab of n-type semi conductor carrying slab n-type semi conductor carrying a current in the + ve X- direction

If magnetic field "B' is acting in he X-direction shown in fig:

Under the influence of magnetic field, electrons experience a force Fl given by

$$\boxed{F_Ł = -Bev}$$

e = Charge of electron

V= Drift velocity

As a result of force FH acting on the electrons in the – ve Y – direction and electrons are tend to downwards.

As a consequence the lower face of the specimen gets – vely charged and upper surface is + vely charged

Hence a potential VH called the Hall Voltage present between the top and bottom faces of the specimen

The Hall field FH, exerts an upwrd force on the electrons is given by

$$F_H = -eE_H$$

The two opposing forces FL and FH establish an equilibrium under which

$$|F_L| = |F_H|$$

$$-Bev = -e\,E_H$$

$$E_H = BV$$

If 'd' is the thickness of th specimen

$$E_H = \frac{V_h}{d} \quad (\therefore E = \frac{V}{d})$$

$$V_H = E_H d$$

$$V_H = Bvd$$

If 'W' is the width of the specimen

$$J = \frac{I}{wd}$$

                                  $J = nev = PV$

N= electron concentration

P=charge density.

$$Pv = \frac{I}{wd}$$

$$V = \frac{I}{pwd}$$

$$\Rightarrow V_H = \frac{Bid}{pwd} = \frac{Bi}{pw}$$

$$\Rightarrow p = \frac{Bi}{V_h w}$$

Hall Coefficient : Hall field Eh, for a given material depends on the current density J and the applied magnetic field B

i.e. $E_H \ \alpha \ JB$

$E_H = R_H \ \alpha \ JB$

SINCE, $V_H = \frac{Bi}{pw}$, $E_H = \frac{Vh}{d}$

$\Rightarrow E_H = \frac{Bi}{pwd}$

$\Rightarrow J = \frac{i}{wd} , \frac{Bi}{pwd} = R_H = (\frac{i}{wd}) \ \mathbf{B}$

i.e $R_H = \frac{I}{J}$

Applications :

1) Determination of the type of Semi-conductors:

The Hall coefficient Rh is _ve for an n-type semiconductor and +ve for p-type semiconductor. Thus the sign of Hall coefficient can be used to determine whether a given Semi-conductor is n or p-type.

2) Calculation of carrier concentration :

$$R_H = \frac{I}{J} = \frac{I}{ne} \ \text{(for } e^- \text{ s)}$$

$$R_H = \frac{I}{pe} \ \text{(for holes)}$$

$$\Rightarrow n = \frac{I}{eR_H}$$

$$\Rightarrow p = \frac{I}{eR_H}$$

3) Determination of Mobility: It the conduction is due to one type carriers, ex: Es

$\sigma = ne\mu n$

$$\mu n = \frac{\sigma}{ne} = \sigma R_H$$
$$\mu = \sigma |R_H|$$

4) <u>Measurement of Magnetic Flux Density:</u> Hall Voltage is proportional to the magnetic flux density B for a given current I. so, Hall Effect can be used as the basis for the design of a magnetic flux density metal.