

3. Semiconductor and transport physics

3.1. Introduction

Semiconducting material has electrical conductivity between a good conductor and a good insulator. It is simply called semiconductor. It is a special class of material which is very small in size and sensitive to heat, light and electricity.

Semiconducting materials behave as insulators at low temperature and as conductors at high temperature. Moreover, those materials have two types of charge carriers i.e., electrons and holes.

Germanium and silicon are two important elemental semiconductor. They are used in LEDs and Laser diodes. The study of semiconducting materials is essential for engineers due to their wide applications in semiconductor devices in engineering and technology.

The invention of semiconductors opened a new branch of technology called solid state electronics. It leads to the development of ICs, microprocessors computers and supercomputers. In short, semiconductors play a vital role in almost all advanced electronic devices.

3.2. Definition

Based on electrical resistance

Semiconductor has electrical resistance which is lesser than an insulator but more than that of a conductor. Its electrical conductivity is in the order of 10^{-4} to 0.5 ohm meter.

Based on energy band

A semiconductor has nearly an empty conduction band and almost filled valence band with a small energy gap (0.1eV)

Properties

- They have crystalline structure
- Bonding between the atoms is formed by covalent bond
- They have empty conduction band at 0 K
- They have almost filled valence band
- The energy gap is small
- They exhibit negative temperature coefficient of resistance.
- If impurities (or) temperature of the semiconductor increases, electrical conductivity also increases.

3.3. Classification of semiconductors

Semiconductors are classified mainly based on the composition of the materials. They are

(i) Elemental semiconductors

(ii) Compound semiconductors

Elemental semiconductors are made from a single element of fourth group of elements in periodic table. They are also called as indirect bandgap semiconductors. Example: Germanium (0.72 eV), Silicon (1.1 eV). These semiconductors are used in diode, transistors, etc.,

Compound semiconductors are formed by combining third and fifth group (or) second and six group elements in the periodic table. They are also called as indirect bandgap semiconductors.

Characteristics

- The compound semiconductor have large forbidden gap and carrier mobility
- They are formed by both ionic and covalent bonds.
- The recombination takes place directly and light photons are emitted in visible (or) infrared region.
- Eg: GaAs, InP (III & V); ZnS, MgO (II a& VI)

These compounds are used in photovoltaic cell, LED and laser diodes.

3.4. Differences between elemental and compound semiconductors

S.No	Elemental semiconductors	Compound semiconductors
1	They are made of single element Eg: Ge, Si	They are made of compounds Eg: GaAs, CdS, MgO
2	They are known as indirect band gap semiconductors	They are known as direct bandgap semiconductors
3	Electron-hole pair recombination takes place through traps which is present in the band gap	Electron-hole pair recombination takes place directly with each other
4	Life time of charge carriers is more due to indirect recombination	Life time of charge carriers is less due to direct recombination
5	Heat energy is produced during recombination	Light photons are emitted during recombination
6	They carry more current	They carry less current
7	They are used for making diodes and transistors	They are used for making LEDs and laser diodes.

3.5. Direct and indirect bandgap semiconductors

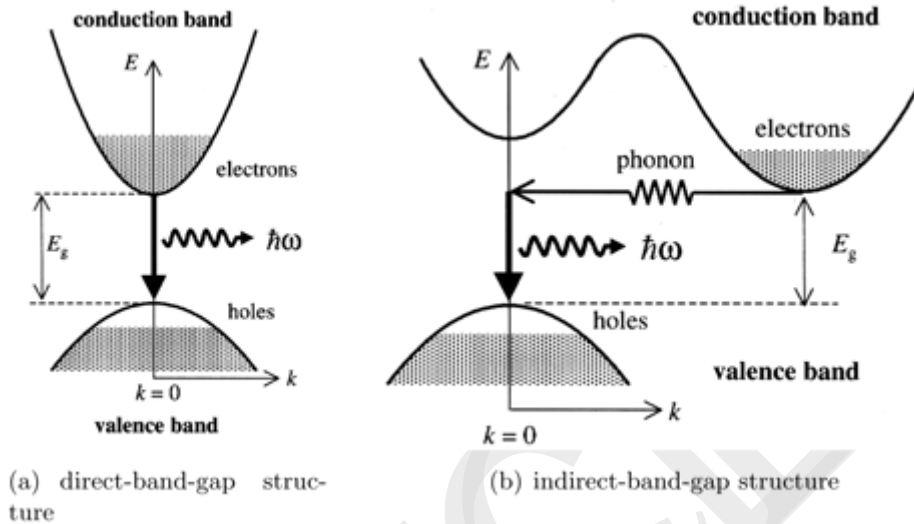
Semiconductors are classified in to (a) Direct bandgap semiconductor, (b) Indirect bandgap semiconductor.

The electrons and holes in a semiconductor have energy and momentum. The momentum (k) depends on energy (E). The lower curves represent energy and momentum values of holes in valence band of semiconductor. Similarly upper curve denote corresponding values for electrons in conduction band.

Indirect band gap semiconductor, the energy maximum of valence band and the energy minimum of the conduction band are having some momentum value.

During recombination of electron from conduction band with hole in valence band, the momentum of the electrons remains virtually constant. The energy equal to band gap energy is released as light photon.

But, in the case of indirect band gap semiconductor, the maximum energy of valence band and minimum energy of conduction band are having different values of momentum. During recombination, electron first loses momentum such that it has momentum equal to the momentum corresponding to energy maximum of valence band. To conserve the momentum, emission of third particle known as a photon is generated. Thus, in this type of recombination photon is produced.



3.6. Intrinsic semiconductors

A semiconductor in extremely pure form is called intrinsic semiconductor. Its electrical conductivity is changed only by thermal excitation.

The common examples for intrinsic semiconductors are pure silicon (Si) and germanium (Ge). They belong to fourth group elements in the periodic table. Germanium has 32 electrons and silicon has 14 electrons in their atomic structures. They are tetravalent atoms since they have four valence electrons. The neighbouring atoms from covalent bonds by sharing four electrons with each other so as to form a stable structure.

Energy band diagram

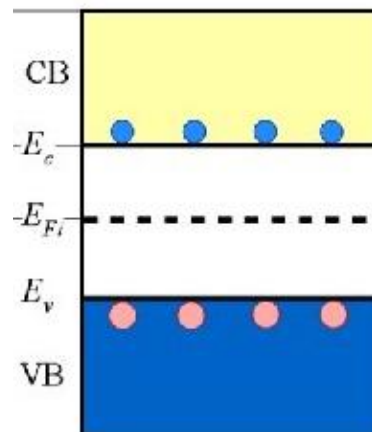
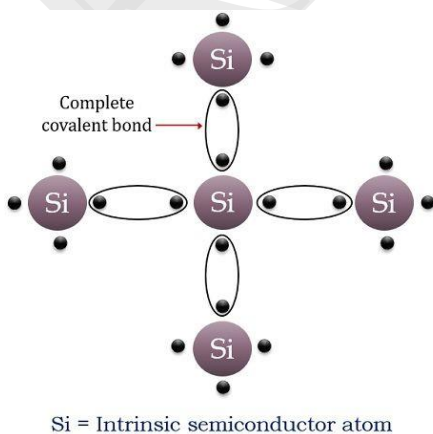


Figure shows a 2D crystal structure of Silicon and energy band representation of intrinsic semiconductor at very low temperature. At very low temperature say 0 K, no free electrons are available for conduction. Hence, this semiconductor behaves as an insulator at very low temperature.

3.7. Charge carriers in intrinsic semiconductors

To get free electrons, covalent bonds must be broken. There are many ways of breaking the covalent bond and setting electron free. One such way is to increase temperature above 0 K.

When the temperature of intrinsic semiconductor is increased, some of the electron get sufficient energy to break covalent bonds. Once the electrons are liberated from bond, they become free electrons and move randomly throughout the crystal. The energy required to break the covalent bond depends on the semiconductors. For example Ge requires 0.72 eV while Si required 1.1 eV to break the bond which is the bandgap energy E_g . When an electron acquires energy E_g , it jumps from valence band to conduction band. As a result a vacant is created in valence band. This vacant site is called as hole. A hole can attract an electron and hence it acts as a positive charge.

When an electric field is applied these free electrons acquire directional motion and contribute to electrical conductivity. For every electron freed from covalent band, one hole is created in the crystal. It is relatively easy for a valence electron in a neighbouring atom to leave its covalent bond and fill this hole.

As a result, an electron moving from a covalent bond to fill a hole leaves behind a hole in its original position. The hole effectively moves in a direction opposite to that of an electron. The hole in its new position may now be filled by an electron from another covalent bond. Thus hole will correspondingly move one more step in the direction opposite to the motion of the electron. Therefore, in intrinsic semiconductor, current conduction is due to the movement of both electrons and holes. Here, the number of electrons is equal to the number of holes at any given temperature.

3.8. Carrier concentration in intrinsic semiconductors (derivation)

Definition

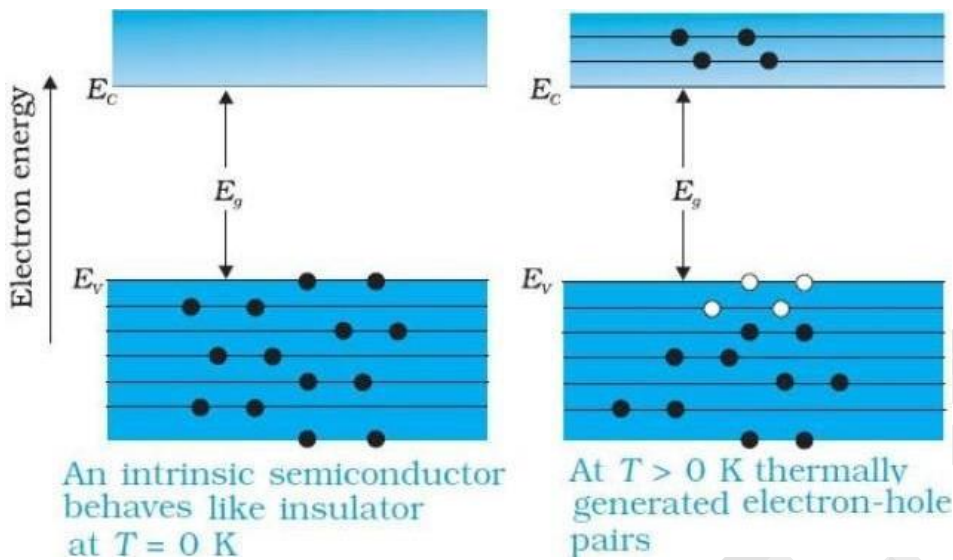
The number of electrons in conduction band per unit volume of the material is called as electron concentration (**n**)

The number of holes in valence band per unit volume of the materials is called the hole concentration (**p**)

The number of charge carriers per unit volume of the material is called carrier concentration (or) density of charge carriers.

Density of electrons in conduction band (**n**)

The number of charge carriers per unit volume of the material is called carrier concentration or density of charge carriers



Electrons in Conduction Band

The number of electrons whose energy lies in the range “E” & “E+dE” in the conduction band is given by

$$dn = Z(E) F(E) dE \quad (1)$$

Where $Z(E)$ – density of states in the energy ranges ‘E’ & ‘E + dE’

$F(E)$ – Probability of number of electron occupying in the conduction band

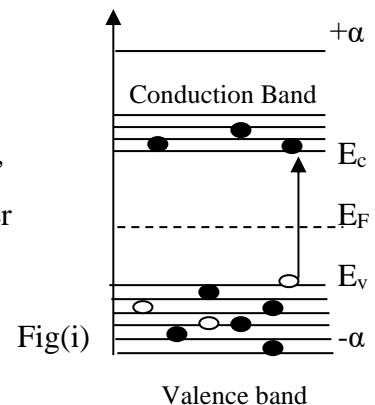
The number of electrons in the conduction band for the entire region is calculated by integrating equation (1) from top energy level ‘ E_c ’ to bottom energy level ‘ α ’

$$\text{i.e., } n = \int_{E_c}^{\alpha} Z(E) F(E) dE \quad (2)$$

W.K.T, Density of states in the conduction band in the energy range ‘E’ & ‘E+dE’ is given by

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

The bottom edge of the conduction band (E_c) represents the potential energy of an electron at rest. Therefore, $(E - E_c)$ is the kinetic energy of the conduction electron at higher energy levels. Therefore the equation (3) is modified as



Fig(i)

$$Z(E) dE = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} (E - E_c)^{\frac{1}{2}} dE \quad (4)$$

Since the electron is moving in a periodic potential, its mass m is replaced by its effective mass m_e^* .

The probability of electron occupancy is given by $F(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$ (5)

Substituting (4) & (5) in (2), we get, $n = \int_{E_c}^{\infty} \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} (E - E_c)^{\frac{1}{2}} \times \frac{1}{1 + e^{(E-E_F)/kT}} dE$ (6)

For all possible temperature, $E - E_F \gg kT$, hence in the denominator, $1 + e^{\frac{E-E_F}{kT}} \cong e^{\frac{E-E_F}{kT}}$

Now equation (6) becomes, $n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} \int_{E_c}^{\infty} \frac{(E - E_c)^{\frac{1}{2}}}{e^{(E-E_F)/kT}} dE$

(or) $n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} \int_{E_c}^{\infty} (E - E_c)^{\frac{1}{2}} e^{-(E-E_F)/kT} dE$

(or) $n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} e^{E_F/kT} \int_{E_c}^{\infty} (E - E_c)^{\frac{1}{2}} e^{-E/kT} dE$ (7)

To solve this, assume the following:

$E - E_c = x$	$E = E_c$	$E = +\alpha$
$E = E_c + x$	$E_c - E_c = x$	$\alpha - E_c = x$
$dE = dx$	$x = 0$	$x = \alpha$

Now, $n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} e^{E_F/kT} \int_0^{\infty} x^{\frac{1}{2}} e^{-(E_c+x)/kT} dx$

(or) $n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} e^{(E_F-E_c)/kT} \int_0^{\infty} x^{\frac{1}{2}} e^{-x/kT} dx$ (8)

Using gamma function, $\int_0^{\infty} x^{\frac{1}{2}} e^{-x/kT} dx = \frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2}$ (9)

Substituting eqn. (9) in (8), we get, $n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} e^{(E_F-E_c)/kT} \times \frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2}$

(or)

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}} e^{(E_F - E_C)/kT} \quad (10)$$

This is the expression of electrons in the conduction band of an intrinsic semiconductor.

