Unit - V

Semiconductors and Semiconductor devices

Semiconductors:

Fermi Level in Intrinsic and Extrinsic Semiconductors. Carrier concentration of Intrinsic and Extrinsic Semiconductor (qualitative). Direct & Indirect Band Gap Semiconductors, Hall Effect in semiconductors.

Introduction

Semiconductors are materials whose electronic properties are intermediate between those of **Metals and Insulators.**

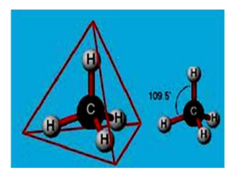
They have conductivities in the range of 10^{-4} to 10^{+4} Siemens per meter (S/m).

The interesting feature about semiconductors is that they are **bipolar** and current is transported by **two** charge carriers of **opposite** sign.

These intermediate properties are determined by

1. ***Crystal Structure bonding Characteristics.***
2. ***Electronic Energy bands.***

- **Silicon** and **Germanium** are elemental semiconductors and they have **four valence electrons** which are distributed among the outermost **S and p** orbital's.
- These outer most **S and p** orbital's of Semiconductors involved in **Sp^3 hybridization.**
- These **Sp^3 orbital's** form **four covalent** bonds of equal angular separation leading to a **tetrahedral** arrangement of atoms in space results **tetrahedron** shape, resulting crystal structure is known as **Diamond cubic** crystal structure.

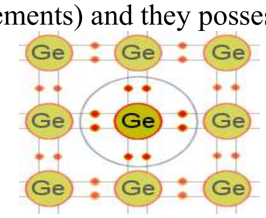


Semiconductors are mainly two types
1. Intrinsic (Pure) Semiconductors
2. Extrinsic (Impure) Semiconductors

Intrinsic semiconductors

A Semiconductor which does not have any kind of impurities behaves as an Insulator at 0k and behaves as a Conductor at higher temperature is known as Intrinsic Semiconductor or Pure Semiconductor.

Ex: Germanium & **Silicon** (4^{th} group elements) and they possess diamond cubic crystalline structure.



Extrinsic semiconductors:

A semiconductor which is in an impure form (with doping) is called an extrinsic semiconductor.

Doping:

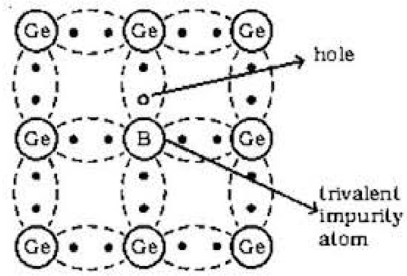
Adding a suitable impurity to pure semiconductor is known as doping.

Extrinsic semiconductors are further divided into two types

- P- type semiconductors
- N-type semiconductors

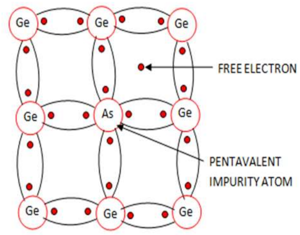
P- type semiconductors:

Adding the trivalent impurity to pure semiconductor (like Al, Ga, In etc) then it becomes P-type semiconductor.

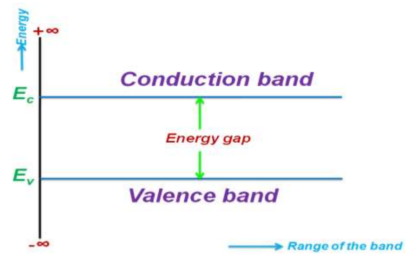


N- type semiconductors:

Adding the penta-valent impurity to pure semiconductor (like P, As, Sb etc) then it becomes N-type semiconductor.



Note: Extrinsic semiconductors are more useful than intrinsic semiconductors.



Valence band:

The highest range of electron energies where electrons are normally present at absolute zero is called valence band.

