2. Semiconductor Physics

Intrinsic Semiconductors - Energy band diagram - direct and indirect band gap semiconductors - Carrier concentration in intrinsic semiconductors - extrinsic semiconductors - Carrier concentration in *N*-type & *P*-type semconductors - Variation of carrier concentration with temperature - variation of Fermi level with temperature and impurity concentration - Carrier transport in Semiconductor: random motion, drift, mobility and diffusion - Hall effect and devices - Ohmic contacts - Schottky diode.

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, these materials have two types of charge carriers i.e., **electrons and holes**.

Germanium and **silicon** are two important elemental semiconductors. They are used in diodes and transistors.

Gallium arsenide (GaAs) and indium phosphide (InP) are two important compound semiconductors. 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.

Definition

Based on Electrical resistance

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

Based on Energy band

A semiconductor has nearly an empty conduction band and almost filled valence band with a very small energy gap (≃ 1 eV). (Fig 2.1)

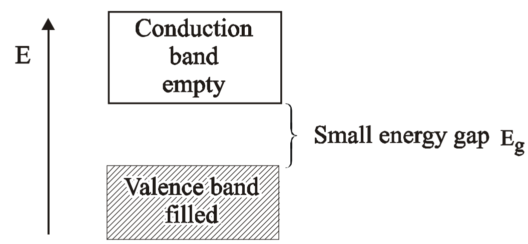


Fig. 2.1 Energy band diagram of a semiconductor

General properties of the semiconductors

- They have crystalline structure.
- Bonding between the atoms is formed by covalent bond.
- They have empty conduction band at 0K.
- They have almost filled valence band.
- The energy gap is small.
- They exhibit a negative temperature coefficient of resistance. ie., increase in temperature leads to decrease in resistance.

- **If impurities are added to a semiconductor, its electrical conductivity increases. Further, if temperature of the semiconductor is increased, its electrical conductivity increases**.

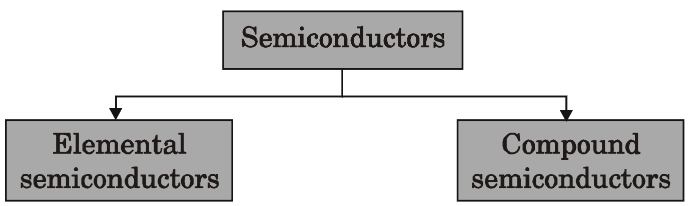
This property is in contrary to that of metals in which if temperature is increased or impurities are added, their electrical conductivity decreases.

Classification of semiconductors

The semiconductors are classified mainly into two types *based on the composition of materials. They are*

(i) Elemental semiconductors

(ii) Compound semiconductors



Elemental Semiconductors (Indirect band gap semiconductor)

The semiconductors which are made from a single element of fourth group elements in periodic table are known as elemental semiconductors.

They are also called as **indirect band gap semiconductors.**

Example

Two important elemental semiconductors and their energy band gaps are given in table 2.1.

Table 2.1

S.No.	Element	E_g in eV
1	Germanium	0.72
2	Silicon	1.1

Compound semiconductors
(Direct band gap semiconductors)

Semiconductors which are formed by combining third and fifth group or second and sixth group elements in the periodic table are known as compound semiconductors.

They are also called as **direct bandgap semiconductors.**

Characteristics

- The compound semiconductor have large forbidden gap and carrier mobility.
- They are formed by both ionic and covalent bonds.
- The recombination of electron and hole takes place directly. During this process, the light photons are emitted in visible or infrared region.

Some important compound semiconductors are given in table 2.2.

Table 2.2

S.No.	Group	Compound semiconductor
1.	Combination of third and fifth group elements (III and V)	Gallium Phosphide (GaP) Gallium Arsenide (GaAs) Indium Phosphide (InP) Indium Arsenide (InAs)
2.	Combination of second and sixth group elements (II and VI)	Magnesium Oxide (MgO) Magnesium Silicon (MgSi) Zinc Oxide (ZnO) Zinc Sulphide (ZnS)

Uses

The compound semiconductors are used in photovoltaic materials, photoconductive cell, LEDs [Light Emitting Diode] and Laser diodes.

The differences between elemental and compound semiconductors are given in table 2.3.

Table 2.3

Differences between elemental and compound semiconductors (indirect and direct band gap semiconductor)

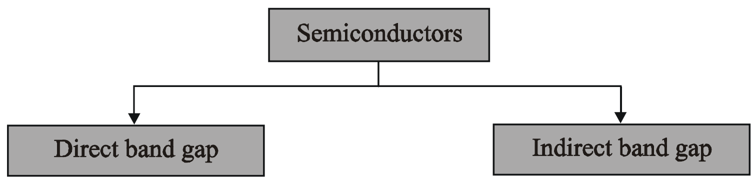
S.No.	Elemental Semiconductors	Compound Semiconductors
1.	They are made of a single element Example: Germanium (Ge), Silicon (Si).	They are made of compounds Example: GaA, GaP, CdS, MgO.
2.	They are known as **indirect band gap semiconductors.**	They are known as **direct band gap semiconductors.**
3.	Electron - hole recombination takes place through traps which are present in band gap.	Electron - hole recombination takes place directly with each other.
4.	Life time of charge carriers is more due to indirect recombination.	Life time of charge carrier 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 LED's and Laser diodes.

2.1 DIRECT AND INDIRECT BAND GAP SEMICONDUCTORS

Semiconductors are also classified into

(a) Direct band gap semiconductor

(b) Indirect band gap semiconductor.



The electrons and holes in a semiconductor have energy and momentum. The momentum (k) depends on energy (E). A plot of energy versus momentum is as shown in fig. 2.2

The lower curves represent energy and momentum values of holes in valence band of semiconductor. Similarly upper curves denote corresponding values for electrons in conduction band.

In direct band gap semiconductor, the energy maximum of valence band and the energy minimum of the conduction band are having same momentum value.

During the recombination of electron from conduction band with hole in valence band, the momentum of the electrons remains vitually 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 firstly loses momentum such that it has momentum equal to the momentum corresponding to energy maximum of valance band.

To conserve the momentum, emission of third particle known as a phonon is generated. Thus, in this type of recombination phonon is produced.

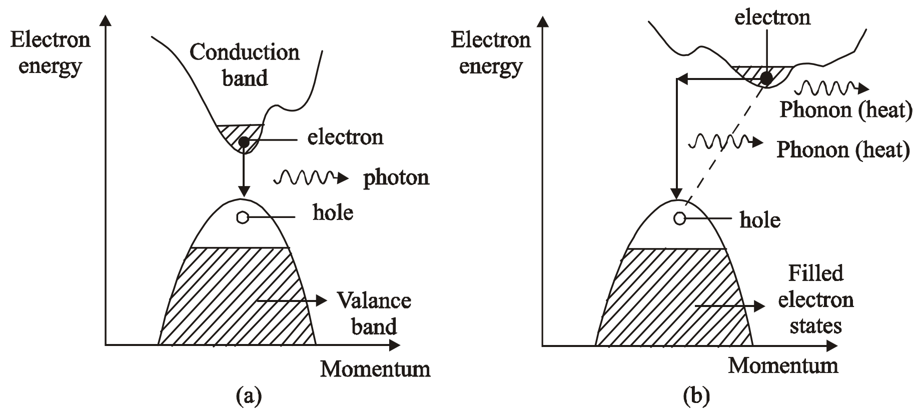


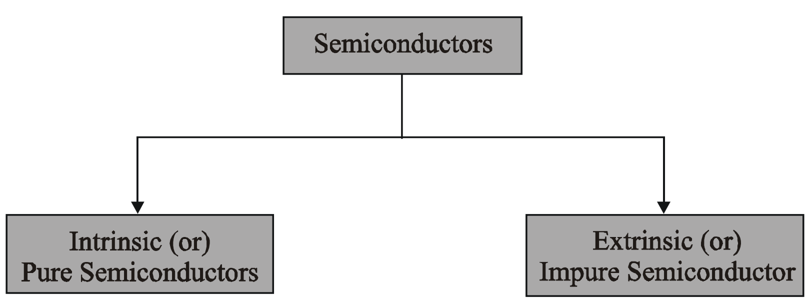
Fig. 2.2 Energy - momentum diagram
(a) Direct band gap semiconductor
(b) Indirect band gap semiconductor

Types of Semiconductors

When a **suitable impurity is added to a pure semiconductor, its electrical conductivity changes**. Based on this property, the semiconductors are classified into two types. They are

(i) ***Intrinsic semiconductor or pure semiconductor***

(ii) ***Extrinsic semiconductor or impure semiconductor or Doped semiconductor***



2.2 INTRINSIC SEMICONDUCTORS

A semiconductor in extremely pure form is known as 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 form ***covalent bonds*** by sharing four electrons with each other so as to form a **stable structure**.

2.3 ENERGY BAND DIAGRAM

Fig. 2.3 shows a two-dimensional crystal structure of germanium and energy band representation of intrinsic semiconductor at very low temperature.

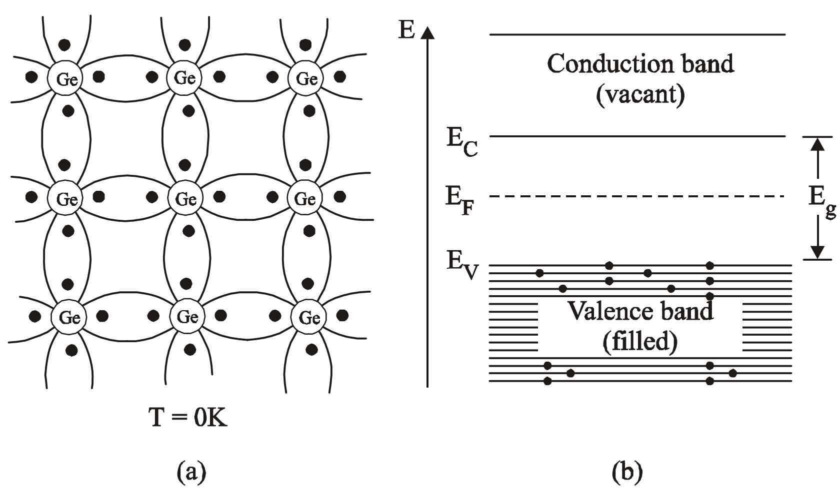


Fig. 2.3 Germanium crystal at 0K

Fig. 2.3(a) ***Two-dimensional representation of germanium solid. No free electron is available as all the valence electrons are engaged in covalent bonds.***

Fig. 2.3(b) ***Energy band representation. Valence band is fully occupied and conduction band is completely vacant.***

At very low temperature say 0K, no free electrons are available for conduction. Hence, this semiconductor behaves as an insulator at very low temperature.

Charge carriers in intrinsic semiconductor

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

When the temperature of intrinsic semiconductor is increased, some of the electrons get sufficient energy to break covalent bonds.

Once the electrons are liberated from bond, they become free electrons. These free electrons move randomly through crystal. (Fig. 2.4(a))

As shown in fig. 2.4 (b), the energy required to break a covalent bond and to set an electron free is equal to band gap energy E_g. It is about 0.72 eV for germanium and 1.1 eV for silicon.

When an electron acquires energy E_g, it jumps from valence band to conduction band. As a result, a vacant site (empty space) is created in valence band.

This vacant site is called as a hole. The absence of an electron in covalent bond is known as hole. A hole can attract an electron and hence it acts as a positive charge.