Concentration of holes in the Valence band

We know that if an electron is transferred from valence band to conduction band, a hole is created in valence band. Let dp be the number of holes in the valence band for the energy range E & $E+dE$.

$$\therefore dp = Z(E) (1 - F(E)) dE \quad (11)$$

Where $Z(E)$ – Density of states in the energy range E & $E+dE$

$(1 - F(E))$ – Probability of unoccupied (vacant) electron state (presence of hole) in valence band

$$\therefore (1 - F(E)) dE = 1 - \frac{1}{1 + e^{(E-E_F)/kT}} = \frac{1 + e^{(E-E_F)/kT} - 1}{1 + e^{(E-E_F)/kT}} = \frac{e^{(E-E_F)/kT}}{1 + e^{(E-E_F)/kT}} \quad (12)$$

$\because E < E_F$ in valence band, $(E - E_F)$ has negative quantity & hence in denominator $e^{(E-E_F)/kT}$ is very small when compared with 1, hence $1 + e^{(E-E_F)/kT} \cong 1$

$$\therefore 1 - F(E) = e^{(E-E_F)/kT} \quad (13)$$

E_v is the top level in the valence band and having potential energy of a hole at rest. Hence $(E_v - E)$ is the kinetic energy of the hole at level below E_v . Hence,

$$\text{Density of states in the valence band is } Z(E)dE = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} (E_v - E)^{\frac{1}{2}} dE \quad (14)$$

Where, m_h^* - effective mass of the hole in the valence band

$$\text{Substituting equation (14), (13) in (11), we get, } dp = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} (E_v - E)^{\frac{1}{2}} e^{(E-E_F)/kT} dE \quad (15)$$

The number of holes in the valence band for the entire energy range is obtained by integrating

Above equation between the limits $-\infty$ to E_v

$$\text{i.e., } \int dp = \int_{-\infty}^{E_v} \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} (E_v - E)^{\frac{1}{2}} e^{(E-E_F)/kT} dE$$

$$\text{(or) } dp = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} e^{-E_F/kT} \int_{-\infty}^{E_v} (E_v - E)^{\frac{1}{2}} e^{E/kT} dE \quad (16)$$

To solve this, assume the following:

$E_v - E = x$	$E = -\alpha$	$E = E_v$
$E = E_v - x$	$E_v - (-\alpha) = x$	$E_v - E_v = x$
$dE = -dx$	$x = \alpha$	$x = 0$

$$p = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} e^{-E_F/kT} \int_{\infty}^0 x^{\frac{1}{2}} e^{-(x+E_v)/kT} (-dx)$$

$$(or) \quad p = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} e^{(E_v - E_F)/kT} \int_0^{\infty} x^{\frac{1}{2}} e^{-x/kT} dx \quad (17)$$

$$\text{Using gamma function, } \int_0^{\infty} x^{\frac{1}{2}} e^{-x/kT} dx = \frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2} \quad (18)$$

$$\text{Substituting eqn (18) in (17), we get, } p = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} e^{(E_v - E_F)/kT} \times \frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2}$$

$$(or) \quad \boxed{p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{\frac{3}{2}} e^{(E_v - E_F)/kT}} \quad (19)$$

This is the expression of holes in the valence band of an intrinsic semiconductor

Intrinsic Carrier Concentration:

In intrinsic semiconductor, carrier concentration of electrons in conduction band (n_i) = carrier concentration of holes in valence band n_p &

hence the intrinsic carrier concentration is $n_i^2 = n_i \times n_p$

$$n_i^2 = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}} e^{(E_F - E_C)/kT} \times 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{\frac{3}{2}} e^{(E_v - E_F)/kT} \quad (20)$$

$$(or) \quad n_i^2 = 4 \left(\frac{2\pi kT}{h^2} \right)^3 (m_e^* \times m_h^*)^{\frac{3}{2}} e^{(E_v - E_C)/kT}$$

$$(or) \quad n_i^2 = 4 \left(\frac{2\pi kT}{h^2} \right)^3 (m_e^* \times m_h^*)^{\frac{3}{2}} e^{-E_g/kT} \quad (21)$$

$$(or) \quad n_i = 2 \left(\frac{2\pi kT}{h^2} \right)^{\frac{3}{2}} (m_e^* \times m_h^*)^{\frac{3}{4}} e^{-\frac{E_g}{2kT}}$$

Where $E_c - E_v = E_g$ is the forbidden energy gap.

Fermi level and its variation with temperature

Fermi level is a characteristic energy level of the material. The position of Fermi level is important in determining the electron and hole concentrations in a semiconductor.

In intrinsic semiconductor, the number of electrons in conduction band is equal to the number of holes in valence band.

i.e., $n = p$

Substitute the values from equations (10) and (19), we get

$$2 \times \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} e^{(E_v - E_f)/kT} = 2 \times \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} e^{(E_f - E_c)/kT}$$

$$\text{(or)} \quad (m_h^*)^{3/2} e^{(E_v - E_f)/kT} = (m_e^*)^{3/2} e^{(E_f - E_c)/kT}$$

$$\text{(or)} \quad \left(\frac{m_h^*}{m_e^*} \right)^{3/2} e^{(E_v + E_c)/kT} = e^{(E_f + E_f)/kT}$$

$$\text{(or)} \quad \left(\frac{m_h^*}{m_e^*} \right)^{3/2} e^{(E_v + E_c)/kT} = e^{(2E_f)/kT}$$

$$\text{(or)} \quad \log \left(\left(\frac{m_h^*}{m_e^*} \right)^{3/2} e^{(E_v + E_c)/kT} \right) = \log \left(e^{(2E_f)/kT} \right)$$

$$\text{(or)} \quad \log \left(\frac{m_h^*}{m_e^*} \right)^{3/2} + \log \left(e^{(E_v + E_c)/kT} \right) = \frac{2E_f}{kT}$$

$$\text{(or)} \quad \log \left(\frac{m_h^*}{m_e^*} \right)^{3/2} + \frac{E_v + E_c}{kT} = \frac{2E_f}{kT}$$

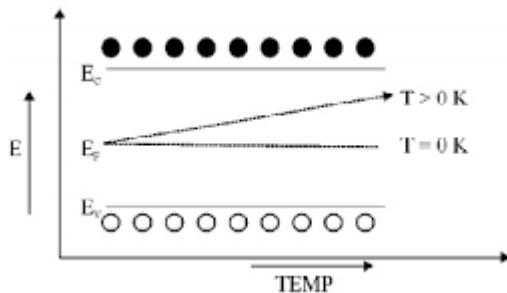
$$\text{(or)} \quad E_f = \frac{kT}{2} \left(\log \left(\frac{m_h^*}{m_e^*} \right)^{3/2} \right) + \frac{E_v + E_c}{2}$$

$$\text{(or)} \quad E_f = \frac{3kT}{4} \log \left(\frac{m_h^*}{m_e^*} \right) + \frac{E_v + E_c}{2} \quad (23)$$

If $m_h^* = m_e^*$, then $\log_e \left(\frac{m_h^*}{m_e^*} \right) = \log_e 1 = 0$,

Then equation 23 becomes $E_f = \frac{E_v + E_c}{2}$ (24)

Thus, Fermi level is located half way between the top of valence band and bottom of conduction band. Its position is independent of temperature. In reality, $m_h^* > m_e^*$, Fermi level is just above the middle of energy gap and it rises slightly with increasing temperature.



Limitations

Intrinsic semiconductors cannot be directly used to fabricate devices due to:

- Electrical conductivity is low. Eg: Ge has $1.67\ \Omega^{-1}\ \text{m}^{-1}$ which is 10^7 times smaller than copper
- Electrical conductivity is a function of temperature and increases exponentially as temperature increases.
- The carrier concentration of electrons and holes are very low at normal temperatures.

3.9. Extrinsic Semiconductors

The application of intrinsic semiconductors is restricted due to its low conductivity.

In electronic devices, high conducting semiconductors are more essential. The concentration of either electrons or holes in a semiconductor is increased depending upon the requirements in the electronic devices.

Extrinsic Semiconductors are classified into two categories based on the concentration of the charge carriers namely:

1. n – type semiconductors (electrons), and
2. p – type semiconductors (holes).

2.9.1. n – type semiconductors

When a pentavalent atom such as arsenic (antimony, bismuth, phosphorus) is added as a dopant to the tetravalent silicon atom, the arsenic atom will occupy one site of the silicon atom. Thus, out of five free electrons in arsenic, four electrons make covalent bonds with the four neighbouring silicon atoms and the fifth one is loosely bound to the silicon atom, as shown in fig. 2

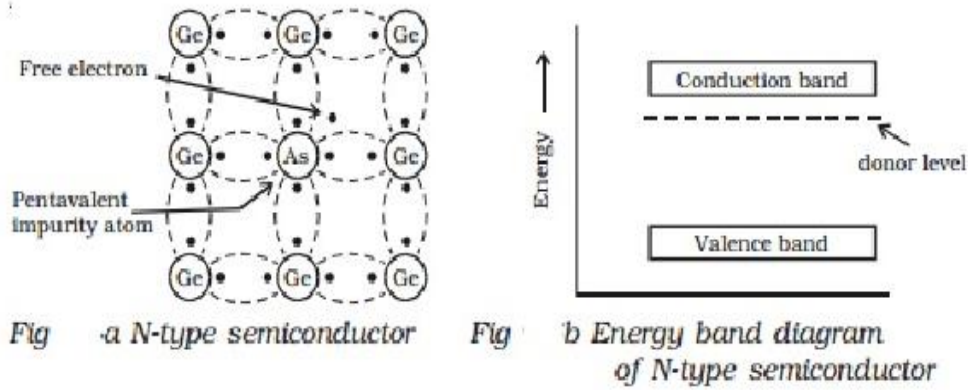


Fig. 2 Doping in n-type semiconductors.

The energy required to ionize the fifth electron is very less and hence, the thermal energy of the material shifts the free electron to the conduction band. Each arsenic atom contributes one free electron to the crystal and hence, it is called a donor impurity. In this type of semiconductor, the concentration of charge carriers (i.e., electrons) is more than that of holes. Therefore, these semiconductors are called n-type semiconductors. In an n-type semiconductor, electrons are the majority carriers while holes are the minority carriers.

3.9.2. p - type semiconductors

Instead of a pentavalent atom, the addition of a trivalent atom indium (In) to the tetravalent silicon atom, occupies the crystal site of the silicon atom as shown in Fig.3

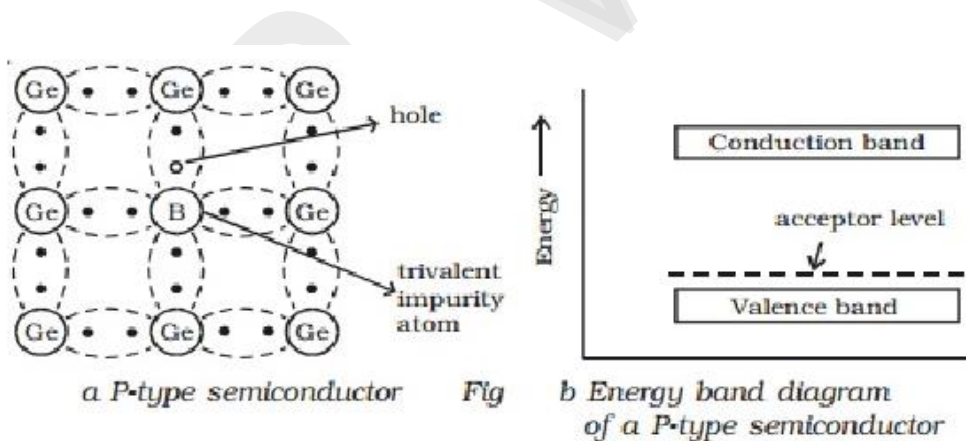


Fig.3

The three valence electrons in indium make covalent bands with the three neighbouring silicon atoms, whereas the fourth bond has an empty space known as hole due to the deficiency of one electron. Therefore, when a trivalent atom is added to silicon, it creates a hole in the valence band. The dopant (indium) accepts an electron from the neighbouring silicon atom to form a covalent bond and hence, it is called an acceptor. The hole in the valence band moves freely and hence, the current flows through the material.

This type of electrical conduction will take place only when the dopant valency is less than that of the parent atom. Such semiconductors are called p – type semiconductors. In a p – type semiconductor, holes are the majority current carriers and electrons are the minority current carriers.

3.10. EXTRINSIC SEMICONDUCTOR

Consider an intrinsic Si crystal is doped with pentavalent impurities such as P,As, Sb, etc., and the regular Si atom is replaced by these impurity atoms. Since these impurity atoms are having five valence electrons, four electrons occupy the regular lattice site and form covalent bonding.

The one excess electron is loosely bound to the parent atom. The excess of electron is lightly bound to the parent atom (~0.01 eV). Since, the thermal energy is sufficient to excite this electron, this electron can contribute to the conduction process. Since, the pentavalent impurity donate an electron, it is said to be a donor impurity. According to the energy band theory of solids, these excess electrons possess an energy level just below the conduction band. This energy level is known as the donor level. The semiconductor are shown in Fig.-6

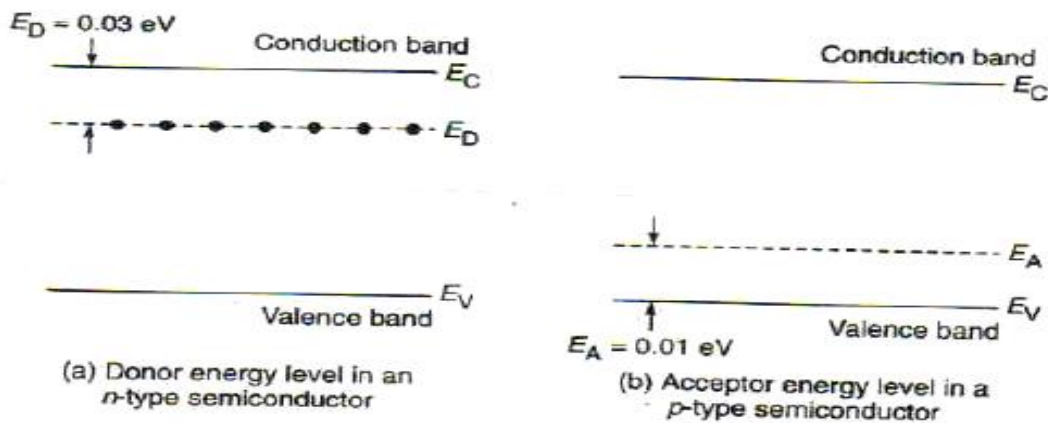


Fig. – 6 Donor and acceptor energy levels in an n-type and p-type semiconductors

Consider an intrinsic semiconductor doped with trivalent impurities such as B, Al, Ga, etc. When a trivalent impurity is doped, it occupies the regular site of a Si atom. All the three electrons are shared by three different Si atoms. A covalent bond is not completed, because the trivalent impurity has only three electrons. Therefore, a hole is created due to the trivalent impurity doping. This hole is free to move within the crystal. At 0 K, all the states in the valence band is completely occupied. The excess of hole produced due to the trivalent impurity doping occupies an energy level just above the valence band. This energy level is known as the acceptor level.

3.11. *n* - type semiconductor

A semiconductor doped with donor impurities is known as an n-type semiconductor. For example, if a tetravalent silicon atom is doped with pentavalent atoms such as As and Bi, it will become an n-type semiconductor.

Fermi level

In n –type semiconductor, the donor level is just below the conduction band. N_d denotes the donor concentration & E_d represents the energy of the donor level.

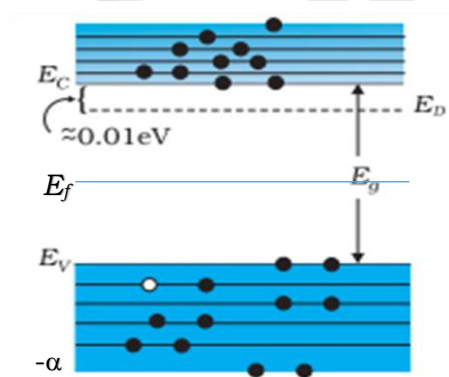
Density of electrons per unit volume in the conduction band is given by

$$n = 2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}} e^{(E_F - E_c)/kT} \tag{1}$$

Where E_f – Fermi energy; E_c – Energy corresponding to the bottom of the conduction band

Density of the ionized donors = $N_d [1 - F(E)]$

$$\begin{aligned} &= N_d \left[1 - \frac{1}{1 + e^{(E_d - E_F)/kT}} \right] \\ &= N_d \left[\frac{1 + e^{(E_d - E_F)/kT} - 1}{1 + e^{(E_d - E_F)/kT}} \right] \\ &= N_d \left[\frac{e^{(E_d - E_F)/kT}}{1 + e^{(E_d - E_F)/kT}} \right] \end{aligned}$$



$$\text{Density of ionized donors} = \left[\frac{N_d}{1 + e^{(E_d - E_F)/kT}} \right] = \left[\frac{N_d}{1 + e^{(E_F - E_d)/kT}} \right] \tag{2}$$

At equilibrium, the density of electrons in conduction band = Density of ionized donors.

$$\text{Equating (1) \& (2), } 2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}} e^{(E_F - E_c)/kT} = \frac{N_d}{1 + e^{(E_F - E_d)/kT}} \tag{3}$$

E_F lies more than few kT above donor levels, hence $e^{(E_d - E_F)/kT}$ is large compared to ‘1’. Hence the ‘1’ in denominator of R.H.S of equation (3) is neglected.