Conduction band:

The range of electron energy, higher than that of the valence band, sufficient to make the electrons free to accelerate under the influence of an applied electric field is known as conduction band.

Electron – Hole pair generation

When a suitable form of Energy is supplied to Semiconductor then electrons takes transition from Valence band to Conduction band.

Hence a free electron in Conduction band and simultaneously free hole in Valence band is formed.

This phenomenon is known as **Electron-Hole pair generation**.

Recombination:

The process of combination of a conduction electron with a valence hole is known as recombination.

Note: During this process, some energy is released, which is equal to energy gap of a semiconductor.

Carrier lifetime:

The duration of time (or) the time elapses between the processes of electron–hole pair generation or recombination can be defined as carrier life time.

Note: In a pure semiconductor without structural defect the charge life time is 2000 µS – 3000 µS.

Carrier concentration:

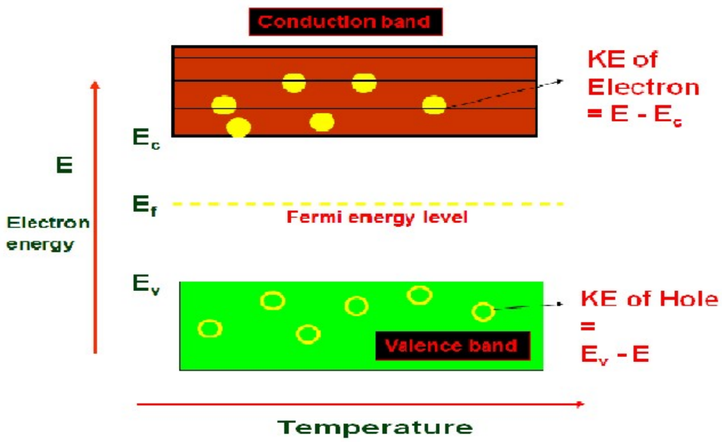
The number of charge carriers per unit volume is defined as carrier concentration.

Units: number of electrons/m^3

Note: In Intrinsic Semiconductor the Number of Conduction electrons will be equal to the Number of Vacant sites or holes in the valence band.

Carrier concentration and Fermi energy level in Intrinsic Semiconductor:

The number of electrons and holes per unit volume is defined as carrier concentration of intrinsic semiconductor.
The number of Conduction electrons will be equal to the number of Vacant sites or holes in the valence band.



Concentration (density) of electrons in the conduction band of intrinsic semiconductor is

$$n = 2(\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}} exp(\frac{E_F - E_C}{kT})$$

Concentration (density) of holes in the valence band of intrinsic semiconductor is

$$p = 2(\frac{2\pi m_h^* kT}{h^2})^{\frac{3}{2}} exp(\frac{E_v - E_F}{kT})$$

Intrinsic Carrier Concentration

In intrinsic Semiconductors **n = p,**

Hence **n = p = n$_i$** is called intrinsic Carrier Concentration

We know that,

$$n_i^2 = np$$

$$n_i = \sqrt{np}$$

$$n_i = \sqrt{\{2\ (\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}} \exp(\frac{E_F - E_c}{kT})\}\{2(\frac{2\pi m_h^* kT}{h^2})^{\frac{3}{2}} \exp(\frac{E_v - E_F}{kT})\}}$$

$$n_i = 2(\frac{2\pi kT}{h^2})^{\frac{3}{2}} (m_e^* m_h^*)^{\frac{3}{4}} \exp(\frac{E_v - E_c}{2kT})$$

$$n_i = 2(\frac{2\pi kT}{h^2})^{\frac{3}{2}} (m_e^* m_h^*)^{\frac{3}{4}} \exp(\frac{-E_g}{2kT})$$

Fermi level in intrinsic Semiconductors:

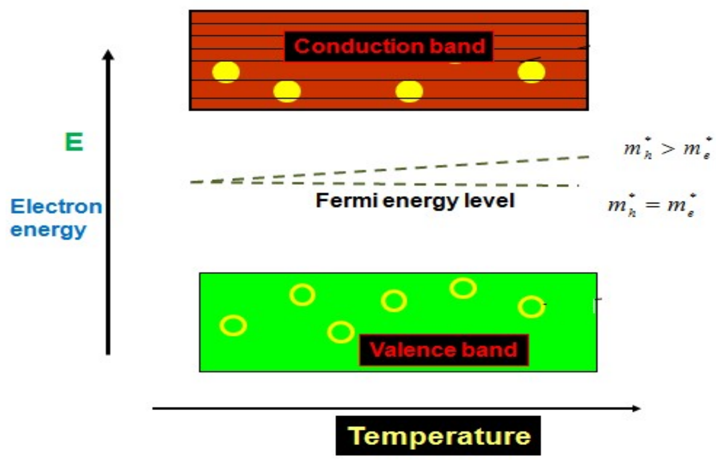
In intrinsic semiconductors n = p

$$2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_F - E_c}{kT}\right) = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_v - E_F}{kT}\right)$$

$$\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_F - E_c}{kT}\right) = \left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_v - E_F}{kT}\right)$$

$$\exp\left(\frac{2E_F}{kT}\right) = \left(\frac{m_h^*}{m_e^*}\right)^{\frac{3}{2}} \exp\left(\frac{E_v + E_c}{kT}\right)$$

taking logarithms on both sides



$$\frac{2E_F}{kT} = \frac{3}{2}\log\left(\frac{m_h^*}{m_e^*}\right) + \left(\frac{E_v + E_c}{kT}\right)$$

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

In intrinsic semiconduc tor we know that $m_e^* = m_h^*$

$$E_F = \left(\frac{E_v + E_c}{2}\right)$$

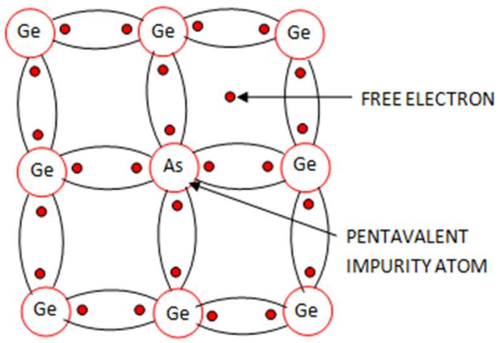
Thus the Fermi energy level **E$_F$** is located in the middle of the forbidden band.

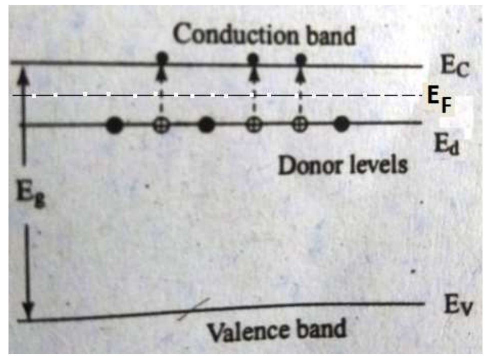
Since **m$_h$*** is greater than **m$_e$***, **E$_F$** is just above the middle and rise slightly with increasing temperature.

<u>Carrier Concentration and Fermi energy level in n-type Semiconductor</u>

The Intrinsic Semiconductors doped with pentavalent impurities are called N-type Semiconductors.

- The pentavalent impurities are called **donor impurities.**
- The energy level of fifth electron is called **donor** level.