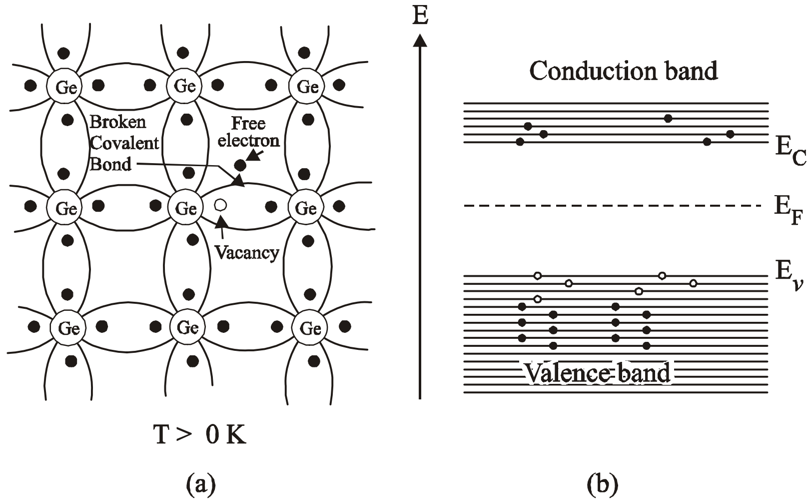


Fig. 2.4 Germanium crystal at temperature above 0K.

(a) ***Thermal vibrations of atoms lead to breaking up of covalent bonds. Consequently, a free electron and a vacancy are produced simultaneously.***

(b) ***Energy band representation. Energy*** $E_g\ (= E_c - E_v)$ ***causes transition of electrons from valence band to conduction band, leaving vacancies (hole) behind.***

When an electrical field is applied, these free electrons acquire directional motion and contribute to electrical conductivity.

For every electron freed from covalent bond, 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.

2.4 CARRIER CONCENTRATION IN INTRINSIC SEMICONDUCTORS

Definition

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

Similarly the number of holes in valence band per unit volume of the material is called hole concentration (***p***).

In general, the number of charge carriers per unit volume of the material is called carrier concentration. It is also known as density of charge carriers.

Density of Electrons in Conduction Band (Derivation)

The number of electrons per unit volume in conduction band for energy between E and $E + dE$ is given by

$$dn = Z(E)\,F(E)\,dE \qquad ...(1)$$

where $Z(E)\,dE$ – Density of states in energy between E and $E + dE$

$F(E)$ – Probability of electron occupancy.

Number of electrons in conduction band for the entire range is calculated by integrating eqn (1) between energy E_C and $+\infty$.

$$\int dn = n = \int_{E_C}^{+\infty} Z(E)\,F(E)\,dE \qquad ...(2)$$

E_C is energy corresponding to the bottom most level and $+\infty$ is energy corresponding to the upper most level in conduction band. (Fig 2.5).

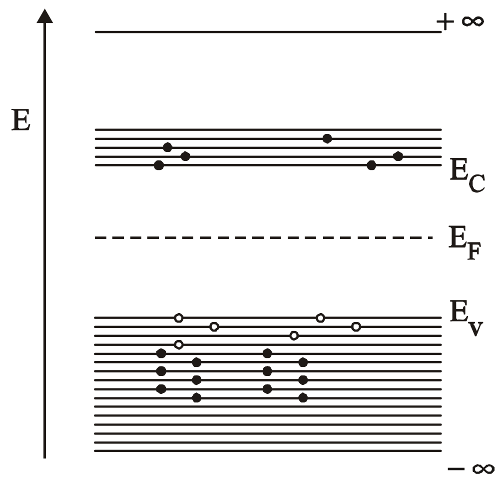


Fig. 2.5 Energy band diagram of intrinsic semiconductor

Density of states in conduction band between the energy range E and $E + dE$ is given by

$$Z(E)\,dE = \frac{4\pi}{h^3}(2m_e^*)^{3/2} E^{1/2}\,dE \qquad ...(3)$$

The bottom edge of the conduction band (E_C) denotes the potential energy of an electron at rest. Therefore, $(E - E_C)$ is the kinetic energy of conduction electron at higher energy levels.

Thus, in eqn (3), E is replaced as $(E - E_C)$

$$Z(E)\,dE = \frac{4\pi}{h^3}(2m_e^*)^{3/2}(E - E_C)^{1/2}\,dE \qquad ...(4)$$

The electrons in conduction band are not totally free. They move in a periodic potential of the crystal lattice. Therefore, in eqn (3), the mass of the electron (m) is replaced by its effective mass m_e^* according to band theory of solids.

The probability of electron occupation is given by Fermi distribution function

$$F(E) = \frac{1}{1 + e^{(E - E_F)/kT}} \quad ...(5)$$

Substituting eqns (4) and (5) in (2), we get

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

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \int_{E_C}^{+\infty} \frac{(E - E_C)^{1/2}}{1 + e^{(E - E_F)/kT}} \, dE \quad ...(6)$$

Since kT is very small and $(E - E_F)$ is greater than kT, $e^{(E - E_F)/kT}$ is very large compared to '1' Hence, '1' from the denominator of eqn (6) is neglected.

ie., $1 + e^{(E - E_F)/kT} \approx e^{(E - E_F)/kT}$.

Now, eqn (6) becomes

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

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

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

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

To evaluate above integral in eqn (7), let us assume

	when	when
$E - E_C = x$	$E = E_C$	$E = +\infty$
$E = E_C + x$	$E_C - E_C = x$	$+\infty - E_C = x$
$dE = dx$	$\therefore\ x = 0$	$\therefore\ x = +\infty$

Substituting above values in eqn (7), we have

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

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

Using the gamma function, it is shown that

$$\int_0^\infty x^{1/2} e^{-x/kT} dx = \frac{(kT)^{3/2} \pi^{1/2}}{2} \qquad \text{... (9)}$$

Substituting eqn (9) in eqn (8), we have

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} e^{(E_F - E_C)/kT} \left[\frac{(kT)^{3/2} \pi^{1/2}}{2}\right]$$

$$n = \frac{2\pi}{h^3}(2m_e^*)^{3/2} (kT)^{3/2} \pi^{1/2} e^{(E_F - E_C)/kT}$$

$$n = \frac{2\pi\pi^{1/2}(2m_e^*)^{3/2}(kT)^{3/2} e^{(E_F - E_C)/kT}}{(h^2)^{3/2}}$$

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

Equation (10) is the expression for concentration of electrons in the conduction band of intrinsic semiconductor.

Density of holes in Valence Band of Intrinsic Semiconductor (Derivation)

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 per unit volume in valence band between the energy E and $E + dE$.

$$dp = Z(E)\,(1 - F(E))\,dE \qquad ...(1)$$

where $Z(E)\,dE \rightarrow$ Density of states in the energy range E and $E + dE$.

Since $F(E)$ is the probability of electron occupation $1 - F(E)$ is the probability of an unoccupied electron state, i.e., probability of presence of hole.

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

$$= \frac{1 + e^{(E - E_F)/kT} - 1}{1 + e^{(E - E_F)/kT}}$$

$$1 - F(E) = \frac{e^{(E - E_F)/kT}}{1 + e^{(E - E_F)/kT}} \qquad ... (2)$$

Since E is very small when compared to E_F in valence band, $(E - E_F)$ is a negative quantity. Therefore, $e^{(E - E_F)/kT}$ is very small and it is neglected in the denominator term of eqn (2).

$$\text{i.e.,} \qquad 1 + e^{E - E_F/kT} \approx 1$$

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

Density of states in valence band,

$$Z(E)\,dE = \frac{4\pi}{h^3}(2m_h^*)^{3/2} E^{1/2}\,dE \qquad \text{...(4)}$$

Here, m_h^* is the effective mass of the hole in valence band.

E_v, top of energy level in valence band is the potential energy of a hole at rest. Hence, $(E_v - E)$ is the kinetic energy of the hole at level below E_v. So the term E in eqn (4) is replaced as $(E_v - E)$.

$$Z(E)\,dE = \frac{4\pi}{h^3}(2m_h^*)^{3/2}(E_v - E)^{1/2}\,dE \qquad \text{...(5)}$$

Substituting eqns (3) and (5) in (1), we get

$$dp = \frac{4\pi}{h^3}(2m_h^*)^{3/2}(E_v - E)\,e^{(E - E_F)/kT}\,dE \qquad \text{...(6)}$$

The number of holes in valence band for the entire energy range is obtained by integrating eqn (6) between limits $-\infty$ to E_v.

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

$$p = \frac{4\pi}{h^3}(2m_h^*)^{3/2}\,e^{(-E_F/kT)} \int_{-\infty}^{E_v} (E_v - E)^{1/2}\,e^{E/kT}\,dE \qquad \text{...(7)}$$

To evaluate the integral in eqn (7), let us assume,

	when	when
$E_v - E = x$	$E = -\infty$	$E = E_v$
$E = E_v - x$	$E_v - (-\infty) = x$	$E_v - E_v = x$
$dE = -dx$	$E_v + \infty = x$	$x = 0$
	$x = \infty$	

Substituting these values in eqn (7), we have

$$p = \frac{4\pi}{h^3} (2m_h^*)^{3/2} e^{(-E_F/kT)} \int_{\infty}^{0} x^{1/2} e^{(E_v - x)/kT} (-dx) \qquad ...(8)$$

$$p = \frac{4\pi}{h^3} (2m_h^*)^{3/2} e^{(E_v - E_F)/kT} \int_{0}^{\infty} x^{1/2} e^{-x/kT} dx \qquad ...(9)$$

[–ve sign is omitted by interchanging the limits]

Using the gamma function, it is shown that

$$\int_{0}^{\infty} x^{1/2} e^{-x/kT} dx = \frac{(kT)^{3/2} \pi^{1/2}}{2} \qquad ... (10)$$

Substituting eqn (10) in eqn (9), we have

$$p = \frac{4\pi}{h^3} (2m_h^*)^{3/2} e^{(E_v - E_F)/kT} \left[\frac{(kT)^{3/2} \pi^{1/2}}{2} \right]$$

$$p = \frac{2\pi}{h^3} (2m_h^*)^{3/2} (kT)^{3/2} \pi^{1/2} e^{(E_v - E_F)/kT}$$

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

$$\boldsymbol{p = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} e^{(E_v - E_F)/kT}} \qquad ...(11)$$

The equation (11) is the expression for the concentration of holes in valence band of intrinsic semiconductor.

INTRINSIC CARRIER CONCENTRATION

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

In general, intrinsic carrier concentration n_i is equal to electrons concentration in conduction band (n) or holes concentration in valence band (p).

i.e., $$n_i = n = p \qquad ...(1)$$

$$n_i \times n_i = n_i^2 = np \qquad ...(2)$$

Substituting the expressions of n and p in eqn (2), we have

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

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

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

where $E_C - E_v = E_g$ is forbidden energy gap.

Taking square root on both sides in eqn (3), we have

$$(n_i^2)^{1/2} = \left(4\left(\frac{2\pi kT}{h^2}\right)^3 (m_e^* m_h^*)^{3/2} e^{-E_g/kT} \right)^{1/2}$$

$$n_i = 4^{1/2}\left(\frac{2\pi kT}{h^2}\right)^{3/2} ((m_e^* m_h^*)^{3/2})^{1/2} (e^{-E_g/kT})^{1/2}$$

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

The eqn (4) is expression for intrinsic carrier concentration

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., $\boldsymbol{n = p}$ ...(1)

Substituting the expressions of n and p in eqn (1), we have

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

$$(m_e^*)^{3/2} e^{(E_F - E_c)/kT} = (m_h^*)^{3/2} e^{(E_v - E_F)/kT}$$

Rearranging, we get

$$E_F = \frac{E_v + E_C}{2} + \frac{3\,kT}{4} \log_e \left(\frac{m_h^*}{m_e^*}\right) \quad ...(2)$$

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

Hence, eqn (2) becomes

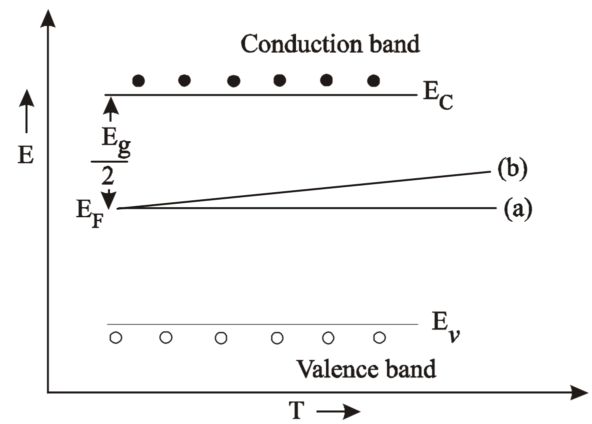


Fig. 2.6 Positions of Fermi level in intrinsic semiconductor at various temperatures.