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

$$\text{(or) } 2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}} e^{(E_F - E_c)/kT} = N_d e^{(E_d - E_F)/kT} \tag{4}$$

Taking log on both sides,

$$\log \left[2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}} \right] + \log_e e^{(E_F - E_c)/kT} = \log_e N_d e^{(E_d - E_F)/kT}$$

$$(or) \log \left[2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}} \right] + \frac{E_F - E_c}{kT} = \log N_d + \frac{E_d - E_F}{kT} \quad (5)$$

$$(or) \frac{E_F - E_c - E_d + E_F}{kT} = \log N_d - \log \left[2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}} \right]$$

$$(or) \frac{2E_F - E_c - E_d}{kT} = \log \left[\frac{N_d}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}}} \right]$$

$$(or) 2E_F = E_d + E_c + kT \log \left[\frac{N_d}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}}} \right]$$

$$(or) E_F = \frac{E_d + E_c}{2} + \frac{kT}{2} \log \left[\frac{N_d}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}}} \right] \quad (6)$$

Substituting the expression of E_F from (6) in (1), we get

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}} \exp \left[\frac{\left(\frac{E_d + E_c}{2} + \frac{kT}{2} \log \left[\frac{N_d}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}}} \right]} - E_c \right)}{kT} \right] \quad (7)$$

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}} \exp \left[\left(\frac{E_d + E_c - 2E_c}{2kT} + \frac{1}{2} \log \left[\frac{N_d}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}}} \right]} \right) \right]$$

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}} \exp \left[\left(\frac{E_d - E_c}{2kT} + \log \left[\frac{(N_d)^{1/2}}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{3/2}} \right] \right) \right]$$

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}} \frac{\left[\frac{N_d}{2} \right]^{1/2}}{\left[\frac{2\pi m_e^* kT}{h^2} \right]^{3/4}} e^{(E_d - E_c)/2kT} \quad (8)$$

Rearranging the expression (8), we have

$$(or) \quad n = (2N_d)^{1/2} \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/4} e^{(E_d - E_c)/2kT}$$

$$(or) \quad n = (2N_d)^{1/2} \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/4} e^{(-\Delta E)/2kT}$$

Where $\Delta E = E_c - E_d$ is the ionization energy to transfer Energy from donor energy level to the conduction band.

Results:

- (i) The density of electrons is proportional to square root of donor concentration and valid at low temperature alone
- (ii) At high temperature, intrinsic carrier concentration must take along with this concentration

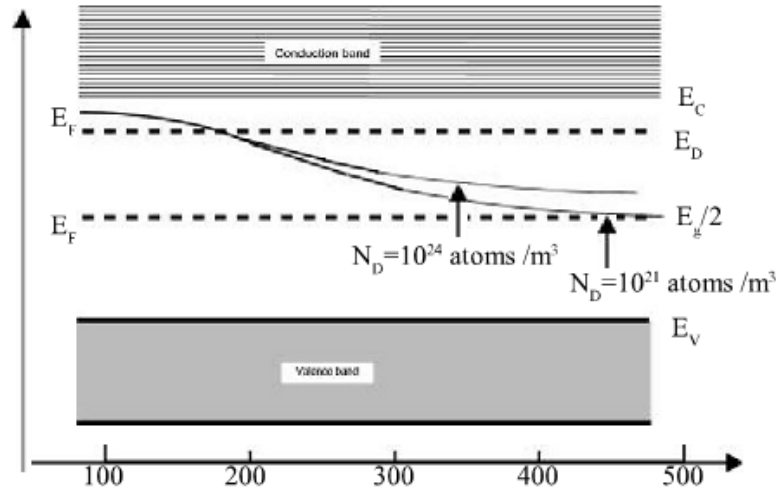
Variation of Fermi level with temperature and impurity concentration:

Fermi level of n – type semiconductor is
$$E_F = \frac{E_d + E_c}{2} + \frac{kT}{2} \log \left[\frac{N_d}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{3/2}} \right] \quad (1)$$

At $T = 0K$, the above equation reduces to
$$E_F = \frac{E_d + E_c}{2} \quad (2)$$

- (i) At $0K$, Fermi level lies exactly at the centre of the donor level and bottom of the conduction band.
- (ii) As the temperature is gradually increased from a low temperature, the contribution of electron increases and at very high temperature, it far exceeds the donor concentration and the intrinsic behaviour predominates at higher temperature.
- (iii) Fermi level shifts downwards when the temperature is increased and finally reaches the middle of the band gap (or) intrinsic Fermi level.

Further when the concentration of donors increases, the extrinsic behaviour also extends up to very high temperature & Fermi level reaches the middle of the band gap only at high temperature.



3.12. p - type semiconductors

A semiconductor doped with acceptor impurities is known as a p – type semiconductor. For example, if Si is doped with B, Al, Ga, etc., it will become a p –type semiconductor.

Fermi Level

In p – type semiconductor, the acceptor energy level is just above the valence band. Let E_a represents the energy of the acceptor level and N_a represents the number of acceptor atoms per unit volume.

Density of holes per unit volume in valence band is given by
$$p = 2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}} e^{(E_v - E_F)/kT} \quad (1)$$

Where E_v is the energy corresponding to the top of the conduction band

Density of the ionized acceptors =
$$N_a F(E_a) = \frac{N_a}{1 + e^{(E_a - E_F)/kT}} \quad (2)$$

Since $E_a - E_F$ is very large when compared to kT . $e^{(E_a - E_F)/kT}$ is a large quantity and thus ‘1’ in denominator of R.H.S of equation(2) is neglected. hence, equation(2), reduces to

$$N_a F(E_a) = \frac{N_a}{e^{(E_a - E_F)/kT}} = N_a e^{(E_F - E_a)/kT} \quad (3)$$

At equilibrium, the density of holes in Valence band = Density of ionized acceptors

$$2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}} e^{(E_v - E_F)/kT} = N_a e^{(E_F - E_a)/kT} \quad (4)$$

Taking log on both sides,

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

$$(or) \log \left[2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}} \right] + \frac{E_v - E_F}{kT} = \log N_a + \frac{E_F - E_a}{kT} \quad (5)$$

Rearranging the expression (5), we have

$$\frac{E_F - E_a - E_v + E_F}{kT} = -\log N_a + \log \left[2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}} \right]$$

$$(or) \frac{2E_F - (E_a + E_v)}{kT} = -\log_e \left\{ \frac{N_a}{2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}}} \right\}$$

$$(or) 2E_F = (E_a + E_v) - kT \log_e \left\{ \frac{N_a}{2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}}} \right\}$$

$$(or) E_F = \frac{(E_a + E_v)}{2} - \frac{kT}{2} \log_e \left\{ \frac{N_a}{2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}}} \right\} \quad (6)$$

Sub. The expression of E_F in equation (6), we get,

$$p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{\frac{3}{2}} \exp \left[\frac{\left(E_v - \frac{E_v - E_a}{2} + \frac{kT}{2} \log \left[\frac{N_a}{2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}}} \right]}{kT} \right)}{kT} \right] \quad (7)$$

$$(or) \quad p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{\frac{3}{2}} \exp \left[\left(\frac{2E_v - E_v - E_a}{2kT} + \frac{1}{2} \log \left[\frac{N_a}{2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}}} \right] \right) \right] \quad (8)$$

$$(or) \quad p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{\frac{3}{2}} \frac{\left[\frac{N_a}{2} \right]^{\frac{1}{2}}}{\left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}}^{\frac{1}{2}}} e^{(E_v - E_a)/2kT}$$

$$(or) \quad p = (2N_a)^{1/2} \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/4} e^{(E_v - E_a)/2kT} \quad (9)$$

If we put $E_a - E_v = \Delta E$, equation (9) becomes,

$$p = (2N_a)^{1/2} \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/4} e^{\Delta E/2kT} \quad (10)$$

Results:

- (i) Density of holes in valence band is proportional to square root of acceptor concentration
- (ii) At very high temperature p – type semiconductor behaves like an intrinsic semiconductor

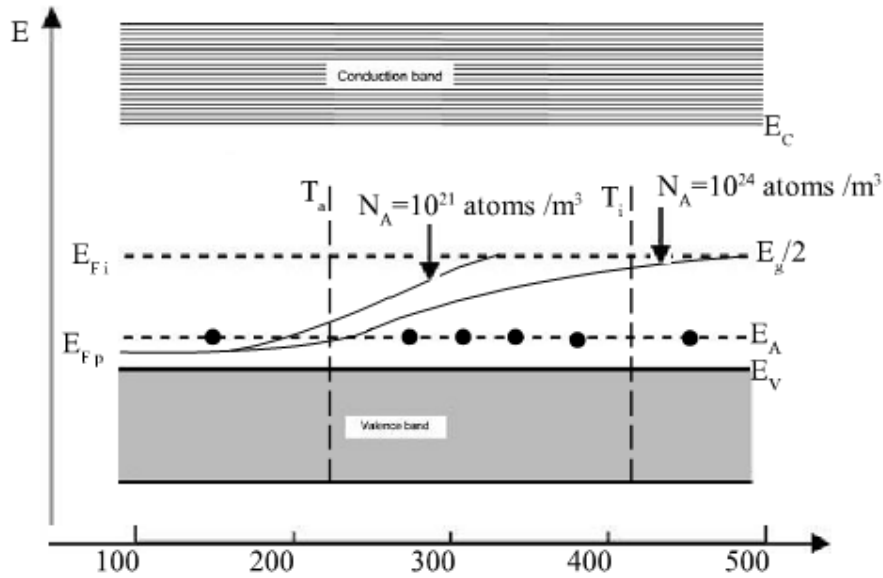
Variation of Fermi level with temperature:

We know that

$$E_F = \frac{(E_a + E_v)}{2} - \frac{kT}{2} \log_e \left\{ \frac{N_a}{2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}}} \right\} \quad (1)$$

At $T = 0K$, the above expression becomes, $E_F = \frac{E_a + E_v}{2}$ (2)

- (i) At $0K$ the Fermi level lies exactly halfway between acceptor level E_a and top of the valence band E_v
- (ii) As the temperature increases, the Fermi level shifts upwards, at a particular temperature, when all the acceptor atoms are ionized and Fermi level crosses the acceptor level
- (iii) At very high temperature, the Fermi level is shifted to intrinsic Fermi level and behave as intrinsic semiconductor.

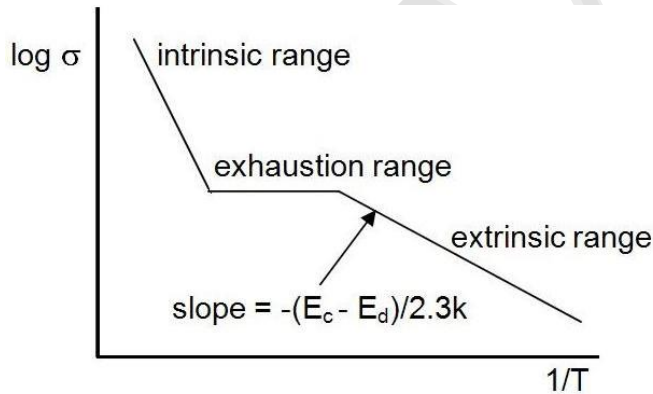


3.13. Variation of carrier concentration with temperature and impurity

In extrinsic semiconductor, the resistivity decreases linearly with increase in temperature. This variation is considered under three different regions:

- (1) Extrinsic (or) impurity range
- (2) Exhaustion range
- (3) Intrinsic range

For a n type semiconductor, the variation of carrier concentration n and p with temperature is shown in figure



At $T = 0$ K, both conduction and valence bands are free from any charge carriers and hence the electrical conductivity is zero. With increase in temperature the donor atoms get ionised and hence electron concentration in conduction band increases with temperature until all the donor atoms are ionized. This range is known as **impurity or extrinsic range**.

When the temperature is further increased to room temperature, there are no more donor atoms to be ionised and hence the concentration of electrons in conduction band remains constant over a certain temperature range. This region is known as **exhaustion range**.

As the temperature is increases further, the electrons in valence band re lifted across the forbidden gap to conduction band. Thus, electron concentration increases in conduction band considerably. With further increase in temperature, more and more electrons from valence band reach conduction band and completely outnumber the donor electrons.

The material practically becomes intrinsic and so this range is called **intrinsic** range. All these ranges are shown in figure. The dotted curve indicates hole concentration in an intrinsic range.

3.14. Differences between intrinsic and extrinsic semiconductors

S.No	Intrinsic	Extrinsic
1.	Pure form of semiconductor	Doping is added to pure semiconductor
2.	Number of electrons = holes	Number of electrons ≠ holes
3.	Conductivity is poor	Conductivity is better than intrinsic

2.15. Differences between n type and p type semiconductors

S.No	n type semiconductors	p type semiconductors
1.	It is formed by adding pentavalent with pure intrinsic semiconductor	It is formed by adding trivalent with pure intrinsic semiconductor
2.	The discrete impurity energy level called donor energy level located just below conduction band	The discrete impurity energy level called acceptor energy level which located just above valence band
3.	It donates electron from donor energy level	It accepts holes from acceptor energy levels
4.	Majority carriers are electrons	Majority carriers are holes
5.	Fermi energy decreases with increase in temperature	Fermi energy increases with increase in temperature.

3.16. Carrier transport in semiconductor

Random motion and mobility

In absence of an electric field, the free electrons move in all directions in a random manner. They collide with other free electron and positive ion core during the motion. This collision is known as elastic collision. As the motion is random, the resultant velocity in any particular direction is zero. When an electric field is applied in a semiconducting material, the free charge carriers such as free electrons and holes attain drift velocity v_d . The drift velocity attain by the carriers is proportional to the electrical field strength E.

$$V_d = \mu E \tag{1}$$

Where μ is a proportionality constant and it is known as the mobility of charge carriers. If $E = 1 \text{ V/m}$ then $\mu = v_d$ thus, mobility μ is defined as the velocity of a charge carrier per unit electric field strength.

In a semiconductor, the electrical conductivity is due to the movement of electrons and holes. The equation for the conductivity of a semiconductor is

$$\sigma = ne\mu_e + pe\mu_h$$

Where n is the concentration of electron, p the concentration of hole and μ_e and μ_h are respectively the mobilities of electron and holes. Since the type of drift of electrons and of

holes are different, the mobility of an electron at any temperature is different from (greater than) that of the hole.

Material	Electron mobility (m ² /volt-sec)	Hole mobility (m ² /volt-sec)
Germanium	0.135	0.048
Silicon	0.39	0.19

Expression for electrical conductivity

If the density of free electrons in the material is n , the net charge available per unit volume of the material for the conduction is equal to ne , where e is the charge of the electron.

When an external electric field E is applied, the electrons move with a drift velocity v_{dn} thus,

$$V_{dn} = \mu_n E \tag{2}$$

Where μ_n is the mobility of electron

The drift current density J_n due to electrons is defined as the charge flowing across unit area of cross section per unit time due to their drift under the influence of an electric field E .

It is given by $J_n = n e v_{dn}$ (3)

If σ_n is the conductivity of a semiconductor due to free electrons, the current density J_n is related to the applied electric field by

$$J_n = \sigma_n E \tag{4}$$

(or) $\sigma_n = \frac{J_n}{E} = \frac{nev_{dn}}{E}$ (5)

Substituting eqn. (2) in eqn. (5), we get $\sigma_n = \frac{ne\mu_n E}{E}$

(or) $\sigma_n = ne\mu_n$ (6)

If p is the number of holes per unit volume and σ_p the conductivity due to the drift of holes, then $\sigma_p = pe\mu_p$ (7)

Where μ_p is the mobility of holes in the material.