Density of electrons in Conduction band is given by

$$n = 2(\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}} \exp(\frac{E_F - E_c}{kT}) \text{ ----(1)}$$

The density of ionized donors is given by

$$N_d\{1 - F(E_d)\} = N_d \, exp(\frac{E_d - E_F}{kT}) \text{ ----(2)}$$

At very low temperatures, the Number of electrons in the conduction band must be equal to the Number of ionized donors.
Therefore, from equation (1) and (2), we get a Fermi energy

$$\boxed{\therefore \; E_F = \frac{kT}{2} \log \frac{N_d}{2(\frac{2\pi m_e^* kT}{h^2})^{\frac{3}{2}}} + \frac{(E_c + E_d)}{2}} \text{ ----(3)}$$

At 0K, the Fermi energy

$$\boxed{E_F = \frac{E_c + E_d}{2}}$$

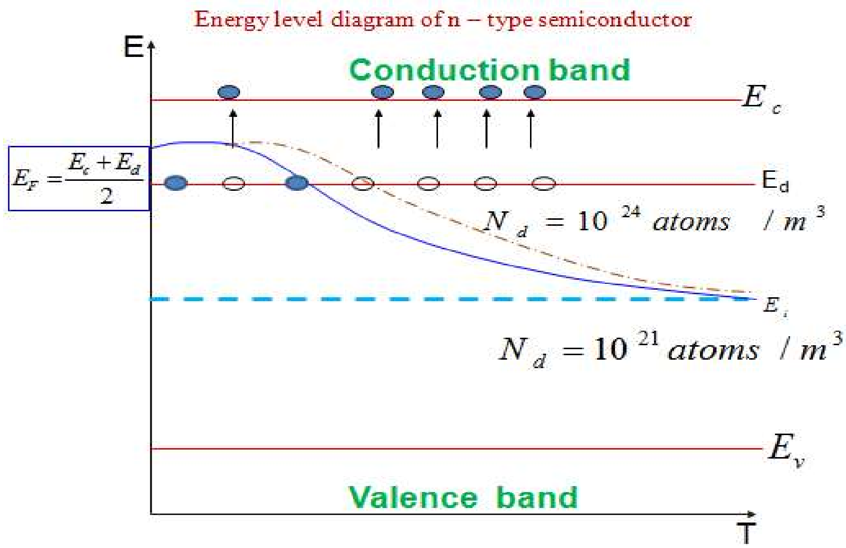
At 0k Fermi level lies exactly at the middle of the donor level and the bottom of the Conduction band
From equation (1) and (3), we get a concentration of n-type semiconductor is

$$n = (2N_d)^{\frac{1}{2}} (\frac{2\pi m_e^* kT}{\boldsymbol{h}^2})^{\frac{3}{4}} \boldsymbol{exp} \frac{(E_d - E_c)}{2kT}$$

Thus, we find that the density of electrons in the conduction band is **proportional** to the square root of the **donor concentration** at moderately low temperatures.

Variation of Fermi level with temperature (N-type semiconductor):

- With increase of temperature E_F increases slightly.
- As the temperature is increased more and more donor atoms are ionized.
- For a particular temperature all the donor atoms are ionized.
- Further increase in temperature results in generation of electron-hole pairs due to breaking of covalent bonds and the material tends to behave as intrinsic.
- At higher temperatures the Fermi level gradually moves towards the intrinsic Fermi level E_i.



At 0k Fermi level lies exactly at the middle of the donor level E_d and the bottom of the conduction band E_c as shown in figure.

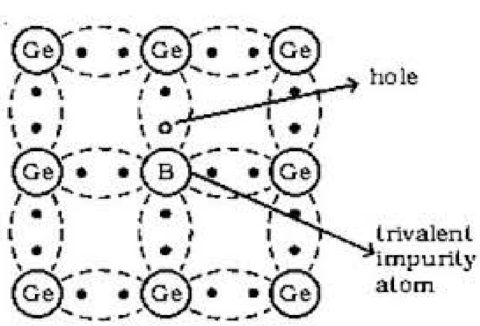
Carrier concentration and Fermi energy in p-type semiconductors:

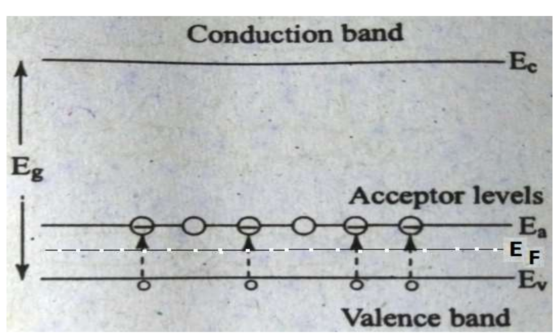
The Intrinsic Semiconductors doped with trivalent impurities are called P-type Semiconductors. The trivalent impurities are called acceptor impurities.
The energy level of this impurity atom is called Acceptor level and this acceptor level lies just above the valence band.
Density of holes in Valence band is given by

$$p = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} exp\left(\frac{E_v - E_F}{kT}\right) \quad \text{----(1)}$$

The density of ionized acceptors is given by

$$N_a F(E_a) \approx N_a\, exp\left(\frac{E_F - E_a}{kT}\right) \quad \text{----(2)}$$





At very low temperatures, the density of holes in the valence band is equal to the density of ionized acceptors.

Therefore, from equation (1) and (2), we get a Fermi energy

$$E_F = \frac{E_v + E_a}{2} - \frac{kT}{2} log \frac{N_a}{2(\frac{2\pi m_h^* kT}{h^2})^{\frac{3}{2}}} ----(3)$$

$$at, .0k$$

$$E_F = \frac{E_v + E_a}{2}$$

i.e. at 0k , Fermi level lies exactly at the middle of the acceptor level and the top of the valence band.

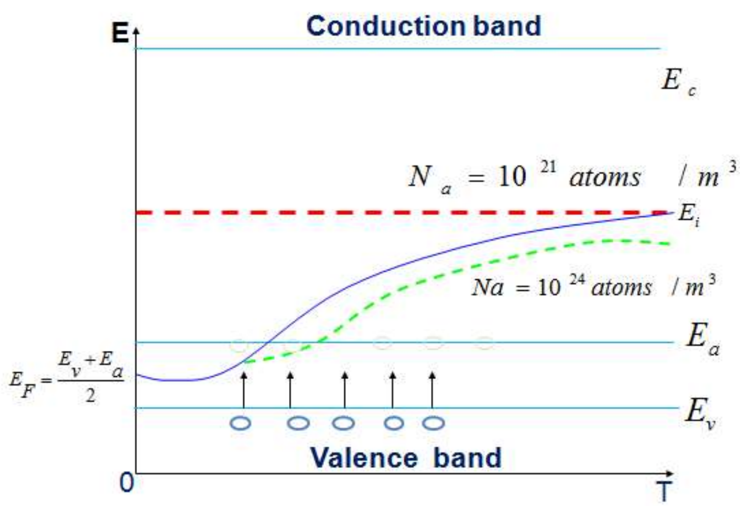
From equation (1) and (3), we get a concentration of p-type semiconductor

$$p = (2N_a)^{\frac{1}{2}} (\frac{2\pi m_h^* kT}{h^2})^{\frac{3}{4}} exp\{\frac{E_v - E_a}{2kT}\}$$

Thus, we find that the density of holes in the valence band is proportional to the square root of the acceptor concentration at moderately low temperatures.