(a) At T = 0K, Fermi level is in the middle of the forbidden band.

(b) As the temperature rises, it shifts upward since $m_h^* > m_e^*$.

$$\boldsymbol{E_F = \frac{E_v + E_C}{2}} \quad \text{... (3)}$$

Thus, Fermi level is located half way between the top of valence band and bottom of conduction band as shown in fig.2.6 (a). 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 of intrinsic semiconductor

Intrinsic semiconductors cannot be directly used to fabricate devices due to the following limitations:

- Electrical conductivity is low. Germanium has a conductivity of 1.67 $\Omega^{-1}m^{-1}$ which is nearly 10^7 times smaller than that of copper.
- Electrical conductivity is a function of temperature and increases exponentially as temperature increases.

In intrinsic or pure semiconductors, the carrier concentration of both electrons and holes is very low at normal temperatures.

In order to get sufficient current density through semiconductor, a large electrical field should be applied. This problem is overcome by adding suitable impurities into intrinsic semiconductors.

2.5 EXTRINSIC OR IMPURE SEMICONDUCTORS

In a semiconducting material, if the charge carriers originate from impurity atoms which are doped to the original material, then this type of semiconductor is known as extrinsic or impure semiconductor.

It is also known as doped semiconductor.

Extrinsic semiconductor is obtained by adding trivalent or pentavalent impurities atoms to a tetravalent semiconductor. The electrical properties of pure semiconductors can be easily changed even with the addition of **very little amount of impurities**.

Doping

*The addition of impurities to a pure semiconductor is known as **doping** and added impurity is called as **doping agent or dopant**.*

The addition of impurities increases the number of free electrons and holes in semiconductor and hence increases its electrical conductivity.

Some of the common doping agents are arsenic, antimony, phosphorus, gallium, aluminium and boron. These elements have either five or three valence electrons in the outermost orbit.

Advantages of Extrinsic semiconductors

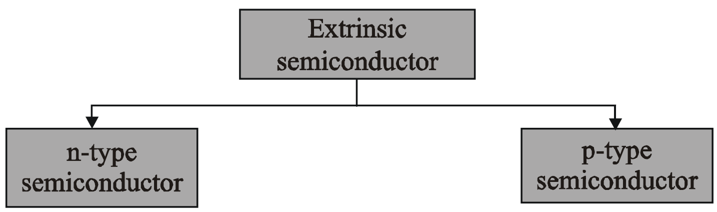
- Electrical conductivity is high.
- Electrical conductivity can be altered to any desired value by controlling of doping concentration.
- Electrical conductivity is not a function of temperature.

Types of Extrinsic semiconductors

The extrinsic semiconductors are classified into two types based on the type of impurity added.

(i) ***n - type semiconductor***

(ii) ***p - type semiconductor***



n - type semiconductor

When a small amount of pentavalent impurity (group V element) is doped to a pure semiconductor, it becomes **n - type semiconductor**.

Such impurities are known as **donor** impurities because they **donate** free electrons to semiconductor crystal.

Typical examples of pentavalent impurities are phosphorus, (Atomic No. 15) and antimony (Atomic No. 51).

Covalent bond in n - type semiconductor

A pentavalent impurity (phosphorus) having five valence electrons is added to a pure semiconductor having four valence electrons (silicon or germanium).

Now, four electrons of germanium form a **covalent bond** with four valence electrons of phosphorus (impurity atom).

The fifth electron which is now free finds no place in covalent bond structure as shown in fig. 2.7 (a).

We have one electron left free. This acts as a conduction electron. A very small amount of energy (0.01 eV for germanium and 0.05 eV for silicon) is needed to detach this fifth electron.

The addition of pentavalent impurity gives a large number of free electrons (negative charges) in semiconductor. Therefore, it is called *n* - type semiconductor where n stands for negative type.

Since every pentavalent atom contributes one free electron, in addition to thermally generated electron-hole pairs, the number of free electrons is more than the number of holes in *n*-type semiconductor.

Thus in this case, **electrons are majority charge carriers and holes are minority charge carriers.**

Energy band of *n* - type semiconductor

The energy band diagram of n - type semiconductor is shown in fig.2.6 (b). When the donor impurities are added, the allowable energy levels (donor energy levels) are introduced.

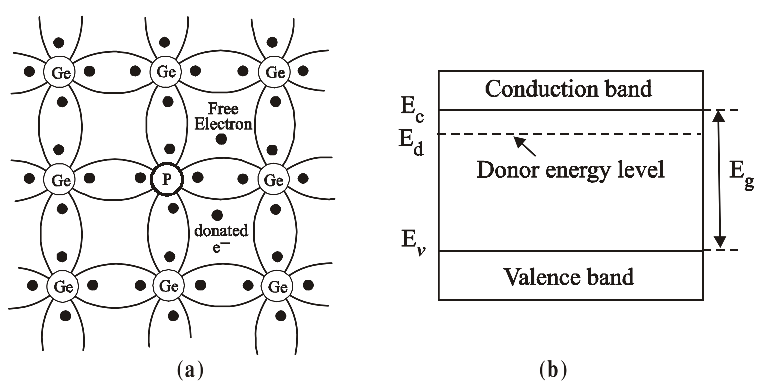


Fig. 2.7 n-type semiconductor
(a) crystal structure (b) Energy band diagram

These donor energy levels are slightly below the conduction band. They are discrete and do not form a band because the impurity atoms are far away in the crystal and hence their interaction is small.

The donor energy level for germanium is 0.01 eV and for silicon it is 0.05 eV below the conduction band. Therefore, even at room temperature, almost all the fifth electrons enter into the conduction band.

2.6 CARRIER CONCENTRATION IN *n* - TYPE SEMICONDUCTORS [Derivation]

The energy band diagram of n - type semiconductor is shown in figure 2.8. In n - type semiconductor, the donor level is just below conduction band.

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

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

E_C – Energy corresponding to the bottom most level of conduction band.

Density of ionised donors = $N_d\,[1 - F(E_d)]$

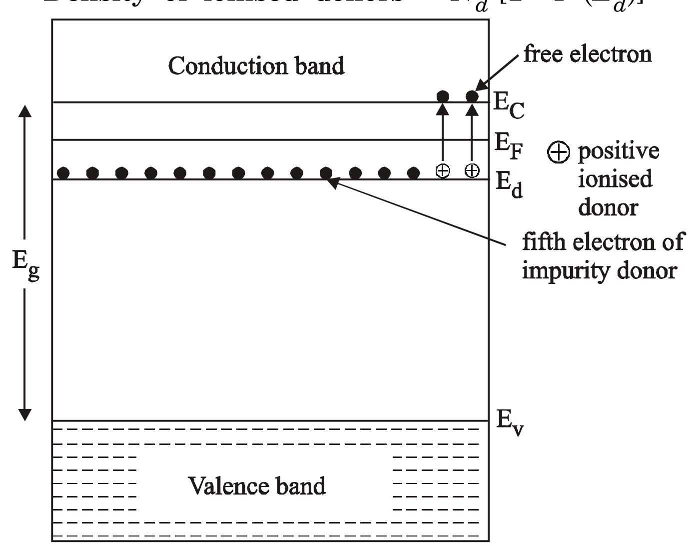


Fig. 2.8 Energy band diagram of n-type semiconductor

Since, $F(E_d)$ is the probability for finding electron in donot energy level (unionised donor), therefore $1 - F(E_d)$ is the probability for finding ionised donors.

E_d represents the donor energy level and N_d denotes donor concentration i.e., the number of donor atoms per unit volume of the material.

$$= N_d \left[1 - \frac{1}{1 + e^{(E_d - E_F)/kT}} \right] \quad ...(2)$$

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

$$= \frac{N_d \, e^{(E_d - E_F)/kT}}{1 + e^{(E_d - E_F)/kT}} \quad ...(3)$$

$e^{(E_d - E_F)/kT}$ is very small in eqn (3) when compared to '1'. Hence, it is neglected.

$$\therefore \quad 1 + e^{(E_d - E_F)/kT} \approx 1$$

Density of ionised donor $= N_d \, e^{(E_d - E_F)/kT}$ ...(4)

At equilibrium, the density of electron in conduction band is equal to the density of ionised donors.

Equating (1) and (4), we get

$$2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} e^{(E_F - E_C)/kT} = N_d \, e^{(E_d - E_F)/kT} \quad ...(5)$$

rearranging the terms, we have,

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

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

$$e^{(E_F - E_C - E_d + E_F)/kT} = \frac{N_d}{2\left(\dfrac{2\pi\, m_e^*\, kT}{h^2}\right)^{3/2}} \qquad ...(6)$$

Taking log on both sides, we have

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

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

$$\left[\because \log_e e^x = x\right]$$

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

or $$2E_F = E_d + E_C + kT\ \log_e\left[\frac{N_d}{2\left(\dfrac{2\pi\, m_e^*\, kT}{h^2}\right)^{3/2}}\right]$$

$$E_F = \frac{E_d + E_C}{2} + \frac{kT}{2} \log_e \left[\frac{N_d}{2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}} \right] \quad ...(7)$$

Substituting the expression of E_F from (7) in (1), we get

$$n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \mathbf{exp}\left[\frac{\frac{(E_d + E_C)}{2} + \frac{kT}{2}\log_e \left\{ \frac{N_d}{2\left\{\frac{2\pi m_e^* kT}{h^2}\right\}^{3/2}} \right\} - E_C}{kT} \right] \quad ... (8)$$

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

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

$$n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \mathbf{e}^{\mathbf{E_d - E_C / 2kT}} \cdot {}_e\log_e \left\{ \frac{N_d^{1/2}}{\left\{2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}\right\}^{1/2}} \right\}$$

$$n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} e^{(E_d - E_C)/2kT} \frac{N_d^{1/2}}{2^{1/2}\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/4}} \quad ... (9)$$

Rearranging the expression (9), we get

$$n = 2\,\frac{N_d^{1/2}}{2^{1/2}}\,\frac{\left(\dfrac{2\pi m_e^* kT}{h^2}\right)^{3/2}}{\left(\dfrac{2\pi m^* kT}{h^2}\right)^{3/4}}\; e^{(E_d - E_C)/2kT}$$

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

$$n = 2^{1/2} N_d^{1/2}\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/4} e^{(E_d - E_C)/2kT} \qquad \ldots (10)$$

$$\boxed{n = (2N_d)^{1/2}\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/4} e^{-\Delta E\,/\,2kT}} \qquad \ldots (11)$$

where $\Delta E = E_C - E_d$ is the ionisation energy of the donor. i.e., ΔE denotes the amount of energy required to transfer an electron from donor energy level E_d to conduction band E_C.

Results

- The density of electrons in conduction band is proportional to the square root of the donor concentration. The equation (11) is valid only at low temperatures.

- At high temperature, we must take into account of intrinsic carrier concentration of semiconductor due to breaking of covalent bond along with electron concentration produced by donor impurity.