Thus the total conductivity σ due to free electrons and holes

$$\sigma = \sigma_n + \sigma_p$$

(or) $\sigma = ne\mu_e + pe\mu_h$

(or) $\sigma = e(n\mu_e + p\mu_h)$ (8)

Where σ is the total conductivity of the material and it is generally expressed in mho/m. For an intrinsic semiconductor $n = p = n_i$

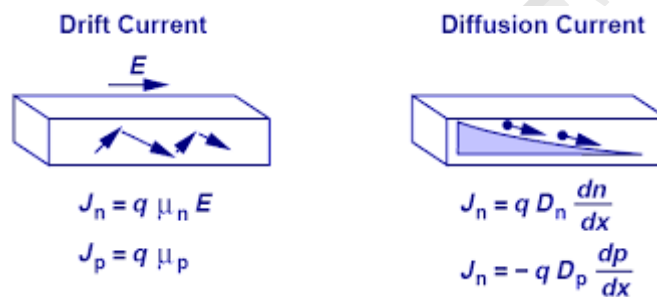
Therefore, the electrical conductivity σ_i of an intrinsic semiconductor having n_i electron-hole pairs per unit volume is given by

$$\sigma = n_i e (\mu_e + \mu_h) \tag{9}$$

The net current flow in semiconductor is due to drift and diffusion transport.

Drift transport

In the absence of electric field, the random motion of charge carriers will not contribute current because the charge movement in one direction is balance by the charge movement in the other direction. When the external field is applied, the electrons are attracte to the positive terminal and the holes are attracte to the negative terminal. This net movement is termed as drift transport. This transport overcomes the thermal movement and produces current density



Substitute (2) in (1), we get

$$J_e = n_e e \mu_e E \tag{3}$$

$$\text{Similarly, for holes, } J_h = n_h e \mu_h E \tag{4}$$

$$\text{Then the total drift current is } j_{dr} = n_e e \mu_e E + n_h e \mu_h E \tag{5}$$

$$\text{We know that } J = \sigma E \tag{6}$$

$$\text{Therefore } \sigma_{dr} = n_e e \mu_e + n_h e \mu_h \tag{7}$$

For an intrinsic semiconductor $n_e = n_h = n_i$

$$\& \text{ Hence } \sigma_{dr} = n_i e [\mu_e + \mu_h] \tag{8}$$

Diffusion transport

The non-uniform distribution of charge carriers creates the regions of uneven concentrations in the semiconductor. The charge carriers moving from the region of higher concentration to the regions of lower concentration leading to diffusion current

Hence the concentration of charge carrier (Δn_e) varies with distance x in a semiconductor.

$$\text{The rate of flow of charge carriers is } \propto \frac{\partial}{\partial x} (\Delta n_e)$$

$$\text{Rate of flow of electrons} = -D_e \frac{\partial}{\partial x} (\Delta n_e)$$

Where D_e is the electron diffusion coefficient

Current density due to electrons = charge X rate of flow of electrons

$$\text{i.e., } J_e = D_e e \frac{\partial}{\partial x} (\Delta n_e)$$

Similarly for holes, $J_h = -D_h e \frac{\partial}{\partial x} (\Delta n_h)$

Thus, if an electric field is applied to the semiconductor, the total current contribution is due to both drift and diffusion transport.

Net current due to both electrons and holes can be obtained as

$$J_{total} = n_e \mu_e e E + e D_e \frac{\partial}{\partial x} (\Delta n_e) + n_h \mu_h e E - D_h e \frac{\partial}{\partial x} (\Delta n_h)$$

3.17. Hall effect

- The electrical conductivity measurements are not sufficient for the determination of number of charge carriers and their mobilities. Moreover, these measurements do not indicate whether current conduction is due to electrons or holes.
- Hence, it is very difficult to distinguish between p type and n type semiconductors. Besides, the electrical conductivity measurements do not give any information about the sign of the majority (n or p type) charge carriers.
- Therefore, Hall effect is used to distinguish between two types of charge carriers (electrons & holes). It also provides information about the sign of charge carriers.

Statement

When a conductor carrying a current (I) is placed perpendicular to a magnetic field (B), a potential difference is produced inside the conductor in a direction perpendicular to both current and magnetic field. This phenomenon is known as Hall effect. The voltage thus generated is called Hall voltage.

Hall effect in n type semiconductor

Explanation

Consider an external field applied along the X-axis of the specimen. Assuming that the material is n -type semiconductor, the current flow consists mainly of electrons moving from right to left, corresponding to the conventional current direction.

When this specimen is placed in a magnetic field 'B' and if 'v' is the velocity of the electrons perpendicular to the magnetic field then each one of them will experience a downward force of magnitude Bev

This downward force (Lorentz Force F_L) due to magnetic field causes the electrons to be deflected in the downward direction and hence there is an accumulation of negative charges on the bottom face of the slab. This causes the bottom face of the slab to be more negative with respect to the top face and a potential difference is established from top to bottom of the

specimen. This potential difference causes a field E_H called Hall field in negative y direction. There is a force eE_H acting on the electron in the upward direction due to this field.

Theory of Hall Effect

At equilibrium, the downward force Bev will balance the upward force eE_H

$$Bev = eE_H \tag{1}$$

In a uniform sample, the electric current density (J) is related to the drift velocity as

$$J = -neV$$

Where n is the concentration of electrons.

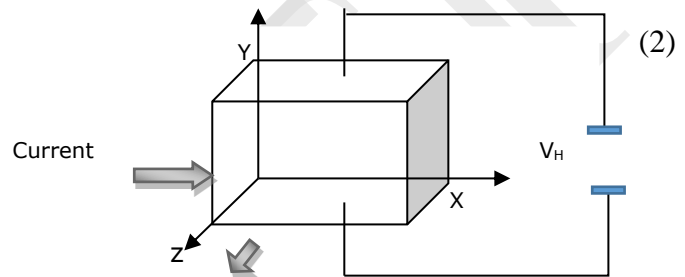
$$V = \frac{-J}{ne}$$

Substituting equation (2) in (1),

$$E_H = \frac{-BJ}{ne}$$

This can be written as $E_H = BJR_H$

⚡ Magnetic field



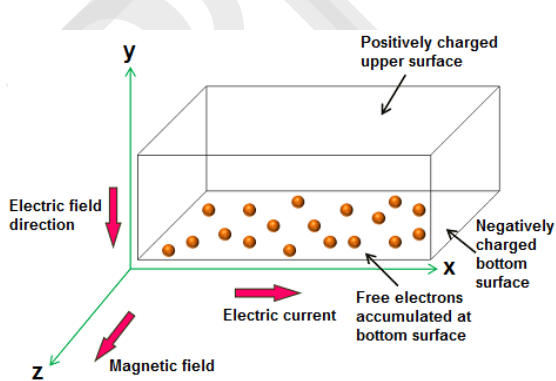
(4)

Where $R_H = -1 / ne$ is called Hall coefficient

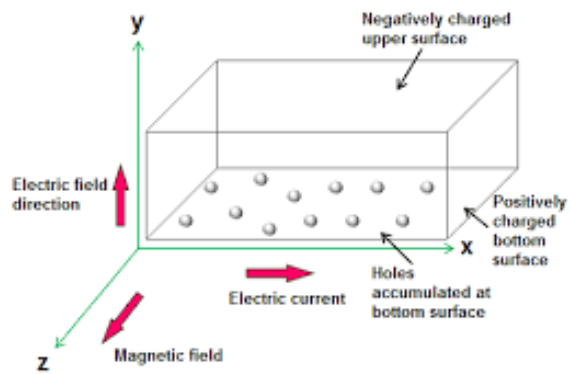
The negative sign indicates that the developed field is in the negative y direction.

III^{rdly}, the Hall coefficient for p – type semiconductor is $R_H = 1 / p e$.

Where p is the concentration of holes



Hall Effect in N-type semiconductor



Hall Effect in P-type semiconductor

Determination of Hall coefficient

The hall field per unit current density per unit magnetic induction is defined as hall coefficient.

If t is the thickness of the sample and V_H is the hall voltage, then $V_H = E_H t$ (5)

Where E_H is hall field.

From equation (4), we get $E_H = R_H J_x B$

Substituting the value of (5) in above equation, we get $V_H = R_H J_x B t$ (6)

Now the current density J_x can be written as $J_x = \frac{I_x}{bt}$ (7)

Where ' b ' is the width and bt is the area of cross section of the sample

Substituting equation (7) in equation (6), we get $V_H = \frac{R_H I_x B t}{bt}$ (8)

$$V_H = \frac{R_H I_x B}{b} \quad (8)$$

$$\text{(or)} \quad R_H = \frac{V_H b}{I_x B} \quad (9)$$

For an n – type semiconductor $R_H = \frac{-V_H b}{I_x B}$ (10)

Mobility of charge carriers

We know that hall coefficient $R_H = \frac{-1}{ne}$

This expression is correct only when the charge carriers is free from any attractive force in energy band and moves with constant drift velocity. But this is not true in the case of semiconductors.

Considering the average speed, it is shown that $R_H = \frac{-1.18}{ne}$ for electrons and $R_H = \frac{1.18}{pe}$ for holes.

We know that the electrical conductivity and mobility is related by $\sigma = n e \mu_e$

$$\text{(or)} \quad \mu_e = \frac{\sigma}{ne} \quad \& \quad \text{hence} \quad \mu_e = \frac{\sigma_e}{ne} \quad \text{and hence} \quad \mu_e = \frac{-R_H \sigma_e}{1.18} \quad (11)$$

$$\text{Similarly} \quad \mu_h = \frac{-R_H \sigma_h}{1.18} \quad (12)$$

Experimental Determination of Hall Coefficient:

The experimental setup for the measurement of Hall voltage is shown in figure.

A semiconducting material is taken in the form of a rectangular slab of thickness 't' and breadth 'b'. A suitable current I_x ampere is allowed to pass through this sample along the X axis by connecting it to battery

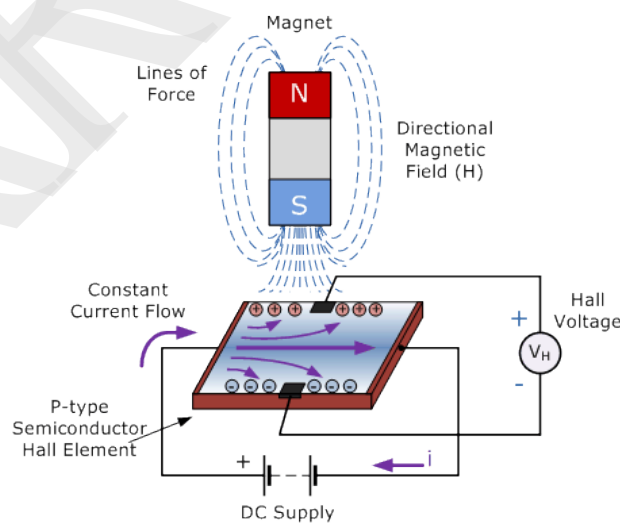
The sample is placed between the poles pieces of an electromagnet such that the applied magnetic field coincides with the z – axis.

Hall voltage (V_H) which is developed in the sample is measured by fixing two probes at the centers of the bottom and top faces of the sample.

By measuring Hall voltage, Hall coefficient is calculated from the formula $R_H = \frac{-V_H b}{I_x B}$

Applications

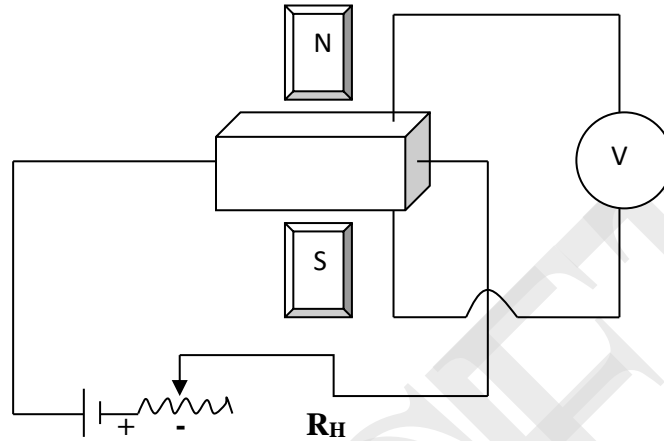
- (i) The sign of the hall coefficient is used to determine whether a give semiconductor is n – type or p – type
- (ii) Once Hall coefficient R_H is measured, the carrier concentration can be determined from $n = 1/e R_H$
- (iii) The mobility of charge carriers can be obtained if conductivity is known. $\mu_e = \sigma_e R_H$
- (iv) Hall voltage V_H for a given current is proportional to B . Hence measurement of V_H measures the magnetic field B .
- (v) This instrument gives an output proportional to the product of two signals. Thus if current I is made proportional to one input and if B is made proportional to the other input, then the Hall voltage V_H is proportional to the product of the two inputs.



3.18. Hall devices

(a) Gauss meter

The hall voltage, we have $V_H = \frac{R_H B_z I_x}{b}$. In this, $V_H \propto B_z$ for a given hall element; R_H and b are constant. The current I through Hall element is also kept constant. This principle is used in Gauss meter. It is used for measuring magnetic field. The variation of Hall voltage with magnetic field is shown in figure. The voltmeter which is used to measure V_H can be directly calibrated in terms of Gauss. The graph can be also used to measure any unknown magnetic fields.



(b) Electronic Multipliers

From Hall effect, we have $V_H = \frac{R_H B_z I_1}{b}$. Since R_H and b are constant for an element

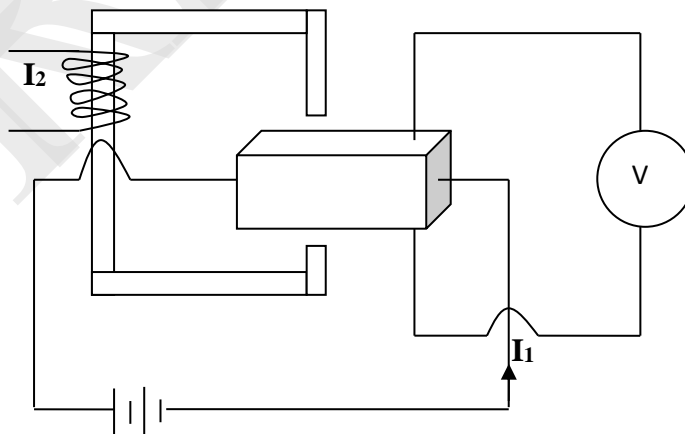
$$V_H \propto B_z I_1$$

But the magnetic field B_z is proportional to current (I_2) through the coil.

i.e., $V_H \propto I_2$

$$\therefore V_H \propto I_1 I_2$$

V_H is a measure of the product of two currents. This is the basic principle used in analog electronic multipliers. The figure shows the circuit diagram for electronic multiplier.



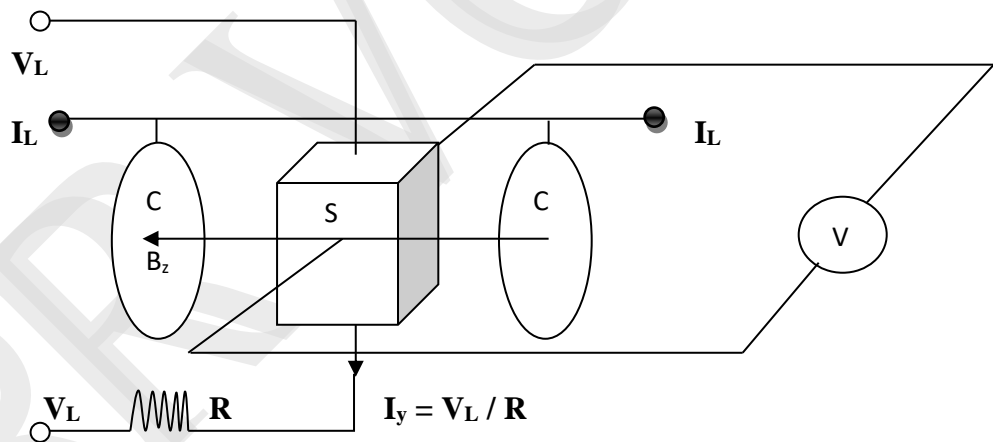
(c) Electronic Wattmeter

Hall effect is used to measure electrical power dissipated in a load. The instrument used to measure the power in a circuit using Hall effect principle is known as Hall effect – Wattmeter.