<u>Variation of Fermi level with temperature (P-type semiconductor):</u>

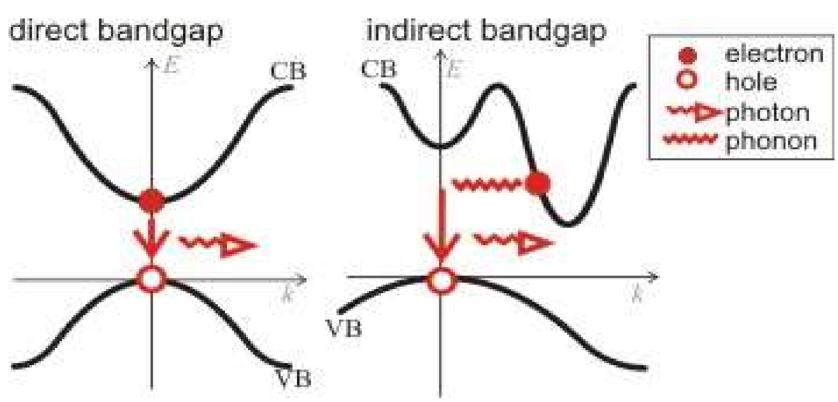
- With increase of temperature E_F increases slightly.
- As the temperature is increased more and more acceptor atoms are ionized.
- For a particular temperature all the acceptor atoms are ionized.
- Further increase in temperature results in generation of electron-hole pairs due to breaking of covalent bonds and the material tends to behave as intrinsic.
- At higher temperatures the Fermi level gradually moves towards the intrinsic Fermi level $\mathbf{E_i}$.



At 0k Fermi level lies exactly at the middle of the acceptor level E_a and the top of the valence band E_v as shown in figure.

Direct band gap and indirect band gap Semiconductors

Direct Band Gap	In direct band Gap
1. In the band diagram the minimum energy of conduction band and maximum energy of valance band are having the same value of wave vector k	1. In the band diagram the minimum energy of conduction band and maximum energy of valance band are having different wave vector k
2. In this an electron from the conduction band can recombine with a hole the valance band directly emitting a light photon of energy hv.	2. In this an electron can recombine with a hole in the valance band indirectly through traps. But there is emission of phonon leading to the rise of temperature of material.
3. Life time (recombination time) is very less.	3. Life time is more.
4. Due to emission of light photon during recombination of charge carriers, these are used to fabricate LED's and LASER diodes.	4. Due to longer life time of charge carriers, these are used to amplify the signals as in the case of diodes and transistors.
5. These are mostly from the compound semiconductors.	5. These are mostly elemental semiconductors
6. GaAs = 1.42 eV, InP= 1.35 eV	6. Ge= 0.7 eV, and Si = 1.12 eV



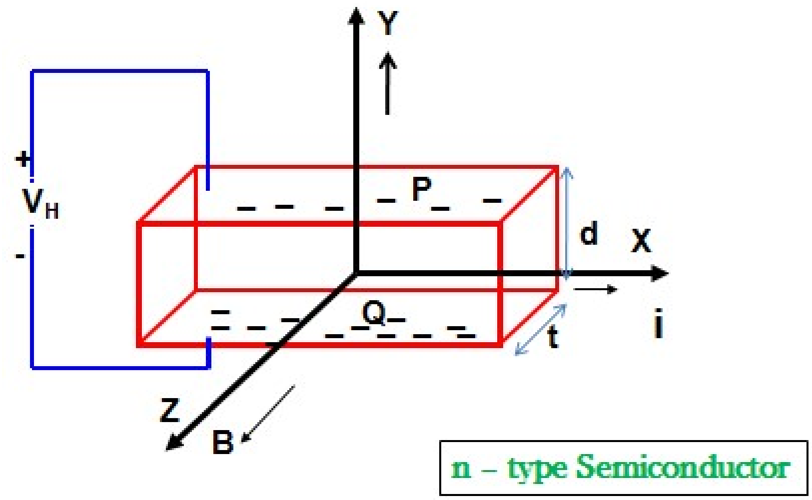
Hall Effect:

When a Magnetic field is applied perpendicular to a current Carrying Conductor or Semiconductor, Voltage is developed across the specimen in a direction perpendicular to both the current and the Magnetic field.

This phenomenon is called the Hall Effect and voltage so developed is called the Hall voltage.

Let us consider a thin rectangular slab carrying Current in the X-direction. If we place it in a Magnetic field B which is in the Z-direction.

Potential difference Vpq will develop between the faces p and q which are perpendicular to the Y-direction.