- At very high temperatures, intrinsic carrier concentration which is generated thermally due to breaking of covalent bond over takes electrons due to donor impurity.
- That is, at very high temperature, n - type semiconductor behaves like intrinsic semiconductor and donor concentration becomes insignificant.

Fermi level

Fermi level gives the probability of finding an electron at a given energy value. If Fermi level lies exactly at the middle of the two levels, then the probability of finding an electron is half, e.g., as in an intrinsic semiconductor.

In extrinsic semiconductor, Fermi level strongly depends on temperature as well as the nature of doping and doping concentration.

The Fermi level is little below conduction band in n-type semiconductor and it is just above valence band in p-type semiconductor.

2.7 VARIATION OF FERMI LEVEL WITH TEMPERATURE AND IMPURITY CONCENTRATION (*n* - type semiconductor)

Fermi level in n - type semiconductor is given by

$$E_F = \frac{E_d + E_C}{2} + \frac{kT}{2} \log_e \left[\frac{N_d}{2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}} \right] \quad \ldots (1)$$

At T = 0K, the eqn (1) reduces to

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

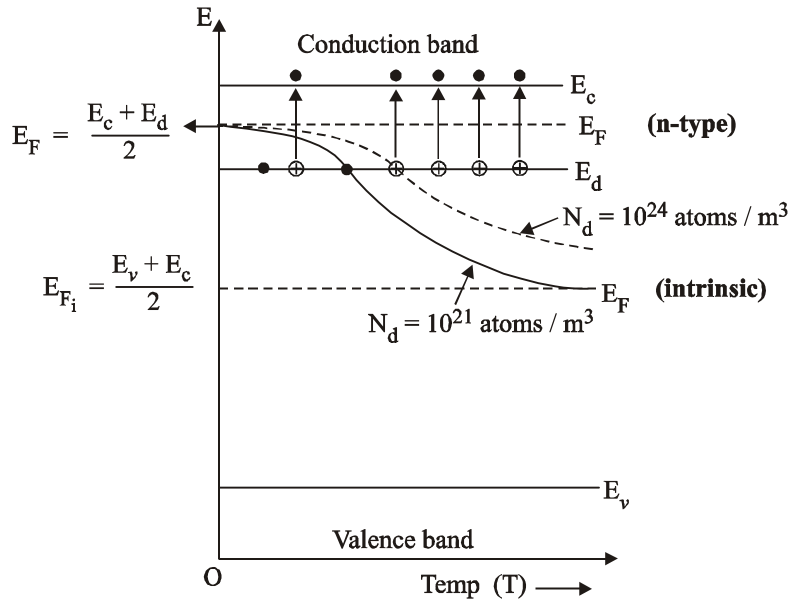


Fig. 2.9 Variation of Fermi level with temperature and impurity concentration in n-type semiconductor

- At 0K, Fermi level lies exactly in the middle of the donor level (E_d) and bottom of the conduction band as shown in fig. 2.9.

- When temperature is gradually increased from a low temperature, the contribution of electron to conduction band from valence band increases.

- At very high temperature (500 K in germanium), concentration of electron in conduction band due to breaking of covalent bond ie., from valence band exceeds very much donor concentration and hence intrinsic behaviour predominates at higher temperature.

- Fermi level shifts downwards when temperature is increased and finally reaches the middle of the band gap (or) that of intrinsic Fermi level.

- When the concentration of donors increases, the extrinsic behaviour increases.

p-type semiconductor

When a small amount of trivalent impurity is doped to a pure semiconductor, it becomes *p* - type semiconductor.

The addition of trivalent impurity provides a large number of holes in semiconductor.

Typical examples of trivalent impurities are gallium (Atomic No: 31) and indium (Atomic No. 49). Such impurities are known as **acceptor impurities** because holes created can **accept electrons**.

In a pure semiconductor (germanium) having 4 valence electrons, if a trivalent impurity (boron) having '3' valence electrons is added, then 3 valence electrons of trivalent impurity form a covalent bond with three valence electrons of germanium.

The fourth valence electron of Ge atom is unable to form a covalent bond. The incomplete covalent bond is being short of one **electron. This missing electron is called a hole. (Fig. 2.10(a))**

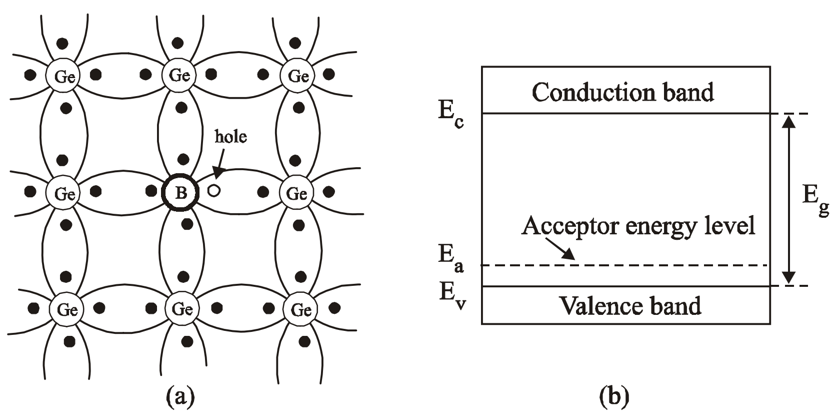


Fig. 2.10 p - type semiconductor (a) crystal structure (b) energy band diagram

Every trivalent impurity atom contributes one hole in addition to thermally generated electron - hole pairs. Therefore, number of holes is more than number of electrons.

The addition of trivalent impurity creates large number of holes (positive charge carriers) in semiconductor and hence it is called *p*-type semiconductor where p stands for positive type.

Hence in this type of semiconductor, holes are majority charge carriers and electrons are minority charge carriers.

In this case, allowable energy level (acceptor energy level) is created just above valence band (fig. 2.10(b)).

A very small amount of energy is needed for an electron to enter acceptor energy level from valence band. Thus, a hole is generated in the valence band corresponding to each ionised acceptor.

In other words, a large number of positive charge carriers are created.

2.8 CONCENTRATION OF HOLES IN VALENCE BAND OF *p* – TYPE SEMICONDUCTORS [Derivation]

In *p*-type semiconductor, acceptor energy level is just above valence band (fig. 2.11).

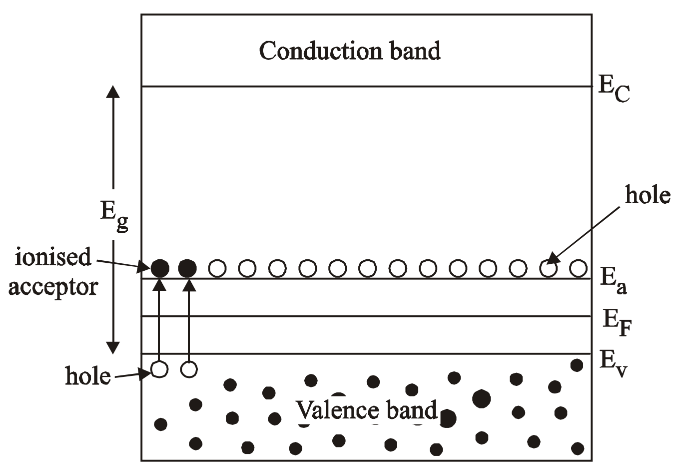


Fig. 2.11 Energy band diagram for p-type semiconductor

Density of holes per unit volume in valence band is given by

$$p = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} e^{(E_v - E_F)/kT} \qquad ...(1)$$

$E_v \rightarrow$ Energy corresponding to top most level of valence band.

Density of ionised acceptors $= N_a F(E_a)$ ... (1)

N_a – the number of acceptor atoms per unit volume.

$$F(E_a) = \frac{1}{1 + e^{(E_a - E_F)/kT}}$$

E_a – acceptor energy level

Here, $F(E_a)$ is probability for finding electron in acceptor energy level ie., ionised acceptor.

The eqn (1) becomes, density of ionised acceptors

$$= \frac{N_a}{1 + e^{(E_a - E_F)/kT}} \qquad ...(2)$$

$e^{(E_a - E_F)/kT}$ is a large quantity and thus '1' from the denominator of R.H.S. of eqn (2) is neglected.

Now, the eqn (2) is modified as,

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

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

Density of ionised acceptors $= N_a e^{(E_F - E_a)/kT}$ ...(3)

At equilibrium,

$$\begin{pmatrix} \text{Density of holes} \\ \text{in valence band} \end{pmatrix} = \begin{pmatrix} \text{Density of} \\ \text{ionised acceptors} \end{pmatrix}$$

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

rearranging eqn (4), we have

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

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

$$e^{(E_v - E_F - E_F + E_a)/kT} = \frac{N_a}{2\left(\frac{2\pi\, m_h^* \, kT}{h^2}\right)^{3/2}} \quad ... (5)$$

Taking log on both sides in eqn (5), we have

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

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

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

Rearranging,

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

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

Substituting eqn of E_F from (7) in (1), we get

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

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

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

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

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

$$p = 2\left(\frac{2\pi\, m_h^*\, kT}{h^2}\right)^{3/2} \mathbf{e}^{(E_v - E_a)\ /2kT}\ e^{\log_e\left[\frac{\left(\frac{N_a}{2}\right)^{1/2}}{\left(\frac{2\pi\, m_h^*\, kT}{h^2}\right)^{3/4}}\right]}$$

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

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

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

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

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

where $\Delta E = E_a - E_v$ is the ionisation energy of acceptors.

Results

- Density of holes in valence band is proportional to the square root of acceptor concentration.
- At high temperature, we must take into account of the intrinsic carrier concentration of semiconductor due to breaking of covalent bond along hole concentration produced by acceptor impurity.
- At very high temperature, intrinsic carrier concentration over takes holes due to acceptor concentration.
- i.e., At very high temperature, p - type semiconductor behaves like an intrinsic semiconductor and acceptor concentration becomes insignificant.

2.9 VARIATION OF FERMI LEVEL WITH TEMPERATURE AND IMPURITY CONCENTRATION IN *p* - TYPE SEMICONDUCTOR

Fermi level in p - type semiconductor is given by

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

Substituting $T = 0\,K$ in expression (1), we have

$$\boxed{\boldsymbol{E_F = \frac{E_a + E_v}{2}}} \qquad ...\ (2)$$

- At 0 K, Fermi level lies exactly middle of the acceptor level E_a and top of valence band E_v. (Fig 2.12)

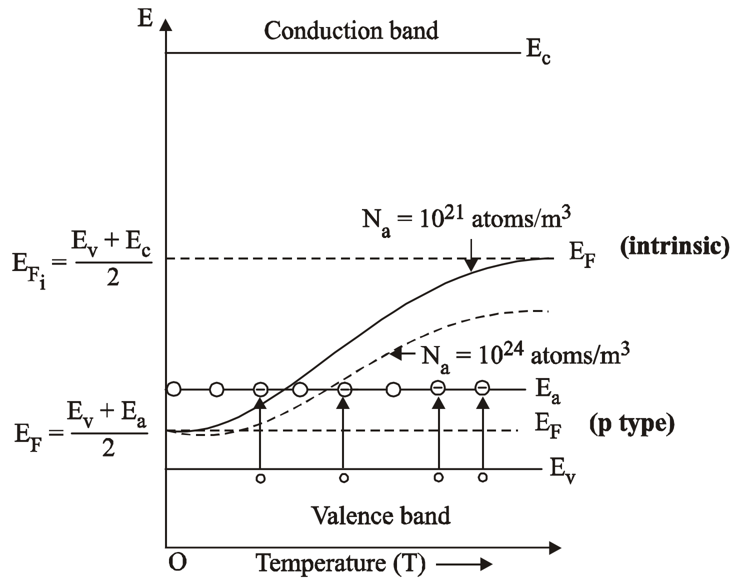


Fig. 2.12 Variation of Fermi level with temperature and impurity concentration in p-type semiconductor

- As temperature increases, more and more acceptor atoms are ionised. Fermi level E_F (p-type) shifts upwards. At a particular temperature, when all the acceptor atoms are ionised, Fermi level crosses acceptor level.
- At very high temperature, Fermi level shifts to intrinsic Fermi level and *p*-type semiconductor behaves like an intrinsic semiconductor.
- Further, when the concentration of acceptor atoms increases, extrinsic behaviour increases. Fermi level reaches intrinsic Fermi level at very high temperature.