S is Hall element sample. It is placed in a magnetic field B_z produced by the load current I_L passing through the coils CC as shown in figure. The voltage across the load V_L drives the current $I_y = V_L / R$ through the sample. R is a series resistance which is \gg than the resistance of the sample and that of the load. Also, $I_y \ll I_L$. If b is the breadth of the sample, then the measured Hall voltage $V_H = \frac{R_H B_z I_y}{b}$. Since V_H and b are constant, $V_H \propto B_z I_y$

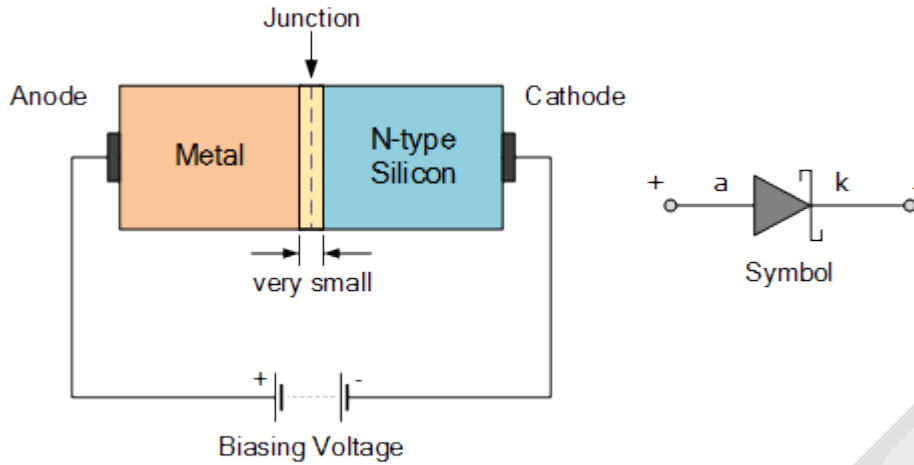
Since $B_z \propto I_L$ and $I_y \propto V_L$ & hence $V_H \propto I_L V_L$

This is the electric power dissipated by the load. The voltmeter that measures V_H can be calibrated to read power directly.



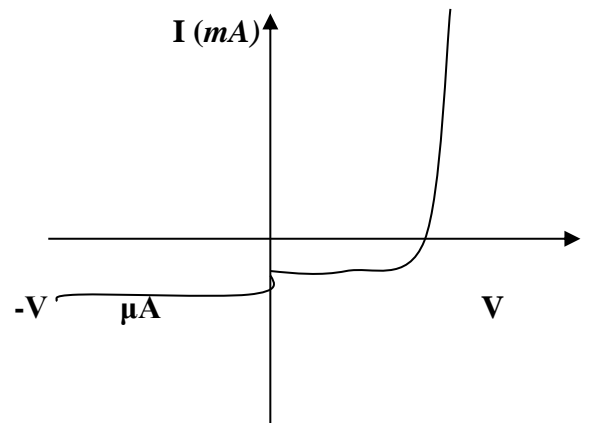
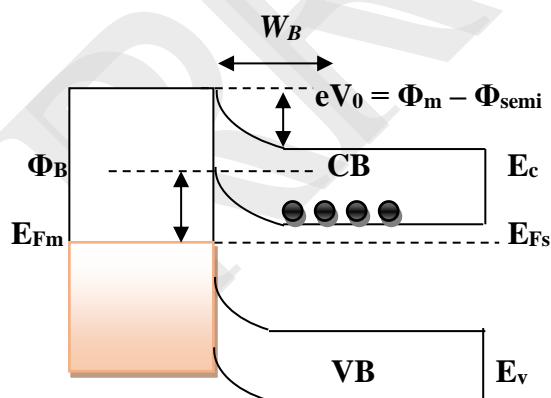
3.19. Schottky diode

It is the junction formed between a metal and n – type semiconductor. When the metal has a higher work function than that of n – type semiconductor then the junction formed is called Schottky diode. The Fermi level of the semiconductor is higher (since its work function is lower) than the metal. Figure shows Schottky diode and its circuit symbol.



The electrons in the conduction level of the semiconductor move to the empty energy states above the fermi level of the metal. This leaves a positive charge on the semiconductor side and a negative charge (due to the excess electrons) on the metal side as shown in figure. This leads to a contact potential

Energy band diagram



When a Schottky junction is formed between metal and semiconductor, fermi level lines up. Also a positive potential is formed on the semiconductor side. The formation of a depletion region of width W_D within the semiconductor is shown in figure. Because the depletion region extends within a certain depth in the semiconductor, there is bending of the energy bands on the semiconductor side. Bands bend up in the direction of the electric field produced in depletion

region. There is a built in potential V_o in the Schottky junction. From the figure this is given by the difference in work functions $eV_o = \phi_m - \phi_{semi}$

Working

The behaviour of Schottky diode is further studied by forward and reverse bias.

(a) Forward Bias

In this bias, metal is connected to positive terminal and n – type semiconductor is connected to negative terminal of the battery. In the forward biased Schottky junction, the external potential opposes the in- built potential. The electrons injected from the external circuit into the n – type semiconductor have a lower barrier to overcome before reaching the metal. This leads to a current in the circuit which increases with increasing external potential.

(b) Reverse Bias

In reverse bias, metal is connected to negative terminal and n – type semiconductor to positive terminal of the battery. In the case of reverse bias, the external potential is applied in the same direction as the junction potential. This increases the width of depletion region further and hence there is no flow of electron from semiconductor to metal. So Schottky junction acts as rectifier. i.e., it conducts in forward bias but not in reverse bias.

$V - I$ Characteristics

The $V - I$ characteristics of the junction is shown in figure. There is an exponential increase in current in the forward bias while there is a very small current in reverse bias.

Advantages

It has very low capacitance

It will immediately switch from ON to OFF state (fast recovery time)

Applying a small voltage is enough to produce large current

It has high efficiency

It operates at high frequencies

It produces less noise.

3.20. Ohmic contact

An ohmic contact is a type of metal semiconductor junction. It is formed by a contact of a metal with a heavily doped semiconductor. When the semiconductor has a higher work function than that of metal, then the junction formed is called the ohmic junction.

Here, the current is conducted equally in both directions and there is a very little voltage drop across the junction. Before contact, fermi levels of the metal and semiconductor are at different positions as shown in figure.

Working

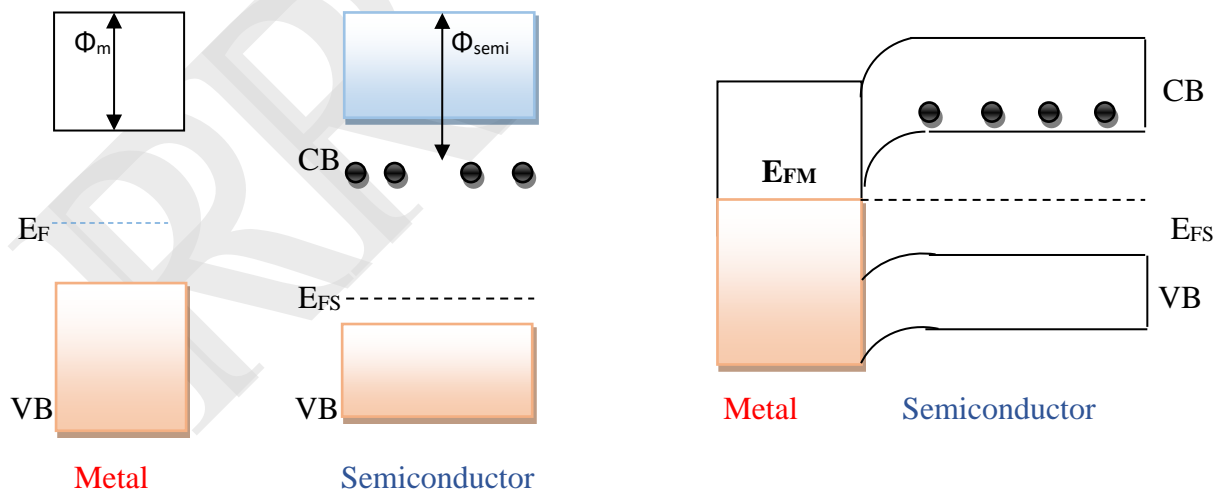
After contact, the ohmic junction is shown in figure. At equilibrium, the electrons move from the metal to the empty states in the conduction band of semiconductor. Thus, there is an accumulation region near the interface (on the semiconductor side). The accumulation region has higher conductivity than the bulk semiconductor due to this higher concentration of electrons. Thus, a ohmic contact behaves as a resistor conducting in both forward and reverse bias. The resistivity is determined by the bulk resistivity of the semiconductor.

V – I Characteristics

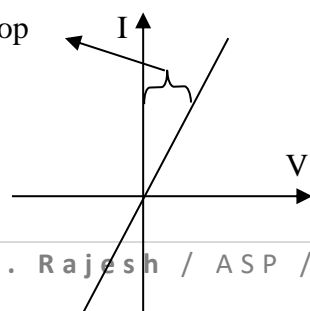
The V-I characteristics of the ohmic contact is shown in figure. The current is directly proportional to the potential across the junction and it is symmetric about the origin, as shown in figure. Thus, ohmic contacts are non-rectifying and show negligible voltage drop and resistance irrespective of the direction and magnitude of current.

Applications

The use of ohmic contacts is to connect one semiconductor device to another, an IC, or to connect an IC to its external terminals.



Negligible voltage drop



Part – A Questions and Answers:

1. State the properties of semiconductor?

- (i) The resistive lies between 10^{-4} to $0.5 \Omega m$
- (ii) At 0K, they behave as insulator
- (iii) The conductivity of the semiconductor increases both due to the temperature & impurity
- (iv) They have negative temperature coefficient of resistance
- (v) In semiconductors both the electron and holes are charge carriers and will take part in conduction.
- (vi) They are formed by covalent bonds

2. What are elemental and compound semiconductor? Give Example?

Elemental semiconductors (Indirect Band gap Semiconductors) are made from single element of fourth group elements of the periodic table.

Eg: Silicon, Germanium

Semiconductors (Indirect Band gap Semiconductors) which are formed by combining third and fifth group elements or second and sixth group elements of the periodic table are called compound semiconductors.

Eg: GaAs, InP, MgO, ZnS, etc.,

3. Differentiate Indirect and Direct Band gap semiconductor?

S.No	Indirect Bandgap Semiconductor	Direct Bandgap Semiconductor
1.	Heat produced during recombination	Photons emitted during recombination
2.	Life time of charge carriers is more	Life time of charge carriers is less
3.	They are used as diodes, transistors, etc.,	They are used as LED's, Laser diodes and IC's, etc.,
4.	Current amplification is more	Current amplification is less

4. What is meant by intrinsic and extrinsic semiconductor?

S.No	Intrinsic Semiconductor	Extrinsic Semiconductor
1.	It is the purest form of Semiconductor	It is due to adding Impurities to semiconductor
2.	Charge carriers are only due to thermal agitation	Charge carriers are due to impurities and thermal agitation
3.	They have low electrical conductivity	They have high electrical conductivity
4.	They have low operating temperature	They have low operating temperature

5.	At 0K, Fermi energy lies between valence band & conduction band	At 0K, Fermi energy is close to conduction band in 'n' type semiconductor & close to valence band in 'p' type semiconductor
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5. Define Fermi level in semiconductors? Mention its position in intrinsic & Extrinsic Semiconductor?

Fermi level is the energy level which separates the filled and empty energy states

Intrinsic Semiconductor: Here the Fermi level exactly lies between lowest energy level of conduction band and highest energy level of valence band $E_f = \frac{E_c + E_v}{2}$

'N-type Semiconductor' the Fermi energy lies exactly between minimum energy level of conduction band and donor energy level $E_f = \frac{E_c + E_d}{2}$

'P-type Semiconductor' the Fermi energy lies exactly between the acceptor energy level and the maximum energy level of valence band $E_f = \frac{E_c + E_a}{2}$

6. Define Hall Effect and Hall Voltage?

When a conductor carrying a current (I) is placed in a transverse magnetic field (B), a potential difference (Electric field) is produced inside the conductor in a direction normal to the direction of both the current and magnetic field. This phenomenon is known as **Hall Effect** and the generated voltage is called **Hall voltage**

7. State the law of mass action in semiconductor?

The product of electron & hole concentration remains constant at a given temperature and is equal to the square of intrinsic carrier concentration i.e., $n_i.n_e = n_i^2$

8. What are the applications of Hall Effect?

- (i) It is used to determine whether the material is p-type or n- type semiconductor
- (ii) It is used to find carrier concentration
- (iii) It is used to determine the sign of the current carrying charges
- (iv) It is used to measure magnetic flux density using a semiconductor sample of known hall coefficient.

9. Mention any four advantages of semiconducting materials?

- (i) It can behave as insulators at 0K and as conductors at high temperature
- (ii) They possess crystalline structure

(iii) N-type & p-type semiconductors are prepared by adding impurities with the charge carriers of electrons and holes respectively.

(iv) They find applications in manufacturing Diodes, Transistors, IC's , etc.,

10. Write an expression for carrier concentration in intrinsic semiconductor?

$$\text{Intrinsic carrier concentration } n_i = 2 \left[\frac{2\pi kT}{h^2} \right]^{\frac{3}{2}} (m_e^* m_h^*)^{\frac{3}{4}} e^{\left[\frac{-E_g}{2kT} \right]}$$

Where m_e^* - Effective mass of electron; m_h^* - Effective mass of hole; E_g – Band gap

11. Write an expression for carrier concentration in n - type semiconductor?

$$\text{Carrier concentration of n – type semiconductor is } n_i = [2N_d]^{1/2} \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{4}} e^{\left[\frac{E_d - E_c}{2kT} \right]}$$

Where m_e^* - Effective mass of electron; N_d – donor concentration; E_d - donor energy level;

E_c – Energy level in conduction band

12. Write an expression for carrier concentration in p - type semiconductor?

$$\text{Carrier concentration of n – type semiconductor is } n_i = [2N_a]^{1/2} \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{4}} e^{\left[\frac{E_v - E_a}{2kT} \right]}$$

Where m_e^* - Effective mass of electron; N_a – acceptor concentration; E_a - acceptor energy level; E_v – Energy level in valence band.

13. Define donors and acceptors and state its ionization energy?

Donors are the penta valent atoms which donates electrons to the pure semiconductors. The energy required to donate an electron from donor energy level to the conduction band by $\Delta E = E_c - E_d$ is called ionization energy of donor

Acceptors are the trivalent atoms which accept electrons from the pure semiconductor. The energy required to move an electron from valence band to acceptor energy level by $\Delta E = E_a - E_v$ is called ionization energy of acceptor.

14. Define drift current

The electric current produced due to the motion of charge carriers under the influence of an external electric field is known as drift current

15. Define diffusion current

The non-uniform distribution of charge carriers creates the regions of uneven concentrations in the semiconductor. The charge carriers moving from the region of higher concentration to the regions of lower concentration leading to diffusion current.

16. Differentiate Schottky diode and ohmic contacts?

S.No	Schottky diode	Ohmic contact
------	----------------	---------------

1.	It acts as a rectifier	It acts as a resistor
2.	Resistance is low during forward bias and very high during reverse bias	Resistance remains same in both the biasing voltage
3.	Work function $\phi_m > \phi_{semi}$	Work function $\phi_m < \phi_{semi}$
4.	Formed by the combination of metal and n – type semiconductor	Formed by the combination of metal and heavily doped semiconductor

17. Differentiate Schottky diode and $p-n$ diode

S.No	Schottky diode	$p-n$ diode
1.	Forward current due to thermionic current	Forward current due to diffusion current
2.	Charge carriers are only due to thermal agitation	Charge carriers are due to impurities and thermal agitation
3.	Reverse current is due to majority charge carrier that overcome the barrier	Reverse current due to minority carriers diffusing to the depletion layer and drifting to the other side
4.	Cut in voltage is ~ 0.3 V	Cut in voltage is ~ 0.7 V
5.	High switching speed	Switching speed is limited

18. What is meant by ohmic contact?

It is a type of metal semiconductor junction formed by a contact of a metal with heavily doped semiconductor. When the semiconductor has a higher work function than that of metal, then the junction formed is called the Ohmic junction

19. What is Schottky diode?

It is a junction formed between a metal and n type semiconductor. When the metal has a higher work function than that of n – type semiconductor then the junction formed is called Schottky diode.