Magnetic deflecting force $F = q(v_d \times B)$

Hall eclectic deflecting force $F = qE_H$

When equilibrium is reached, the Magnetic deflecting force on the charge carriers are balanced by the electric forces due to electric Field.

$$q(v_d \times B) = qE_H$$

$$E_H = (v_d \times B)$$

Where v_d is drift velocity

The relation between current density and drift velocity is

$$v_d = \frac{J}{ne}$$

Where n is the number of charge carriers per unit volume.

$$E_H = (v_d \times B)$$

$$E_H = (\frac{J}{ne} \times B)$$

$$E_H = (\frac{1}{ne} J \times B)$$

$$E_H = R_H (J \times B)$$

$$R_H (Hall,.coefficient) = \frac{1}{ne} \Rightarrow \frac{E_H}{J \times B}$$

If V_H be the Hall Voltage in equilibrium, the Hall Electric field.

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

Where 'd' is the width of the slab.

$$R_H = \frac{E_H}{JB}$$

$$R_H = \frac{1}{JB} \times \frac{V_H}{d}$$

$$V_H = R_H JBd$$

If A is cross sectional area current density

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

$$V_H = R_H (\frac{I}{A}) Bd$$

If t is the thickness of the sample,

$$R_H = \frac{V_H t}{IB} (\because A = d \times t)$$

- Since all the three quantities E_H , J and B are Measurable, the Hall coefficient R_H and hence the carrier density can be find out.
- Generally for N-type material since the Hall field is developed in negative direction compared to the field developed for a P-type material, negative sign is used while denoting hall coefficient R_H.($R_H = -1/ne$)

Applications of Hall effect:

1. Determination of type of semiconductor:

For an n–type semiconductor the Hall coefficient is negative whereas for a p-type semiconductor it is positive.

2. Calculation of carrier concentration: $n = 1/eR_H$

3. Determination of mobility: $\mu=(\sigma/ne)$

4. Measurement of magnetic flux density: $B = (V_H t / IR_H)$

Problems:

1). The following data are given for intrinsic germanium at 300K.

$n_i=2.4X10^{19}/m^3$, $\mu_e=0.39\ m^2V^{-1}s^{-1}$ and $\mu_h=0.19\ m^2V^{-1}s^{-1}$. Calculate the resistivity of the sample.

(Hint: $\sigma_i=n_ie(\mu_e+\mu_h)$ and $\rho=1/\sigma$, Ans: σ=2. 227 $\Omega^{-1}m^{-1}$ ρ =0.449Ωm)

2). A silicon plate of thickness 1mm, breadth 10mm and length 100mm is placed in a magnetic field of 0.5wb/m^2 acting perpendicular to its thickness. If 10^{-2}A current flows along its length, calculate the Hall voltage developed if the Hall coefficient is $3.66X10^{-4}$ m^3/coulomb. (**Hint: $R_H=V_Ht/IB \rightarrow V_H=R_HIB/t$ Ans: V_H=1.83mV**)

3). For a semiconductor, the Hall coefficient is $-6.85X10^{-5}m^3$/coulomb, and electrical conductivity is $250m^{-1}\Omega^{-1}$. Calculate the density and mobility of charge carriers.

(Hint: $R_H = -1/ne$, $n = -1/ R_H e$ & $\sigma=ne\mu \rightarrow \mu= \sigma/ne$ Ans: n=$9.124X10^{22}$ /m^3 & $\mu=17.125X10^{-3}m^2V^{-1}s^{-1}$)

4). The R_H of a specimen is $3.66X10^{-4}m^3C^{-1}$. Its resistivity is $8.93X10^{-3}\Omega$m. Find μ and n.

(Hint: $R_H = 1/ne$, $n =1/ R_H e$ & $\sigma=ne\mu \rightarrow \mu= \sigma/ne =R_H/\rho$ Ans: n=1.708X1022 /m^3 & $\mu=0.041m^2V^{-1}s^{-1}$)

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