2.10 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.

i) ***Extrinsic or impurity range***

ii) ***Exhaustion range***

iii) ***Intrinsic range***

For a *n*-type semiconductor, the variation of carrier concentration *n* and *p* with temperature is shown in fig. 2.13.

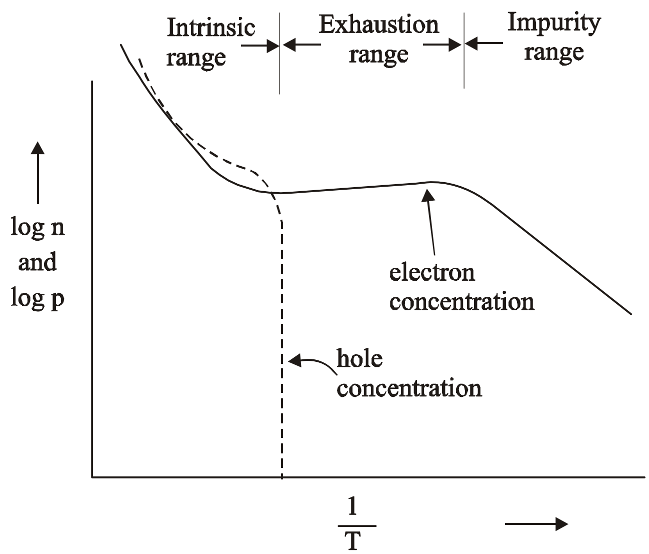


Fig. 2.13 Variation of carrier concentration with temperature in n-type semiconductor

At 0K, 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 ionised. 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 increased further, the electrons in valence band are 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 out-number the donor electrons.

The material practically becomes intrinsic and so this range is called **intrinsic range**. All these ranges are shown in fig. 2.13.

The dotted curve indicates hole concentration in an **intrinsic range**.

Table 2.4

Differences between intrinsic and extrinsic semiconductors

S.No.	Intrinsic semiconductor	Extrinsic semiconductor
1.	It is a pure form of semiconductor.	An impurity or doping agent is added in the pure semiconductor forms extrinsic semiconductor.
2.	Number of electrons and holes are equal.	Number of electrons and holes are not equal because of doping.
3.	Conductivity is poor.	Conductivity is improved.

Table 2.5

Differences between *n* - type and *p* - type semiconductors

S.No.	***n*-type semiconductor**	***p*-type semiconductor**
1.	When pentavalent impurity is doped to intrinsic semiconductor, *n* - type semiconductor is formed.	When trivalent impurity is doped to intrinsic semiconductor, *p* - type semiconductor is formed.

S.No.	*n*-type semiconductor	*p*-type semiconductor
2.	The impurity is called donor impurity since it donates electron.	The impurity is called acceptor impurity since it accepts electron.
3.	Majority charge carriers are electrons.	Majority charge carriers are holes.
4.	Minority charge carriers are holes.	Minority charge carriers are electrons.
5.	The donor energy level is very close to the bottom of the conduction band.	The acceptor energy level is very close to the top of the valence band.
6.	Fermi energy decreases with increase of temperature.	Fermi energy increases with increase of temperature.

CARRIER TRANSPORT IN SEMICONDUCTOR

2.11 RANDOM MOTION & MOBILITY

In absence of an electrical field, the free electrons (electron gas) move in all directions in a random manner. They collide with other free electrons and positive ion core during the motion. This collision is known as **elastic collision** (Fig 2.14).

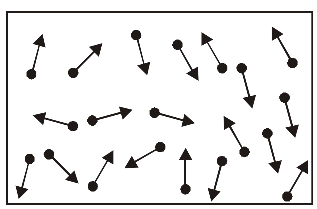


Fig. 2.14 Random motion of free electrons in the absence of electric field (+ ve ion cores are not shown).

As the motion is random, the resultant velocity in any particular direction is zero.

When an electrical 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 attained by the carriers is proportional to the electrical field strength E.

i.e., $v_d \propto E$

$$\boxed{v_d = \mu E} \quad ...(1)$$

where μ is a proportionality constant and it is known as the mobility of the charge carrier.

This velocity v_d is different for different semiconductors and for different types of charge carriers.

If $E = 1\ V/\text{m}$ then $\mu = v_d$ Thus, mobility μ is defined as the velocity of a charge carrier per unit electrical field strength.

μ_n and μ_p denote electron mobility and hole mobility respectively.

Since the types 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.

Table 2.6 gives the values of electron and hole mobilities at 300K.

Table 2.6

Electron and hole mobilities at 300 K

Material	Electron mobility m^2/volt-sec	Hole mobility m^2/volt-sec
Silicon	0.135	0.048
Germanium	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 electrical field E is applied, the electrons move with a drift velocity v_{dn}. Thus,

$$\boxed{v_{dn} = \mu_n E} \quad \text{...(2)}$$

where μ_n is the mobility of electron.

The drift current density $\boldsymbol{J_n}$ 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 electrical field E. It is given by,

$$\boxed{J_n = nev_{dn}} \quad \text{...(3)}$$

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 E by

$$J_n = \sigma_n E \quad \text{...(4)}$$

or

$$\sigma_n = \frac{J_n}{E} = \frac{ne\,v_{dn}}{E} \quad \text{...(5)}$$

Substituting eqn (2) in eqn (5), we have

$$\sigma_n = \frac{n\,e\,\mu_n E}{E}$$

$$\boxed{\boldsymbol{\sigma_n = n\,e\,\mu_n}} \quad \text{...(6)}$$

If p is the number of holes per unit volume and σ_p the conductivity due to the drift of holes, then

$$\boxed{\boldsymbol{\sigma_p = pe\,\mu_p}} \quad \text{...(7)}$$

where μ_p is the mobility of holes in the material.

Thus, total conductivity σ due to a free electrons and holes

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

$$\sigma = ne\,\mu_n + pe\,\mu_p$$

$$\boxed{\sigma = e\,(n\,\mu_n + p\,(\mu_p)} \qquad ...(8)$$

where σ is the total conductivity of the material and it is generally expressed in mho/m.

For the intrinsic semiconductor which contains the same number of free electrons and holes, $n = p = n_i$.

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

From eqn (8)

$$\sigma_i = e\,(n_i\,\mu_n + n_i\,\mu_p)$$

$$\boxed{\sigma_i = en_i\,(\mu_n + \mu_p)} \qquad ...(9)$$

2.12 DRIFT AND DIFFUSION TRANSPORT

The net current flows across a semiconductor has two components:

(i) Drift current

(ii) Diffusion current.

Drift Current

Definition

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

When electrical voltage is applied to a material as shown in fig. 2.15, electric field is produced at every point within the material.

The charge carriers are forced to move in a particular direction due to the electric field. **This is known as the drift motion and the current is known as drift current**.

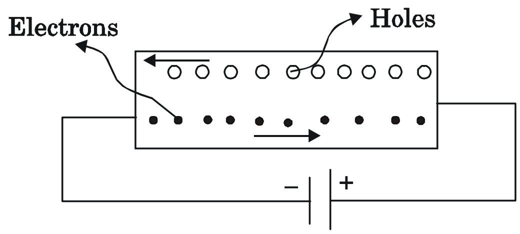


Fig. 2.15 Drift of charge carriers in a semiconductor

Drift current density in a semiconductor due to electrons

$$\boxed{J_n \text{ (drift)} = n \mu_n e E} \quad ...(1)$$

Drift current density due to hole

$$\boxed{J_p \text{ (drift)} = p \mu_p e E} \quad ...(2)$$

where n and p are number of electrons and holes per unit volume. μ_n and μ_p are the mobilities of electrons and holes respectively, e is charge of electrons and E is electric field.

So total drift current density

$$J = J_n \text{ (drift)} + J_p \text{ (drift)}$$

$$\boxed{J = ne \mu_n E + pe \mu_p E} \quad ...(3)$$

For intrinsic semiconductor

$$\boxed{J = n_i e (\mu_n + \mu_p) E} \qquad (\because n = p = n_i)$$

Diffusion Current

Definition

The non-uniform distribution of charge carriers creates the regions of uneven concentrations in the semiconductor.

The charge carriers move from the regions of higher concentration to the regions of lower concentration. This process is known as diffusion. The current is known as diffusion current.

Consider a semiconductor having a concentration gradient of electrons $\frac{dn}{dx}$ within the semiconductor.

The electrons diffuse from high concentration to low concentration due to the concentration gradient as shown in Fig. 2.16.

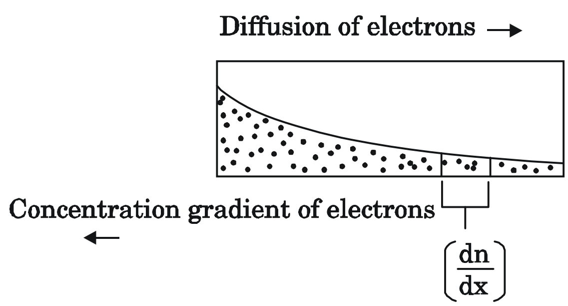


Fig. 2.16 Uneven distribution of electrons in a semiconductor

$$\text{Rate of flow of electrons through unit area} \propto -\left(\frac{dn}{dx}\right)$$

Here, negative sign denotes that the electrons are diffusing from higher concentration to lower concentration region.

$$\text{Rate of flow of electrons through unit area} = -D_n\left(\frac{dn}{dx}\right)$$

where D_n is a proportionality constant and it is known as diffusion coefficient of electrons.

Rate of flow of electrons through unit area

$$= -e \times -D_n \left(\frac{dn}{dx} \right)$$

Rate of flow electrons through unit area is the diffusion current density of electrons J_n (diffusion)

$$J_n \text{ (diffusion) } = e\, D_n \left(\frac{dn}{dx} \right)$$

Similarly, the diffusion current density of holes is given by

$$J_p \text{ (diffusion) } = -e\, D_p \left(\frac{dp}{dx} \right)$$

where D_p is diffusion constant of holes.

2.13 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 (p type or n type) charge carriers.
- Therefore, Hall effect is used to distinguish between two types of charge carriers (electrons and hole). 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. (Fig. 2.17)

This phenomenon is known as Hall effect. The voltage thus generated is called Hall voltage.

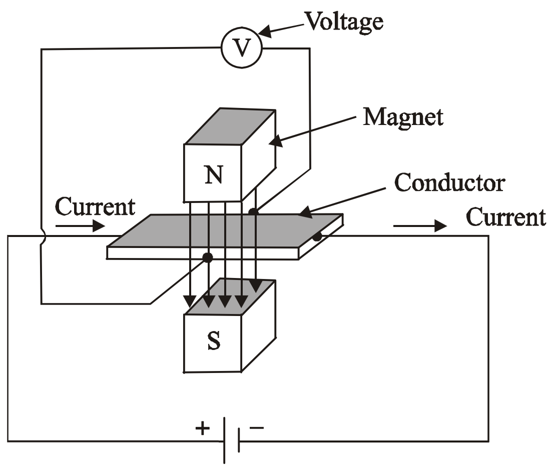


Fig. 2.17 Hall Effect

Hall effect in n - type semiconductor

Consider a n - type semiconductor in the form of a rectangular slab. In this slab, the current flows in X - direction and magnetic field B is applied in Z-direction. Due to Hall effect, voltage is developed along Y - direction as shown in fig. 2.18.