20. Mention any three hall devices?

Gauss meter, Electronic watt meter and an electronic multiplier

21. What are the advantages of Schottky diode?

- (v) It has very low capacitance
- (vi) It will immediately switch from ON to OFF state
- (vii) Small voltage is enough to produce high current
- (viii) It has high efficiency
- (ix) It operates at high frequencies

- (x) It produces less noise
- 22. **What are the uses of ohmic contact?**

It is used to connect one semiconductor device to another, an IC, or to connect an IC to its external terminals.

23. What are the applications of Schottky diode?

- (1) It is used for rectification of signals of frequencies even exceeding 300 MHz
- (2) It is used in switching device at frequencies of 20 GHz
- (3) It is used in radio frequency applications
- (4) It is widely used in power supplies

Part – B Question & Answers

1. Derive an expression for the intrinsic carrier concentration of a semiconductor?

The number of charge carriers per unit volume of the material is called carrier concentration or density of charge carriers

Electrons in Conduction Band

The number of electrons whose energy lies in the range E to $E + dE$ is given by

$$dn = Z(E) F(E) dE \tag{1}$$

Where $Z(E)$ – density of states in the energy ranges ‘E’ & ‘E + dE’
 $F(E)$ – Probability of number of electron occupying in the conduction band

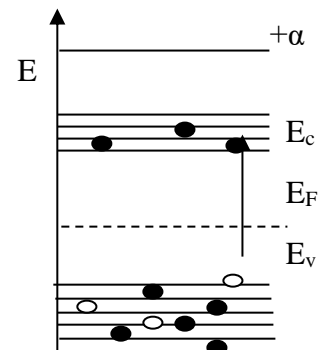
The number of electrons in the conduction band for the entire region is calculated by integrating equation (1) from top energy level ‘ E_c ’ to bottom energy level ‘ α ’

$$i.e., n = \int_{E_c}^{\alpha} Z(E) F(E) dE \tag{2}$$

W.K.T, Density of states in the conduction band in the energy range ‘E’ & ‘E+dE’ is given by

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

The bottom edge of the conduction band (E_c) represents the potential energy of an electron at rest. Therefore, $(E - E_c)$ is the kinetic energy of the conduction electron at higher energy levels. Therefore the equation (3) is modified as



Fig(i)

-α

$$Z(E) dE = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} (E - E_c)^{\frac{1}{2}} dE \quad (4)$$

Since the electron is moving in a periodic potential, its mass m is replaced by its effective mass m_e^* .

The probability of electron occupancy is given by $F(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$ (5)

Substituting (4) & (5) in (2), we get, $n = \int_{E_c}^{\infty} \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} (E - E_c)^{\frac{1}{2}} \times \frac{1}{1 + e^{(E-E_F)/kT}} dE$ (6)

For all possible temperature, $E - E_F \gg kT$, hence in the denominator, $1 + e^{\frac{E-E_F}{kT}} \cong e^{\frac{E-E_F}{kT}}$

Now equation (6) becomes, $n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} \int_{E_c}^{\infty} \frac{(E - E_c)^{\frac{1}{2}}}{e^{(E-E_F)/kT}} dE$

(or) $n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} \int_{E_c}^{\infty} (E - E_c)^{\frac{1}{2}} e^{(E_F-E)/kT} dE$

(or) $n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} e^{E_F/kT} \int_{E_c}^{\infty} (E - E_c)^{\frac{1}{2}} e^{-E/kT} dE$ (7)

To solve this, assume the following:

$E - E_c = x$	$E = E_c$	$E = +a$
$E = E_c + x$	$E_c - E_c = x$	$a - E_c = x$
$dE = dx$	$x = 0$	$x = a$

Now, $n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} e^{E_F/kT} \int_0^{\infty} x^{\frac{1}{2}} e^{-(E_c+x)/kT} dx$

(or) $n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} e^{(E_F-E_c)/kT} \int_0^{\infty} x^{\frac{1}{2}} e^{-x/kT} dx$ (8)

Using gamma function, $\int_0^{\infty} x^{\frac{1}{2}} e^{-x/kT} dx = \frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2}$ (9)

Substituting eqn (9) in (8), we get, $n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} e^{(E_F-E_c)/kT} \times \frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2}$

(or)

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}} e^{(E_F - E_C)/kT} \quad (10)$$

This is the expression of electrons in the conduction band of an intrinsic semiconductor.

Concentration of holes in the Valence band

We know that if an electron is transferred from valence band to conduction band, a hole is created in valence band. Let dp be the number of holes in the valence band for the energy range E & $E+dE$. $\therefore dp = Z(E) (1 - F(E)) dE$

(1)

Where $Z(E)$ – Density of states in the energy range E & $E+dE$

$(1 - F(E))$ – Probability of unoccupied (vacant) electron state (presence of hole) in valence band

$$\therefore (1 - F(E)) dE = 1 - \frac{1}{1 + e^{(E-E_F)/kT}} = \frac{1 + e^{(E-E_F)/kT} - 1}{1 + e^{(E-E_F)/kT}} = \frac{e^{(E-E_F)/kT}}{1 + e^{(E-E_F)/kT}} \quad (2)$$

$\therefore E < E_F$ in valence band, $(E - E_F)$ has negative quantity & hence in denominator $e^{(E-E_F)/kT}$ is very small when compared with 1, hence $1 + e^{(E-E_F)/kT} \cong 1$

$$\therefore 1 - F(E) = e^{(E-E_F)/kT} \quad (3)$$

E_V is the top level in the valence band and having potential energy of a hole at rest. Hence

$(E_V - E)$ is the kinetic energy of the hole at level below E_V . Hence,

$$\text{Density of states in the valence band is } Z(E)dE = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} (E_V - E)^{\frac{1}{2}} dE \quad (4)$$

Where, m_h^* - effective mass of the hole in the valence band

$$\text{Substituting equation (4), (3) in (1), we get, } dp = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} (E_V - E)^{\frac{1}{2}} e^{(E-E_F)/kT} dE$$

(5)

The number of holes in the valence band for the entire energy range is obtained by integrating

Above equation between the limits $-\infty$ to E_V

$$\text{i.e., } \int dp = \int_{-\infty}^{E_V} \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} (E_V - E)^{\frac{1}{2}} e^{(E-E_F)/kT} dE$$

$$\text{(or) } dp = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} e^{-E_F/kT} \int_{-\infty}^{E_V} (E_V - E)^{\frac{1}{2}} e^{E/kT} dE \quad (6)$$

To solve this, assume the following:

$E_v - E = x$	$E = -\alpha$	$E = E_v$
$E = E_v - x$	$E_v - (-\alpha) = x$	$E_v - E_v = x$
$dE = -dx$	$x = \alpha$	$x = 0$

$$p = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} e^{-E_F/kT} \int_{\infty}^0 x^{\frac{1}{2}} e^{-(x+E_v)/kT} (-dx)$$

$$(or) \quad p = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} e^{(E_v-E_F)/kT} \int_0^{\infty} x^{\frac{1}{2}} e^{-x/kT} dx \quad (7)$$

$$\text{Using gamma function, } \int_0^{\infty} x^{\frac{1}{2}} e^{-x/kT} dx = \frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2} \quad (8)$$

$$\text{Substituting eqn (8) in (7), we get, } p = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} e^{(E_v-E_F)/kT} \times \frac{(kT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2}$$

$$(or) \quad p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{\frac{3}{2}} e^{(E_v-E_F)/kT} \quad (9)$$

This is the expression of holes in the valence band of an intrinsic semiconductor

Intrinsic Carrier Concentration:

In intrinsic semiconductor, carrier concentration of electrons in conduction band (n_i) = carrier concentration of holes in valence band n_p &

hence the intrinsic carrier concentration is $n_i^2 = n_i \times n_p$

$$n_i^2 = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{\frac{3}{2}} e^{(E_F-E_C)/kT} \times 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{\frac{3}{2}} e^{(E_v-E_F)/kT} \quad (1)$$

$$(or) \quad n_i^2 = 4 \left(\frac{2\pi kT}{h^2} \right)^3 (m_e^* \times m_h^*)^{\frac{3}{2}} e^{(E_v-E_C)/kT}$$

$$(or) \quad n_i^2 = 4 \left(\frac{2\pi kT}{h^2} \right)^3 (m_e^* \times m_h^*)^{\frac{3}{2}} e^{-E_g/kT} \quad (2)$$

$$(or) n_i = 2 \left(\frac{2\pi kT}{h^2} \right)^{\frac{3}{2}} (m_e^* \times m_h^*)^{\frac{3}{4}} e^{-\frac{E_g}{2kT}}$$

Where $E_c - E_v = E_g$ is the forbidden energy gap.

2. Discuss the variation of Fermi Level with temperature in an intrinsic semiconductor?

We know that, for an intrinsic semiconductor, the density of electron in the conduction band is equal to the density of holes in the valence band.

$$i.e., n_i = n_p \tag{1}$$

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

$$\text{Rearranging, we get, } e^{(E_F - E_c)/kT} = \left(\frac{m_h^*}{m_e^*} \right)^{\frac{3}{2}} e^{(E_v - E_F)/kT}$$

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

Taking log on both sides, we get

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

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

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

$$(or) \boxed{E_F = \frac{3kT}{4} \log_e \left(\frac{m_h^*}{m_e^*} \right) + \left[\frac{E_v + E_c}{2} \right]}$$

(2)

$$\text{If } m_e^* = m_h^*, \text{ then } \log_e \left(\frac{m_h^*}{m_e^*} \right) = \log_e 1 = 0,$$

hence the above equation becomes, $E_F = \left[\frac{E_v + E_c}{2} \right]$

(3)

Thus, the Fermi level is located half way between the top of the valence band and bottom of the conduction band. Its position is independent of temperature. If $m_e^* < m_h^*$, thus, the Fermi level is just above the middle of energy gap and its rises slightly with increasing temperature.

3. Discuss the carrier concentration, the variation of Fermi level with temperature in the case of n –type semiconductors for low doping level?

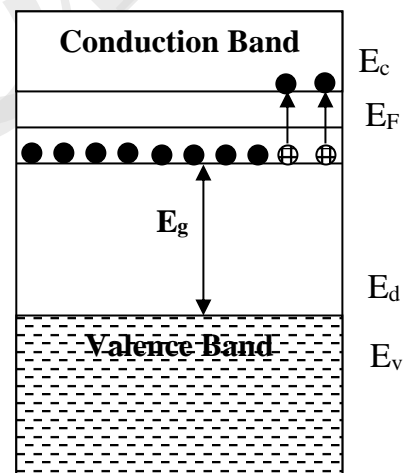
In n –type semiconductor, the donor level is just below the conduction band. N_d denotes the donor concentration & E_d represents the energy of the donor level.

Density of electrons per unit volume in the conduction band is given by

$$n = 2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}} e^{(E_F - E_c)/kT} \tag{1}$$

here E_f – Fermi energy; E_c – Energy corresponding to the bottom of the conduction band

Density of the ionized donors = $N_d [1 - F(E)]$



$$\begin{aligned} &= N_d \left[1 - \frac{1}{1 + e^{(E_d - E_F)/kT}} \right] \\ &= N_d \left[\frac{1 + e^{(E_d - E_F)/kT} - 1}{1 + e^{(E_d - E_F)/kT}} \right] \\ &= N_d \left[\frac{e^{(E_d - E_F)/kT}}{1 + e^{(E_d - E_F)/kT}} \right] \end{aligned}$$

$$\text{Density of ionized donors} = \left[\frac{N_d}{1 + e^{(E_d - E_F)/kT}} \right] = \left[\frac{N_d}{1 + e^{(E_F - E_d)/kT}} \right] \tag{2}$$

At equilibrium, the density of electrons in conduction band = Density of ionized donors.

$$\text{Equating (1) \& (2), } 2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}} e^{(E_F - E_c)/kT} = \frac{N_d}{1 + e^{(E_F - E_d)/kT}} \tag{3}$$

E_F lies more than few kT above donor levels, hence $e^{(E_d - E_F)/kT}$ is large compared to '1'. Hence the '1' in denominator of R.H.S of equation (3) is neglected.

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

$$(or) 2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}} e^{(E_F - E_c)/kT} = N_d e^{(E_d - E_F)/kT} \quad (4)$$

Taking log on both sides,

$$\log \left[2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}} \right] + \log_e e^{(E_F - E_c)/kT} = \log_e N_d e^{(E_d - E_F)/kT}$$

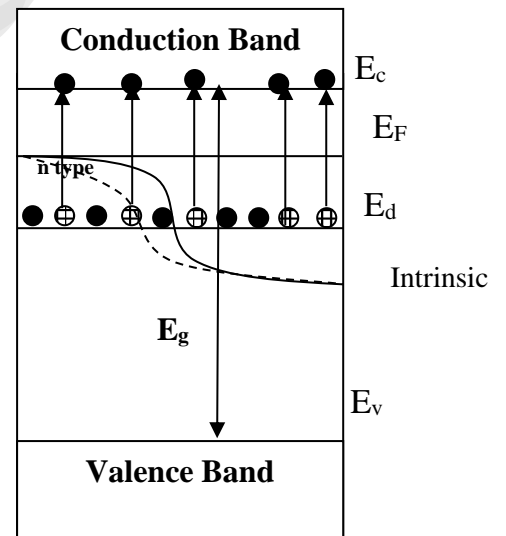
$$(or) \log \left[2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}} \right] + \frac{E_F - E_c}{kT} = \log N_d + \frac{E_d - E_F}{kT} \quad (5)$$

$$(or) \frac{E_F - E_c - E_d + E_F}{kT} = \log N_d - \log \left[2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}} \right]$$

$$(or) \frac{2E_F - E_c - E_d}{kT} = \log \left[\frac{N_d}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}}} \right]$$

$$(or) 2E_F = E_d + E_c + kT \log \left[\frac{N_d}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}}} \right]$$

$$(or) E_F = \frac{E_d + E_c}{2} + \frac{kT}{2} \log \left[\frac{N_d}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{\frac{3}{2}}} \right] \quad (6)$$



Substituting the expression of E_F from (6) in (1), we get

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \exp \left[\frac{\left(\frac{E_d + E_c}{2} + \frac{kT}{2} \log \left[\frac{N_d}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{3/2}} \right] - E_c \right)}{kT} \right] \quad (7)$$

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \exp \left[\left(\frac{E_d + E_c - 2E_c}{2kT} + \frac{1}{2} \log \left[\frac{N_d}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{3/2}} \right] \right) \right]$$

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \exp \left[\left(\frac{E_d - E_c}{2kT} + \log \left[\frac{(N_d)^{1/2}}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{3/2}} \right] \right) \right]$$

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \frac{\left[\frac{N_d}{2} \right]^{1/2}}{\left[\frac{2\pi m_e^* kT}{h^2} \right]^{3/4}} e^{(E_d - E_c)/2kT} \quad (8)$$

Rearranging the expression (8), we have

$$(or) \quad n = (2N_d)^{1/2} \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/4} e^{(E_d - E_c)/2kT}$$

$$(or) \quad n = (2N_d)^{1/2} \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/4} e^{(-\Delta E)/2kT}$$

Where $\Delta E = E_c - E_d$ is the ionization energy to transfer Energy from donor energy level to the conduction band.

Results:

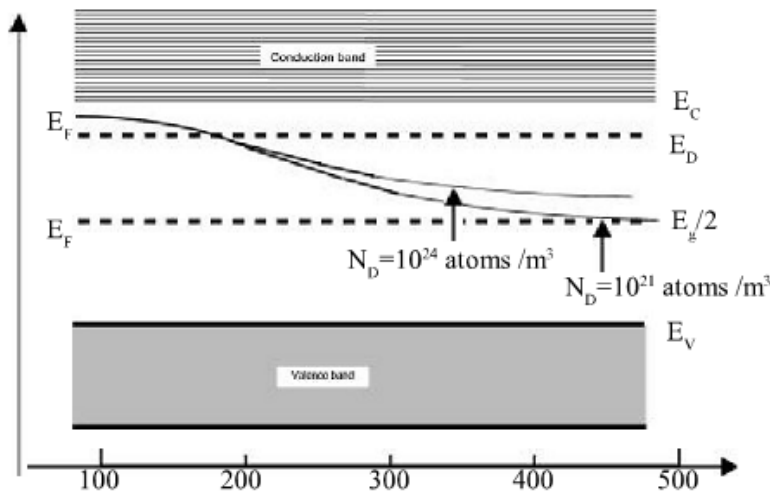
- (iii) The density of electrons is proportional to square root of donor concentration and valid at low temperature alone
- (iv) At high temperature, intrinsic carrier concentration must take along with this concentration

Variation of Fermi level with temperature and impurity concentration

Fermi level of n – type semiconductor is
$$E_F = \frac{E_d + E_c}{2} + \frac{kT}{2} \log \left[\frac{N_d}{2 \left[\frac{2\pi m_e^* kT}{h^2} \right]^{3/2}} \right] \quad (1)$$

At $T = 0K$, the above equation reduces to
$$E_F = \frac{E_d + E_c}{2} \quad (2)$$

- (iv) At $0K$, Fermi level lies exactly at the centre of the donor level and bottom of the conduction band.
- (v) As the temperature is gradually increased from a low temperature, the contribution of electron increases and at very high temperature, it far exceeds the donor concentration and the intrinsic behaviour predominates at higher temperature.
- (vi) Fermi level shifts downwards when the temperature is increased and finally reaches the middle of the band gap (or) intrinsic Fermi level.
- (vii) Further when the concentration of donors increases, the extrinsic behaviour also extends up to very high temperature & Fermi level reaches the middle of the band gap only at high temperature.



4. Discuss the carrier concentration, the variation of Fermi level with temperature in the case of p –type semiconductors for low doping level?

In p – type semiconductor, the acceptor energy level is just above the valence band. Let E_a represents the energy of the acceptor level and N_a represents the number of acceptor atoms per unit volume.

Density of holes per unit volume in valence band is given by
$$p = 2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{3/2} e^{(E_v - E_F)/kT}$$

(1)

Where E_v is the energy corresponding to the top of the conduction band

$$\text{Density of the ionized acceptors} = N_a F(E_a) = \frac{N_a}{1 + e^{(E_a - E_F)/kT}}$$

(2)

Since $E_a - E_F$ is very large when compared to kT . $e^{(E_a - E_F)/kT}$ is a large quantity and thus '1' in denominator of R.H.S of equation(2) is neglected. hence, equation(2), reduces to

$$N_a F(E_a) = \frac{N_a}{e^{(E_a - E_F)/kT}} = N_a e^{(E_F - E_a)/kT}$$

(3)

At equilibrium, the density of holes in Valence band = Density of ionized acceptors

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

(4)

Taking log on both sides,

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

$$\text{(or) } \log \left[2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}} \right] + \frac{E_v - E_F}{kT} = \log N_a + \frac{E_F - E_a}{kT}$$

(5)

Rearranging the expression (5), we have

$$\frac{E_F - E_a - E_v + E_F}{kT} = -\log N_a + \log \left[2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}} \right]$$

$$\text{(or) } \frac{2E_F - (E_a + E_v)}{kT} = -\log_e \left\{ \frac{N_a}{\left[2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{\frac{3}{2}} \right]} \right\}$$

$$(or) \quad 2E_F = (E_a + E_v) - kT \log_e \left\{ \frac{N_a}{2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{3/2}} \right\}$$

$$(or) \quad E_F = \frac{(E_a + E_v)}{2} - \frac{kT}{2} \log_e \left\{ \frac{N_a}{2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{3/2}} \right\} \quad (6)$$

Sub. The expression of E_F in equation (6), we get

$$p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \exp \left[\frac{E_v - \frac{E_v - E_a}{2} + \frac{kT}{2} \log \left[\frac{N_a}{2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{3/2}} \right]}{kT} \right] \quad (7)$$

$$(or) \quad p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \exp \left[\left(\frac{2E_v - E_v - E_a}{2kT} + \frac{1}{2} \log \left[\frac{N_a}{2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{3/2}} \right] \right) \right] \quad (8)$$

$$(or) \quad p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \frac{\left[\frac{N_a}{2} \right]^{1/2}}{\left[\left[\frac{2\pi m_h^* kT}{h^2} \right]^{3/2} \right]^{1/2}} e^{\frac{E_v - E_a}{2kT}}$$

$$(or) \quad p = (2N_a)^{1/2} \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/4} e^{(E_v - E_a)/2kT} \quad (9)$$

If $E_a - E_v = \blacktriangle E$ is the acceptor ionization energy required to move the electron from valence band to acceptor energy level, then equation (9) becomes,

$$p = (2N_a)^{1/2} \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/4} e^{-\blacktriangle E/2kT} \quad (10)$$

Results:

- (iii) Density of holes in valence band is proportional to square root of acceptor concentration
- (iv) At very high temperature p – type semiconductor behaves like an intrinsic semiconductor

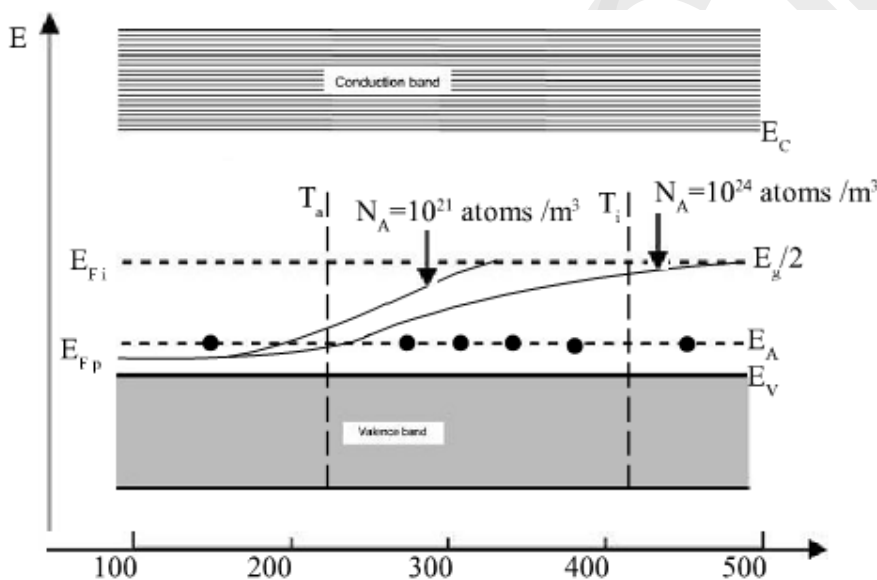
Variation of Fermi level with temperature

We know that

$$E_F = \frac{(E_a + E_v)}{2} - \frac{kT}{2} \log_e \left\{ \frac{N_a}{2 \left[\frac{2\pi m_h^* kT}{h^2} \right]^{3/2}} \right\} \quad (1)$$

At $T = 0K$, the above expression becomes, $E_F = \frac{E_a + E_v}{2}$ (2)

- (iv) At $0K$ the Fermi level lies exactly halfway between acceptor level E_a and top of the valence band E_v



- (v) As the temperature increases, the Fermi level shifts upwards, at a particular temperature, when all the acceptor atoms are ionized and Fermi level crosses the acceptor level
- (vi) At very high temperature, the Fermi level is shifted to intrinsic Fermi level and behave as intrinsic semiconductor

5. What is Hall Effect? Derive an expression of hall coefficient? Describe an experimental setup for the measurement of hall coefficient?

“When the conductor carrying a current (I) is placed in a perpendicular magnetic field (B), a potential difference is developed inside the conductor in a direction normal to the directions of both the current and magnetic field”

This phenomenon is known as Hall Effect and the corresponding voltage thus generated is called Hall voltage

Explanation

Consider an external field applied along the X-axis of the specimen. Assuming that the material is n-type semiconductor, the current flow consists mainly of electrons moving from right to left, corresponding to the conventional current direction.

When this specimen is placed in a magnetic field ‘B’ and if ‘v’ is the velocity of the electrons perpendicular to the magnetic field then each one of them will experience a downward force of magnitude Bev

This downward force (Lorentz Force F_L) due to magnetic field causes the electrons to be deflected in the downward direction and hence there is an accumulation of negative charges on the bottom face of the slab. This causes the bottom face of the slab to be more negative with respect to the top face and a potential difference is established from top to bottom of the specimen. This potential difference causes a field E_H called Hall field in negative y direction. There is a force eE_H acting on the electron in the upward direction due to this field.

Theory of Hall Effect

At equilibrium, the downward force Bev will balance the upward force eE_H

$$Bev = eE_H \tag{1}$$

In a uniform sample, the electric current density (J) is related to the drift velocity as

$$J = -nev$$

Where n is the concentration of electrons.

$$V = \frac{-J}{ne}$$

Substituting equation (2) in (1),

$$E_H = \frac{-BJ}{ne}$$

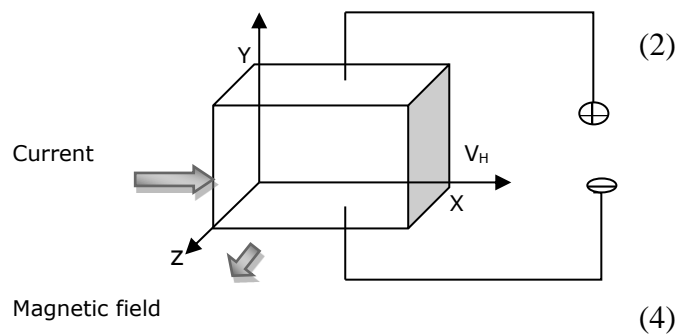
This can be written as $E_H = BJR_H$

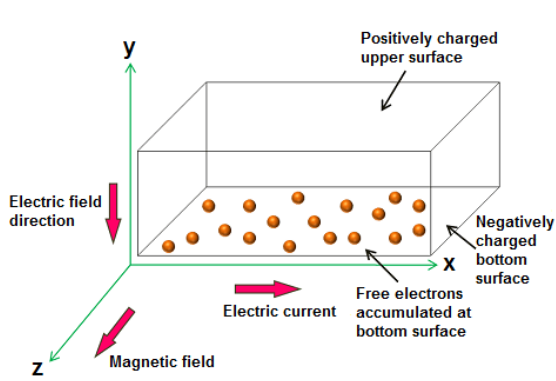
Where $R_H = -1 / ne$ is called Hall coefficient

The negative sign indicates that the developed field is in the negative y direction.

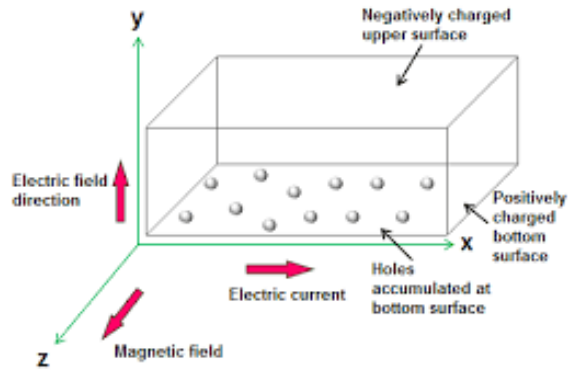
Similarly, the Hall coefficient for p – type semiconductor is $R_H = 1 / pe$.

Where p is the concentration of holes





Hall Effect in N-type semiconductor



Hall Effect in P-type semiconductor

Determination of Hall coefficient

The hall field per unit current density per unit magnetic induction is defined as hall coefficient.

If t is the thickness of the sample and V_H is the hall voltage, then $V_H = E_H t$ (5)

Where E_H is hall field.

From equation (4), we get $E_H = R_H J_x B$

Substituting the value of (5) in above equation, we get $V_H = R_H J_x B t$ (6)

Now the current density J_x can be written as $J_x = \frac{I_x}{bt}$ (7)

Where ' b ' is the width and bt is the area of cross section of the sample

Substituting equation (7) in equation (6), we get $V_H = \frac{R_H I_x B t}{bt}$ (8)

$$V_H = \frac{R_H I_x B}{b}$$

$$(or) \quad \boxed{R_H = \frac{V_H b}{I_x B}} \quad (9)$$

For an n – type semiconductor $\boxed{R_H = \frac{-V_H b}{I_x B}}$ (10)

Mobility of charge carriers

We know that hall coefficient $R_H = \frac{-1}{ne}$

This expression is correct only when the charge carriers is free from any attractive force in energy band and moves with constant drift velocity. But this is not true in the case of semiconductors.

Considering the average speed, it is shown that $R_H = \frac{-1.18}{ne}$ for electrons and $R_H = \frac{1.18}{pe}$

for holes.

We know that the electrical conductivity and mobility is related by $\sigma = n e \mu_e$

(or) $\mu_e = \frac{\sigma}{ne}$ & hence $\mu_e = \frac{\sigma_e}{ne}$ and hence $\mu_e = \frac{-R_H \sigma_e}{1.18}$

(11)

Similarly $\mu_h = \frac{-R_H \sigma_h}{1.18}$

(12)

Experimental Determination of Hall Coefficient:

The experimental setup for the measurement of Hall voltage is shown in figure.

A semiconducting material is taken in the form of a rectangular slab of thickness ‘t’ and breadth ‘b’. A suitable current I_x ampere is allowed to pass through this sample along the X axis by connecting it to battery

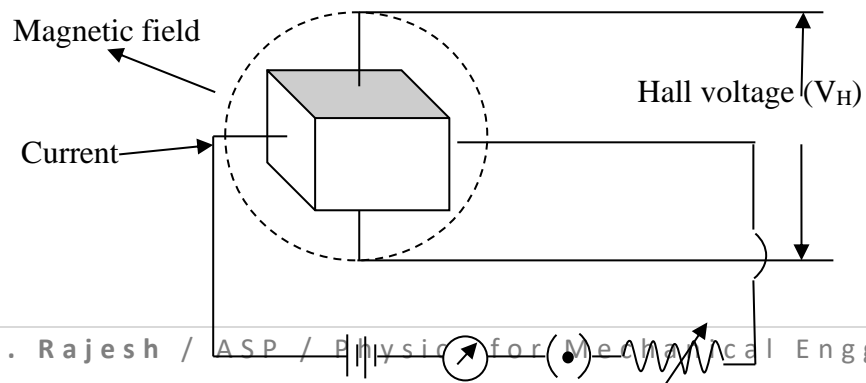
The sample is placed between the poles pieces of an electromagnet such that the applied magnetic field coincides with the z – axis.

Hall voltage (V_H) which is developed in the sample is measured by fixing two probes at the centers of the bottom and top faces of the sample.

By measuring Hall voltage, Hall coefficient is calculated from the formula $R_H = \frac{-V_H b}{I_x B}$

Applications

- (vi) The sign of the hall coefficient is used to determine whether a give semiconductor is n – type or p – type
- (vii) Once Hall coefficient R_H is measured, the carrier concentration can be determined from $n = 1 / e R_H$
- (viii) The mobility of charge carriers can be obtained if conductivity is known. $\mu_e = \sigma_e R_H$
- (ix) Hall voltage V_H for a given current is proportional to B . Hence measurement of V_H measures the magnetic field B .
- (x) This instrument gives an output proportional to the product of two signals. Thus if current I is made proportional to one input and if B is made proportional to the other input, then the Hall voltage V_H is proportional to the product of the two inputs.



+ -
Bt mA key Rh

6. Derive an expression to find the total current density due to drift and diffusion of electrons and holes in semiconductor?

The net current flow in semiconductor is due to drift and diffusion transport.