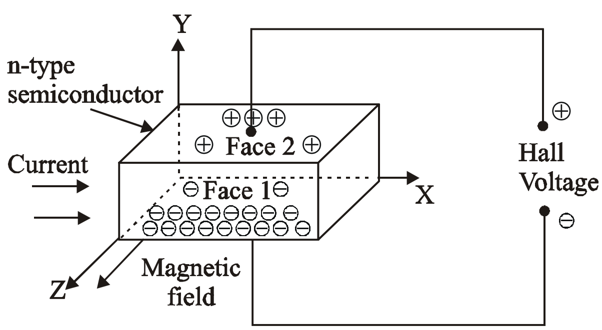


Fig. 2.18 Hall effect

The current flow is entirely due to the flow of electrons moving from right to left along X-direction.

When a magnetic field (B) is applied in Z-direction, then the electrons moving with velocity v experience a downward force.

Downward force experienced by the electrons $= Bev$ ... (1)

This downward force deflects the electrons in downward direction. Hence, there is an accumulation of negative charge (electrons) on the bottom face of the slab (fig 2.19).

It causes bottom face to be more negative with respect to top face.

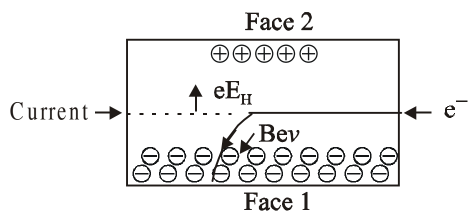


Fig. 2.19 Hall effect in n-type semiconductor

Now, a potential difference is developed between top and bottom faces of the slab.

This potential difference produces an electric field E_H in negative Y - direction. It is called **Hall field**.

This electric field develops a force (Lorentz force). This force is acting in the upward direction on each electron.

Upward force acting on each electron $= eE_H$ ... (2)

At equilibrium, **downward force balances upward force**.

$$\therefore \quad Bev = eE_H$$

$$E_H = Bv \quad ...(3)$$

The current density (J_x) along X - direction is related to velocity v as

$$J_x = -nev \quad ...(4)$$

where n is concentration electrons.

$$v = \frac{-J_x}{ne} \quad ...(5)$$

Substituting eqn (5) in eqn (3), we have

$$E_H = \frac{-B J_x}{ne} \quad ...(6)$$

$$E_H = R_H J_x B \quad ...(7)$$

where $R_H = -\frac{1}{ne}$ (for electrons)

$$\boxed{R_H = \frac{E_H}{J_x B}} \quad ...(8)$$

R_H is a constant and it is known as Hall coefficient.

The negative sign indicates that the electric field is developed in negative Y – direction.

Hall effect in *p*-type semiconductor

Similar to *n*-type semiconductor, we can write for *p*-type semiconductor

$$E_H = R_H J_x B$$

where **Hall coefficient**.

$$\boxed{R_H = +\frac{1}{pe}}$$

where p is concentration of holes.

The positive sign indicates that the electrical field (Hall field) is developed in positive Y - direction.

Hall coefficient in terms of Hall voltage

If t is the thickness of the sample and V_H is the voltage developed, then

$$V_H = E_H t$$

where E_H is Hall field. ...(1)

Substituting eqn (7) in eqn (8), we have

$$V_H = R_H J_x B t \quad ...(2)$$

If b is breadth of the sample, then

Cross sectional area of the sample (A)

$$= \text{Breadth } (b) \times \text{Thickness } (t)$$

$$= bt$$

$$\text{Current density} \quad J_x = \frac{I_x}{\text{Area of the sample (A)}}$$

$$= \frac{I_x}{bt} \quad ...(3)$$

Substituting eqn (3) in eqn (2), we get

$$V_H = \frac{R_H I_x Bt}{bt}$$

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

$$\boxed{\text{Hall coefficient} \quad R_H = \frac{V_H b}{I_x B}} \quad ...(4)$$

Note:

For n-type, the polarity (sign) of V_H is opposite to that of p-type.

Determination of Hall coefficient

The experimental arrangement to measure Hall-coefficient is shown in fig. 2.20.

A semiconductor is taken in the form of a rectangular slab of thickness t and breadth b. A suitable current I_x ampere is passed into this sample along X-axis by connecting it to a battery.

Now, it is placed in between north and south poles of an electromagnet. The magnetic field is applied along Z-axis.

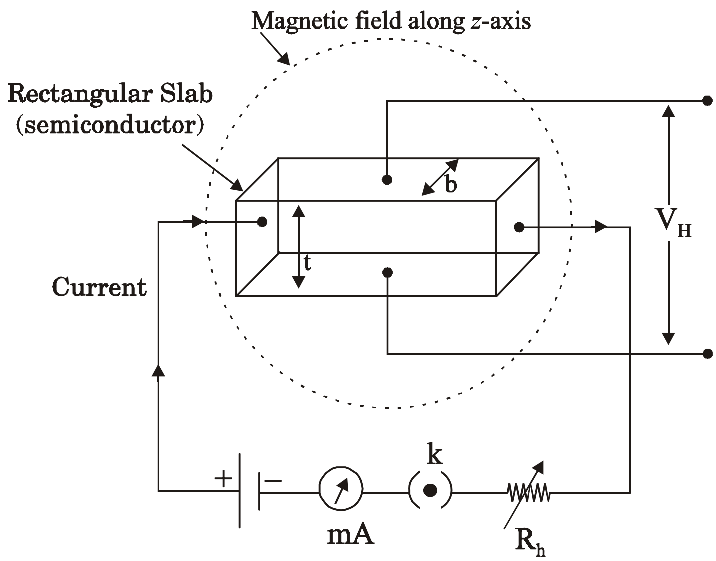


Fig. 2.20 Experimental arrangement to measure Hall coefficient

Due to Hall effect, Hall voltage (V_H) is developed in the sample. This voltage 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 determined from the formula

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

From Hall coefficient, carrier concentration and mobility can be determined.

Applications of Hall effect

(i) Determination of semiconductor type

The sign of the Hall coefficient is used to to find whether a given semiconductor is n-type or p-type.

(ii) Calculation of carrier concentration

By measuring Hall coefficient R_H, carrier concentration is determined from the relation

$$\boxed{n = \frac{1}{e R_H}}$$

(iii) Determination of mobility

We know that electrical conductivity,

$$\sigma_e = ne\,\mu_e.$$

$$\mu_e = \frac{\sigma_e}{ne}$$

$$\boxed{\mu_e = \sigma_e R_H}$$

Thus, by measuring electrical conductivity and Hall coefficient of a sample, the mobility of charge carriers can be calculated.

2.14 HALL DEVICES

The device which uses the hall effect for its application is known as Hall device.

There are three types of Hall devices.

They are

(a) **Gauss Meter**

(b) **Electronic Multiplier**

(c) **Electronic Wattmeter**

(a) Gauss Meter

The Hall voltage $V_H = \frac{R_H B_Z I_x}{t}$. In this, $V_H \propto B_Z$ for a given hall element; R_H and t 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. (Fig. 2.21)

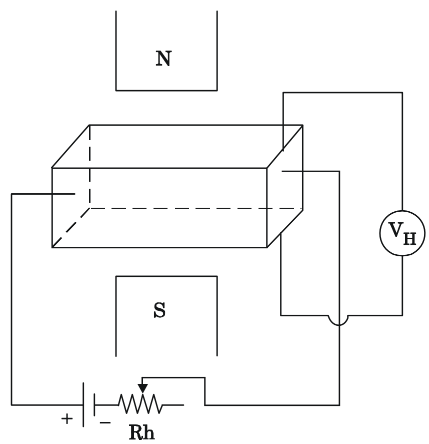


Fig. 2.21 Gauss Meter

The variation of Hall voltage with magnetic field is shown in fig. 2.22. 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.

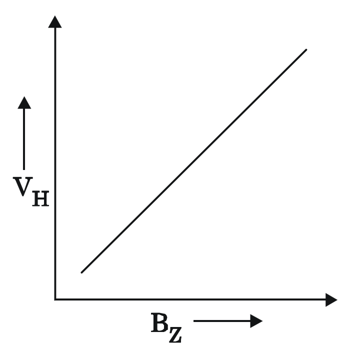


Fig. 2.22 B_Z Verses V_H

(b) Electronic Multipliers

From Hall effect, we have $V_H = \dfrac{R_H B_Z I_1}{t}$

Since R_H and t 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.

$$\text{i.e.,} \quad B_Z \propto I_2$$

$$\therefore \quad V_H \propto I_1 I_2$$

i.e., V_H is a measure of the product of two currents. This is the basic principle used in analog electronic multipliers. The fig. 2.23 shows the circuit diagram for electronic multiplier.

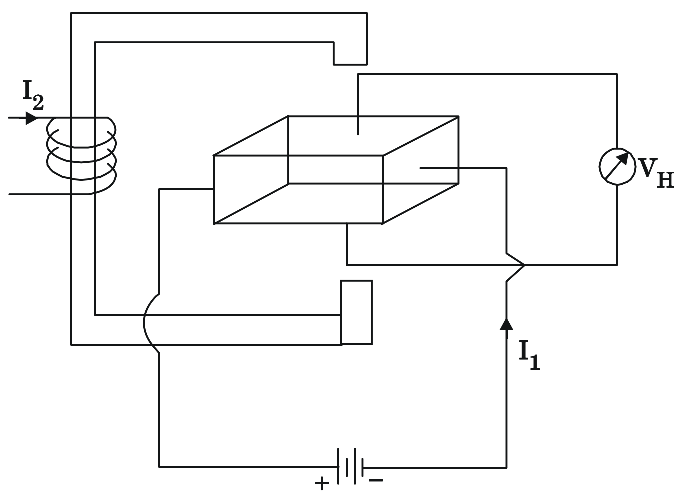
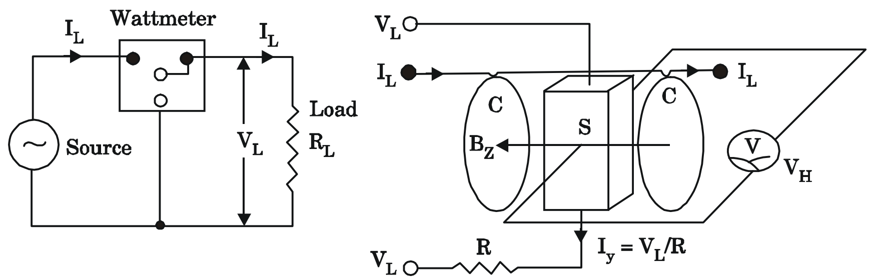


Fig. 2.23 Electronic multiplier

(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 - Watt meter.

S is Hall effect 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 fig. 2.24.



V_L - Load voltage I_L - Load Current C, C - Coils to set magnetic field B

Fig. 2.24 Hall effect wattmeter

The voltage across the load V_L drives the current $I_y = \frac{V_L}{R}$ through the sample. R is a series resistance which is $>>$ than the resistance of the sample and that of the load. Also $I_y << I_L$.

If 't' thickness of the sample, then the measured Hall voltage

$$V_H = \frac{R_H B_Z I_y}{t}$$

$$V_H \propto B_Z \cdot I_y \quad \text{(Since } R_H \text{ and } t \text{ are constant)s}$$

$$\text{Since } B_Z \propto I_L \text{ and } I_y \propto V_L$$

$$V_H \propto I_L V_L$$

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

Metal - Semiconductor (MS) Contact

Metal-Semiconductor (MS) contact plays a very important role in the present day electronic devices and Integrated Circuit (IC) technology.

When a metal and a semiconductor are brought into contact, there are two types of junctions formed depending on the work functions of the metal and semiconductor.