Drift transport

In the absence of electric field, the random motion of charge carriers will not contribute current because the charge movement in one direction is balance by the charge movement in the other direction. When the external field is applied, the electrons are attracte to the positive terminal and the holes are attracte to the negative terminal. This net movement is termed as drift transport. This transport overcomes the thermal movement and produces current density

Therefore, current density due to electron drift is $J_e = n_e e v_d$ (1)

Since $v_d = \mu_e E$ (2)

Substitute (2) in (1), we get

$J_e = n_e e \mu_e E$ (3)

Similarly, for holes, $J_h = n_h e \mu_h E$ (4)

Then the total drift current is $j_{dr} = n_e e \mu_e E + n_h e \mu_h E$ (5)

We know that $J = \sigma E$ (6)

Therefore $\sigma_{dr} = n_e e \mu_e + n_h e \mu_h$ (7)

For an intrinsic semiconductor $n_e = n_h = n_i$

& Hence $\sigma_{dr} = n_i e [\mu_e + \mu_h]$ (8)

Diffusion transport

The non-uniform distribution of charge carriers creates the regions of uneven concentrations in the semiconductor. The charge carriers moving from the region of higher concentration to the regions of lower concentration leading to diffusion current

Hence the concentration of charge carrier (Δn_e) varies with distance x in a semiconductor.

The rate of flow of charge carriers is $\propto \frac{\partial}{\partial x} (\Delta n_e)$

Rate of flow of electrons = $-D_e \frac{\partial}{\partial x} (\Delta n_e)$

Where D_e is the electron diffusion coefficient

Current density due to electrons = charge X rate of flow of electrons

$$\text{i.e., } J_e = D_e e \frac{\partial}{\partial x} (\Delta n_e)$$

Similarly for holes, $J_h = -D_h e \frac{\partial}{\partial x} (\Delta n_h)$

Thus, if an electric field is applied to the semiconductor, the total current contribution is due to both drift and diffusion transport.

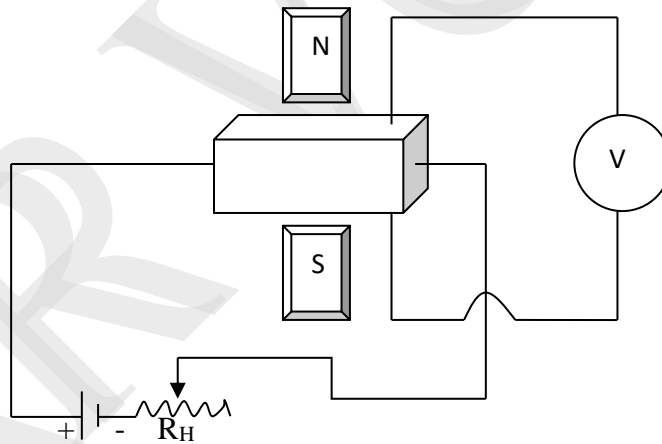
Net current due to both electrons and holes can be obtained as

$$J_{total} = n_e \mu_e e E + e D_e \frac{\partial}{\partial x} (\Delta n_e) + n_h e \mu_h E - D_h e \frac{\partial}{\partial x} (\Delta n_h)$$

7. Explain any three hall devices?

(d) Gauss meter

The hall voltage, we have $V_H = \frac{R_H B_Z I_X}{b}$. In this, $V_H \propto B_z$ for a given hall element; R_H and b are constant. The current I through Hall element is also kept constant. This principle is used in Gauss meter. It is used for measuring magnetic field. The variation of Hall voltage with magnetic field is shown in figure. The voltmeter which is used to measure V_H can be directly calibrated in terms of Gauss. The graph can be also used to measure any unknown magnetic fields.



(e) Electronic Multipliers

From Hall effect, we have $V_H = \frac{R_H B_Z I_1}{b}$. Since R_H and b are constant for an element

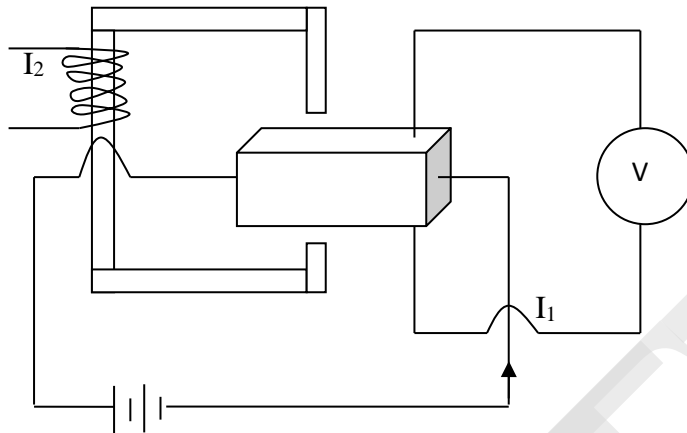
$$V_H \propto B_z I_1$$

But the magnetic field B_Z is proportional to current (I_2) through the coil.

$$\text{i.e., } V_H \propto I_2$$

$$\therefore V_H \propto I_1 I_2$$

V_H is a measure of the product of two currents. This is the basic principle used in analog electronic multipliers. The figure shows the circuit diagram for electronic multiplier.



(f) Electronic Wattmeter

Hall effect is used to measure electrical power dissipated in a load. The instrument used to measure the power in a circuit using Hall effect principle is known as Hall effect – Wattmeter.

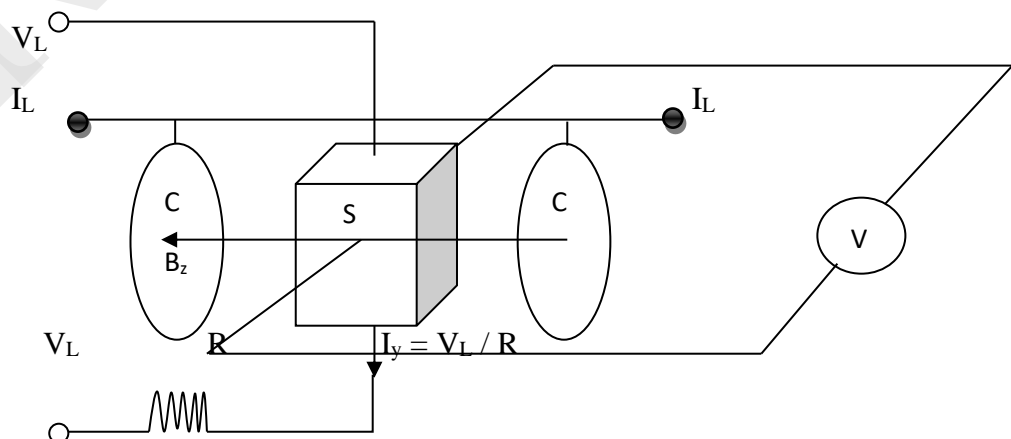
S is Hall element sample. It is placed in a magnetic field B_z produced by the load current I_L passing through the coils CC as shown in figure. The voltage across the load V_L drives the current $I_y = V_L/R$ through the sample. R is a series resistance which is \gg than the resistance of the sample and that of the load. Also, $I_y \ll I_L$. If b is the breadth of the sample, then the measured Hall voltage

$$V_H = \frac{R_H B_z I_y}{b}$$

Since V_H and b are constant, $V_H \propto B_z I_y$

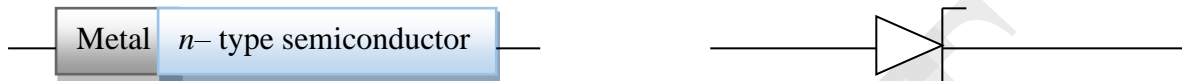
Since $B_z \propto I_L$ and $I_y \propto V_L$ & hence $V_H \propto I_L V_L$

This is the electric power dissipated by the load. The voltmeter that measures V_H can be calibrated to read power directly.

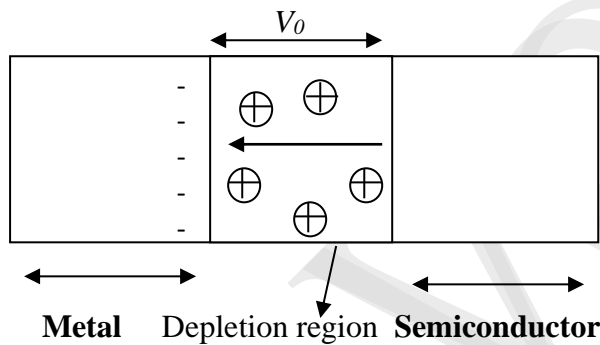


8. Describe the construction and working of Schottky diode? What are its advantages?

It is the junction formed between a metal and n – type semiconductor. When the metal has a higher work function than that of n – type semiconductor then the junction formed is called Schottky diode. The fermi level of the semiconductor is higher (since its work function is lower) than the metal. Figure shows Schottky diode and its circuit symbol.

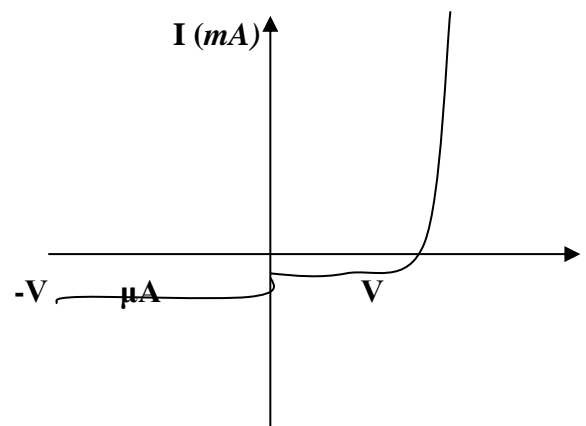
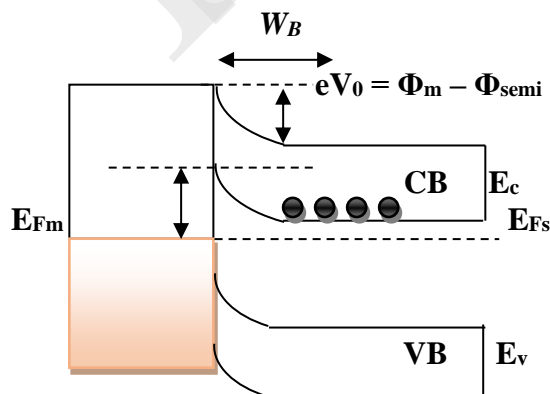


The electrons in the conduction level of the semiconductor move to the empty energy states above the Fermi level of the metal. This leaves a positive charge on the semiconductor side and a negative charge (due to the excess electrons) on the metal side as shown in figure. This leads to a contact potential.



When a Schottky junction is formed between metal and semiconductor, fermi level lines up. Also a positive potential is formed on the semiconductor side. The formation of a depletion region of width W_D within the semiconductor is shown in figure. Because the depletion region extends within a certain depth in the semiconductor, there is bending of the energy bands on the semiconductor side. Bands bend up in the direction of the electric field produced in depletion region. There is a built in potential V_0 in the Schottky junction. From the figure this is given by the difference in work functions $eV_0 = \phi_m - \phi_{semi}$

Energy band diagram



Working

The behaviour of Schottky diode is further studied by forward and reverse bias.

(c) Forward Bias

In this bias, metal is connected to positive terminal and n – type semiconductor is connected to negative terminal of the battery. In the forward biased Schottky junction, the external potential opposes the in- built potential. The electrons injected from the external circuit into the n – type semiconductor have a lower barrier to overcome before reaching the metal. This leads to a current in the circuit which increases with increasing external potential.

(d) Reverse Bias

In reverse bias, metal is connected to negative terminal and n – type semiconductor to positive terminal of the battery. In the case of reverse bias, the external potential is applied in the same direction as the junction potential. This increases the width of depletion region further and hence there is no flow of electron from semiconductor to metal. So Schottky junction acts as rectifier. i.e., it conducts in forward bias but not in reverse bias.

 $V - I$ Characteristics

The $V - I$ characteristics of the junction is shown in figure. There is an exponential increase in current in the forward bias while there is a very small current in reverse bias.

Advantages

It has very low capacitance

It will immediately switch from ON to OFF state (fast recovery time)

Applying a small voltage is enough to produce large current

It has high efficiency

It operates at high frequencies

It produces less noise.

9. Write a note on ohmic contact?

An ohmic contact is a type of metal semiconductor junction. It is formed by a contact of a metal with a heavily doped semiconductor. When the semiconductor has a higher work function than that of metal, then the junction formed is called the ohmic junction.

Here, the current is conducted equally in both directions and there is a very little voltage drop across the junction. Before contact, Fermi levels of the metal and semiconductor are at different positions as shown in figure.

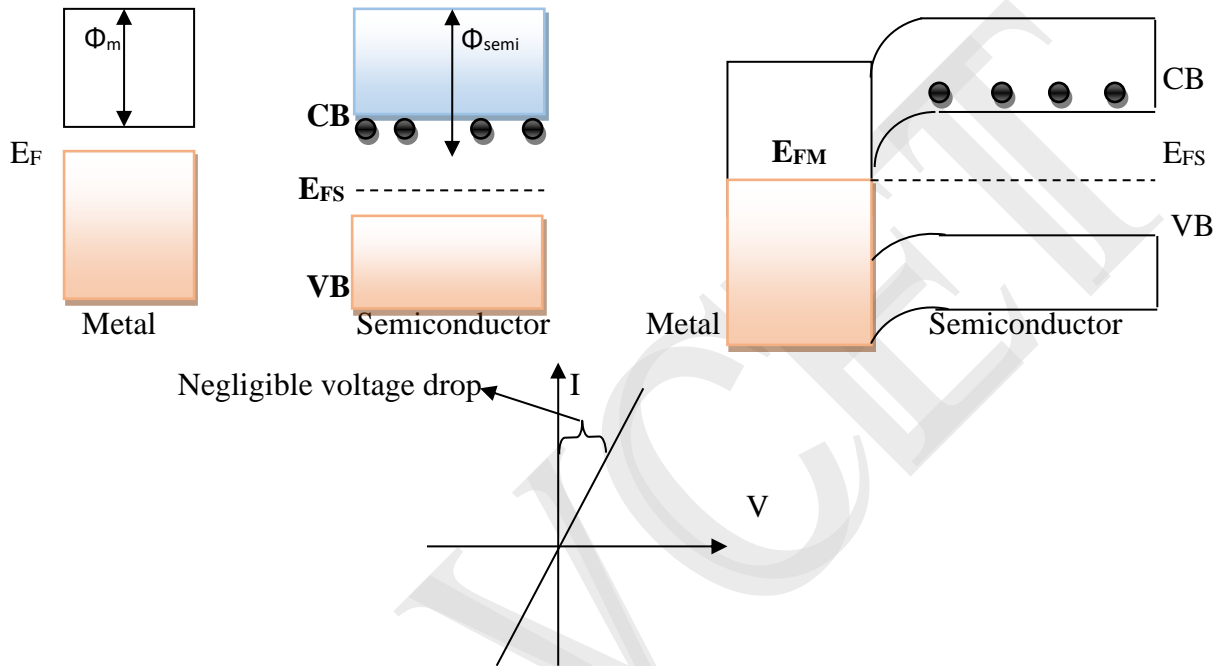
Working

After contact, the ohmic junction is shown in figure. At equilibrium, the electrons move from the metal to the empty states in the conduction band of semiconductor. Thus, there is an accumulation region near the interface (on the semiconductor side). The accumulation region has higher conductivity than the bulk semiconductor due to this higher concentration of

electrons. Thus, an ohmic contact behaves as a resistor conducting in both forward and reverse bias. The resistivity is determined by the bulk resistivity of the semiconductor.

V – I Characteristics

The V-I characteristics of the ohmic contact is shown in figure. The current is directly proportional to the potential across the junction and it is symmetric about the origin, as shown in figure. Thus, ohmic contacts are non-rectifying and show negligible voltage drop and resistance irrespective of the direction and magnitude of current.



Applications

The use of ohmic contacts is to connect one semiconductor device to another, an IC, or to connect an IC to its external terminal.