Types of Metal - Semiconductor junction

(i) Schottky junction - $\phi_m > \phi_{\text{semi}}$

(ii) Ohmic junction - $\phi_{\text{semi}} < \phi_{\text{semi}}$

ϕ_m – Work function of metal

ϕ_z – Work function of semiconductor

Work Function: Energy required to raise the electrons from the metal or the semiconductor to the vacuum level.

2.15 SCHOTTKY DIODE

Definition:

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. The Fermi level of the semiconductor is higher (since its work function is lower) than the metal.

Fig. 2.25 shows schottky diode and its circuit symbol.

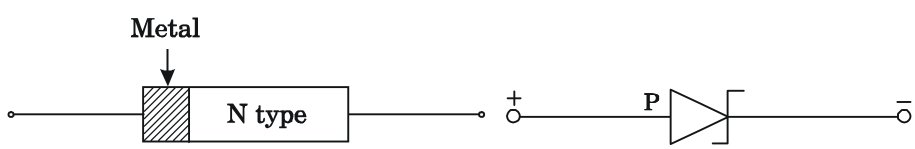


Fig. 2.25 Schottky Diode
(a) metal-semiconductor contact and (b) circuit symbol

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 2.26. This leads to a *contact potential*.

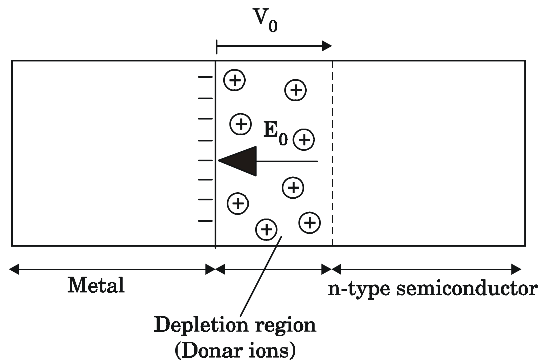


Fig. 2.26 Schottky junction between metal and n-type semconductor

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.

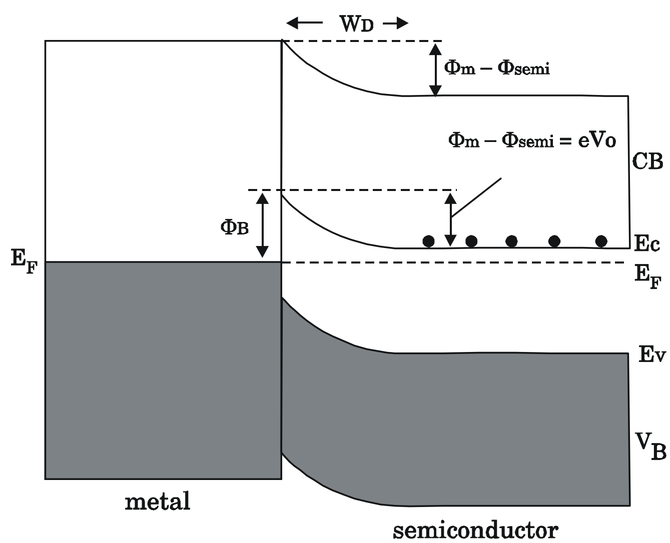


Figure 2.27 Schottky junction energy band

The **formation of a depletion region** of width W_D within the semiconductor is shown in figure 2.27.

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 2.27, this is given by the difference in work functions.

$$\boxed{eV_0 = \phi_m - \phi_{\text{semi}}}$$

The contact potential thus formed prevents *further* motion of the electrons between the metal and semiconductor. This is called the **Schottky barrier** and denoted by ϕ_B.

Working

The behaviour of the schottky diode is further studied by biasing (applying voltage). The voltage is applying in two ways

(a) Forward bias

(b) 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 a 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 a Schottky junction acts as a **rectifier** ie. it conducts in forward bias but not in reverse bias.

V-I Characteristics

The $V-I$ characteristics of the junction is shown in figure 2.28. There is an exponential increase in current in the forward bias while there is a very small current in reverse bias.

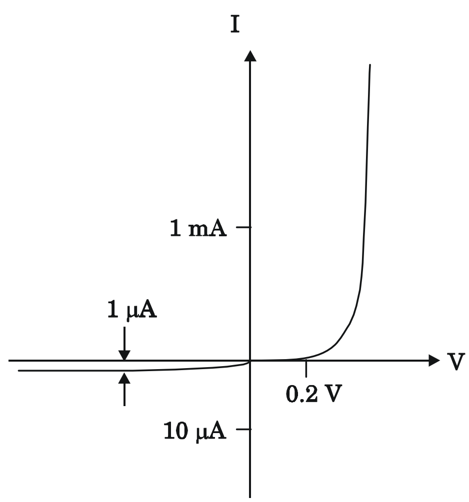


Fig. 2.28 V – I characteristics of the Schottky diode

Advantages of schottky diode

- In schottky diode, stored charges or depletion region is negligible. So a schottky diode has a very low capacitance.
- In schottky diode, the depleting region is negligible. So the schottky diode will immediately switch from ON to OFF state (fast recovery time).
- The depletion region is negligible in schottky diode. So applying a small voltage is enough to produce large current.
- It has high efficiency.

- It operates at high frequencies.
- It produces less noise.

Applications of schottky diode

- Schottky diode can be used for rectification of signals of frequencies even exceeding 300 MHz.
- It is commonly used in switching device at frequencies of 20 GHz.
- It is used in radio frequency (RF) applications.
- It is widely used in power supplies.
- It is used to detect signals.
- It is used in logic circuits.
- Its low noise figure finds application in sensitive communication receivers like radars.
- It is also used in clipping and clamping circuits and in computer gating.

Note

This diode is also referred as hot carrier diode because when it is forward biased, conduction electrons on the *N* side gains sufficient energy to cross the junction and enter the metal. Since these electrons enter into the metal with large energy, they are commonly called as hot carrier.

Table 2.7

Differences between schottky diode and *p*–*n* diode

S.No.	Schottky Diode	*p*–*n* Diode
1.	Forward current due to thermionic emission (majority carrier transport)	Forward current due to diffusion currents (majority carrier transport)
2.	Reverse current only due to majority carriers that overcome the barrier (less temperature dependent)	Reverse current due to minority carriers diffusing to the depletion layer and drifting to the other side (strong temperature dependence)

S.No.	Schottky Diode	*p–n* Diode
3.	Cut-in voltage is small (about 0.3 V)	Cut-in voltage is large (about 0.7V)
4.	High switching speed, because of majority carrier transport. No recombination time needed	Switching speed limited by the recombination time of the injected minority carriers

2.16 OHMIC CONTACTS

Definition

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 fig. 2.29(a).

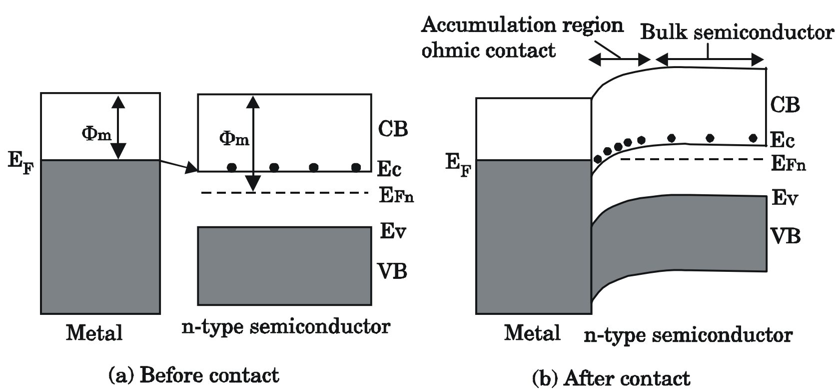


Fig. 2.29 Ohmic junction (a) before and (b) after contact.

Working

After contact, the ohmic junction is shown in figure 2.29 (b).

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).

It results in line up of Fermi levels of metal and semiconductor as shown in Fig. 2.29 (b).

The accumulation region has a 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 (Fig. 2.30). The resistivity is determined by the bulk resistivity of the semiconductor.

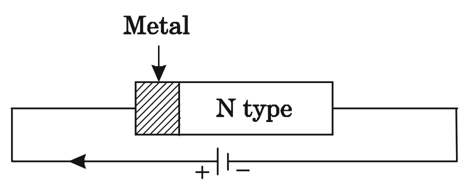


Fig. 2.30 Ohmic contact: Metal-semiconductor contact

V-I characteristics

The volt-ampere (V-I) characteristic of the ohmic contact is shown in Fig. 2.31.

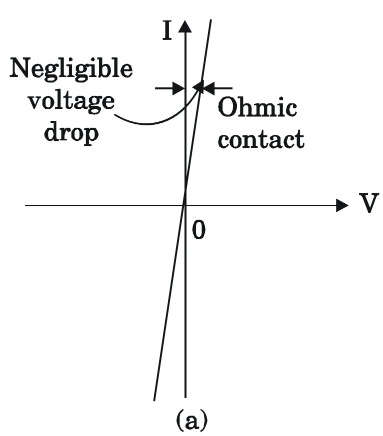


Fig. 2.31 Voltage - Current (V – I) characteristics of ohmic contact

The current is directly proportional to the potential across the junction and it is symmetric about the origin, as shown in fig. 2.31.

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.

Table 2.8

Differences between schottky diode and ohmic contact

S.No	Schottky Diode	Ohmic contact
1.	It acts as a rectifier	It acts as a resistor
2.	Very low forward resistance but very high reverse biased resistance	Resistance is same in both forward and reverse bias
3.	Work function of metal is greater than that of semiconductor $\phi_m > \phi_{\text{semi}}$	Work function of metal is smaller than that of semiconductor $\phi_m < \phi_{\text{semi}}$

ANNA UNIVERSITY SOLVED PROBLEMS

Carrier concentration in an intrinsic semiconductor

Problem 2.1

Find the resistance of an intrinsic germanium rod 1 cm long, 1 mm wide and 1 mm thick at 300 K.

For germanium $n_i = 2.5 \times 10^{19} \text{m}^{-3}$

$\mu_e = 0.39 \text{ m}^2 \text{V}^{-1} \text{s}^{-1}$

$\mu_h = 0.19 \text{ m}^2 \text{V}^{-1} \text{s}^{-1}$ **at 300 K**

[A.U. Dec. 2014]

Given data

Intrinsic carrier concentration $n_i = 2.5 \times 10^{19} \text{ m}^{-3}$

Electron mobility $\mu_e = 0.39 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$

Hole mobility $\mu_h = 0.19 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$

l = length of the rod $= 1 \text{ cm} = 1 \times 10^{-2} \text{m}$

A = Area of cross-section (width × thickness)

$$A = (1 \times 10^{-3})(1 \times 10^{-3})$$

Solution

Electrical conductivity of an intrinsic semiconductor

$$\sigma = n_i e (\mu_e + \mu_h)$$

Substituting given values, we have

$$\sigma = 2.5 \times 10^{19} \times 1.6 \times 10^{-19} \times (0.39 + 0.19)$$

$$\sigma = 2.32 \ \Omega^{-1} \text{m}^{-1}$$

Resistance $R = \frac{\rho l}{A}$ or $R = \frac{l}{\sigma A}$ $\left(\because \sigma = \frac{1}{\rho}\right)$

$$R = \frac{1 \times 10^{-2}}{2.32 \times (1 \times 10^{-3} \times 1 \times 10^{-3})} = \frac{1}{2.32} \times 10^{-2} \times 10^{6}$$

$$= 4310\ \Omega$$

$$\boxed{\text{Resistance of germanium} = 4310\ \Omega.}$$

Extrinsic semiconductor

Problem 2.2

Find the concentration of holes and electrons in *n* - type silicon at 300 K, if the conductivity is 3×10^4 ohm^{-1} m^{-1}. Also find these values for *p* - type silicon.

Given data

For silicon at 300 K, $n_i = 1.5 \times 10^{16}$ m^{-3}

$$\mu_e = 1300 \times 10^{-4}\ \text{m}^2\ \text{V}^{-1}\ \text{s}^{-1}$$

$$\mu_h = 500 \times 10^{-4}\ \text{m}^2\ \text{V}^{-1}\ \text{s}^{-1}$$

(A.U. May 2015)

Solution

(a) Concentration in *n*-type silicon

$$\sigma = ne\mu_e$$

$$n = \frac{\sigma}{e\mu_e}$$

$$n = \frac{3 \times 10^4}{1.6 \times 10^{-19} \times 1300 \times 10^{-4}}$$

$$= 1.442 \times 10^{24}\ \text{m}^{-3}$$

We know that $np = n_i^2$

(From the law of mass action)

$$p = \frac{n_i^2}{n}$$

$$p = \frac{(1.5 \times 10^{16})^2}{1.442 \times 10^{24}}$$

$$\boxed{p = 1.56 \times 10^{8}\ \text{m}^{-3}}$$

(b) Concentration in p-type silicon

$$\sigma = pe\mu_h$$

$$p = \frac{\sigma}{e\mu_h}$$

$$p = \frac{3 \times 10^{4}}{1.6 \times 10^{-19} \times 500 \times 10^{-4}}$$

$$p = 3.75 \times 10^{24}\ \text{m}^{-3}$$

$$n = \frac{n_i^2}{p}$$

$$= \frac{(1.5 \times 10^{16})^2}{3.75 \times 10^{24}}$$

$$\boxed{n = 0.6 \times 10^{8}\ \text{m}^{-3}}$$

Problem 2.3

A silicon material is uniformly doped with phosphorus atoms at a concentration of 2×10^{19} m^{-3}. The mobilities of holes and electrons are 0.05 and 0.12 m^2 V^{-1} s^{-1} respectively, $n_i = 1.5 \times 10^{16} m^{-3}$. Find the electron and hole concentrations and electrical conductivity.

(A.U. June 2014)

Solution

$$\text{Hole concentration} \quad p = \frac{n_i^2}{N_D} = \frac{(1.5 \times 10^{16})^2}{2 \times 10^{19}}$$

$$= 1.125 \times 10^{13} / \text{ m}^3$$

$$\text{Electron concentration } n = N_D = 2 \times 10^{19} / \text{ m}^3$$

$$\text{Electrical conductivity} \quad \sigma = e\, N_D\, \mu_e$$

$$\sigma = 1.602 \times 10^{-19} \times 2 \times 10^{19} \times 0.12$$

$$\boxed{\sigma = 0.384 \text{ ohm}^{-1} \text{ m}^{-1}}$$

Problem 2.4

Find the hole and electron concentrations in a *p*-type semiconductor, if the acceptor density is 10^{20} atoms/m^3 and the intrinsic concentration is 2.5×10^{19} per m^3 at 300 K. ***(A.U. May 2016)***

Solution

In a p-type semiconductor, the hole concentration is equal to the acceptor density.

$$p = N_a = 10^{20} \text{ holes/m}^3$$

$$n = \frac{n_i^2}{N_a} = \frac{(2.5 \times 10^{19})^2}{10^{20}} = 6.25 \times 10^{18} \text{ electrons/m}^3$$

$$\boxed{\boldsymbol{n = 6.25 \times 10^{18} \text{ m}^{-3}}}$$

Hall effect

Problem 2.5

The Hall coefficient of a specimen of a doped silicon is found to be 3.66×10^{-4} m^3/C. The resistivity of the specimen is 8.93×10^{-3} Ω m. Find the mobility and density of the charge carriers. ***(A.U.April 2015)***

Given data

Hall coefficient of the specimen $R_H = 3.66 \times 10^{-4}$ m^3/C

Resistivity of the specimen $\rho = 8.93 \times 10^{-3}$ Ω m

Mobility of the carrier $\mu_h = ?$

Density of charge carriers $n_h = ?$

Solution

We know that density of charge carriers

$$n_h = \frac{1}{R_H e}$$

Substituting the given values, we have

$$n_h = \frac{1}{3.66 \times 10^{-4} \times 1.610 \times 10^{-19}}$$

$$n_h = 1.708 \times 10^{22} \text{ m}^{-3}$$

$$\mu_h = \frac{1}{\rho \, n_h \, e}$$

$$\mu_e = \frac{R_H}{\rho}$$

$$\mu_h = \frac{3.66 \times 10^{-4}}{8.93 \times 10^{-3}}$$

$$\boxed{\mu_h = 0.041 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}}$$

Problem 2.6

Find the Hall coefficient and electron mobility of germanium for a given sample (length 1 cm, breadth 5 mm, thickness 1 mm). A current of 5 milliampere flows from a 1.35 volt supply and develops a Hall voltage of 20 millivolt across the specimen in a magnetic field of 0.45 Wb/m². ***(A.U. May 2013)***

Given data

Current through the specimen $I = 5$ mA or 5×10^{-3} A

Voltage across the specimen $V = 1.35$ V

Length of the sample $L = 1$ cm or 1×10^{-2} m

Breadth of the sample $b = 5$ mm or 5×10^{-3} m

Thickness of the sample $t = 1$ mm or 1×10^{-3} m

Hall voltage $V_y = 20 \times 10^{-3}$ V

Magnetic field $H = 0.45$ Wb/m^2

Solution:

We know that resistivity $\rho = \frac{Ra}{l}$

where $R \rightarrow$ Resistance of the specimen

$$R = \frac{V}{I} = \frac{1.35}{5 \times 10^{-3}}$$

$a \rightarrow$ Area of cross-section $= b \times t$

$$a = 5 \times 10^{-3} \times 1 \times 10^{-3}$$

$$= 5 \times 10^{-6} \text{ m}^2$$

$$\rho = \frac{1.35}{5 \times 10^{-3}} \times \frac{5 \times 10^{-6}}{1 \times 10^{-2}}$$

$$= 0.135 \ \Omega \text{ m}$$

$$\text{Hall field } E_y = \frac{V_y}{\text{Thickness}} = \frac{20 \times 10^{-3}}{1 \times 10^{-3}}$$

$$= 20 \text{ Vm}^{-1}$$

$$\text{Current density } J_x = \frac{\text{Current}}{\text{Area of cross–section}}$$

$$J_x = \frac{5 \times 10^{-3}}{5 \times 10^{-6}}$$

$$= 1 \times 10^{3} \text{ Am}^{-2}$$

$$\frac{1}{ne} = \frac{E_y}{HJ_x} = \frac{20}{0.45 \times 10^{3}}$$

$$= 0.044 \text{ m}^3/\text{C}$$

Hall coefficient

$$R_H = 1.18 \times \frac{1}{ne} = 1.18 \times 0.044$$

$$= 0.0524 \text{ m}^3/\text{C}$$

$$R_H = 0.0524 \text{ m}^3/\text{C}$$

Electron mobility

$$\mu_e = \frac{R_H}{\rho} = \frac{0.0524}{0.135}$$

$$= 0.39 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$$

$$\boxed{\mu_e = 0.39 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}}$$

Problem 2.7

A copper strip 2.0 cm wide and 1.0 mm thick is placed in a magnetic field with B = 1.5 weber/m^2 perpendicular to the strip. Suppose a current of 200 A is set up in the strip. What Hall potential difference would appear across the strip?

Given $N = 8.4 \times 10^{28}$ electrons /m^3. ***(A.U. May 2015)***

Given data

Current flowing $I_x = 200$ A

Applied magnetic field H_z = 1.5 Wb m^{-2}

Number of electrons,

per unit volume n = 8.4×10^{28} electrons m^{-3}

Thickness of the strip t = 1.0×10^{-3} m

Solution

$$\text{Hall potential } V_y = \frac{R_H I_x B_z}{b}$$

$$V_y = \frac{I_x B_z}{n\,e\,b} \qquad \left(\because R_H = \frac{1}{ne}\right)$$

Substituting the given values, we have

$$V_H = \frac{200 \times 1.5}{(8.4 \times 10^{28})\,(1.6 \times 10^{-19})\,(1.0 \times 10^{-3})}$$

$$\boxed{V_H = 2.2 \times 10^{-5}\ \text{V}}$$

Note: This problem is important in the sense that it shows that Hall voltage can be also observed in metals besides semiconductor.

In semiconductors, Hall voltage is comparatively much larger; it is of the order of milli-volts as compared to the order of micro-volts in metals.

Moreover, to observe Hall voltage in metals, current of the order of amperes is needed when compared to the order of milliamperes as in the case of semiconductors.

Part - A '2' Marks Q & A

ANNA UNIVERSITY Q&A

1. What are elemental semiconductors? Give some important elemental semiconductors. ***(A.U Dec 2014)***

Elemental semiconductors are made from single element of the fourth group elements of the periodic table.

Example

Germanium and silicon.

2. What are the properties of semiconductors?

(A.U. June 2013)

- They are formed by covalent bond.
- They have empty conduction band.
- They have almost filled valence band.
- These materials have comparatively narrow energy gap.

3. What are compound semiconductors? Give some important compound semiconductors. ***(A.U April 2015)***

Semiconductors which are formed by combining third and fifth group elements or second and sixth group elements in the periodic table are called compound semiconductors.

S.No.	Group	Compound semiconductor
1.	Combination of third and fifth group elements (III and V)	Gallium Phosphide (GaP) Gallium Arsenide (GaAs) Indium Phosphide (InP) Indium Arsenide (InAs)
2.	Combination of second and sixth group elements (II and VI)	Magnesium Oxide (MgO) Magnesium Silicon (MgSi) Zinc Oxide (ZnO) Zinc Sulphide (ZnS)

4. Mention any four advantages of semiconducting materials. ***(April 2013, April 2014)***

- It behaves as insulator at 0 K and as conductor at high temperatures.
- It has some properties of both conductor and insulator.
- On doping, *n* and *p*-type semiconductors are produced with charge carriers of electrons and holes respectively.
- It has many applications in electronic field such as manufacturing of diodes, transistors, LED's, IC etc.

5. What are the differences between elemental semiconductors and compound semiconductors?

(A.U June 2012, April 2014, Dec 2015)

S. No.	Elemental Semiconductors	Compound Semiconductors
1.	They are made of single element. Examples: Ge, Si	They are made of compounds. Examples: GaAs, GaP, MgO etc.
2.	Heat is produced during recombination.	The photons are emitted during recombination.
3.	They are used for the manufacture of diodes and transistors.	They are used for making LED's, Laser diodes and IC's.

6. Write an expression for the concentration of electrons in the conduction band of an intrinsic semiconductor.

(A.U. Jan 2014)

The concentration of electrons in the conduction band of an intrinsic semiconductor is given by

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

where $m_e^* \rightarrow$ effective mass of electron

$E_F \rightarrow$ Fermi energy level

$E_C \rightarrow$ Energy corresponds to the bottom of conduction band

$T \rightarrow$ Absolute temperature

7. Write an expression for the concentration of holes in the valence band of an intrinsic semiconductor.

(A.U. May 2015)

The concentration of holes in the valence band is given by

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

m_h^* → effective mass of hole

T → absolute temperature

E_F → Fermi energy

E_v → Energy corresponds to the top of valence band

8. What is Fermi level in a semiconductor?

(A.U. May 2016)

Fermi level in a semiconductor is the energy level situated in the band gap of the semiconductor. It is exactly located at the middle of the band gap in the case of an intrinsic semiconductor.

9. Write an expression for carrier concentration in n-type semiconductor. ***(A.U. May 2015)***

The carrier concentration in n-type semiconductor is given by

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

where

$\Delta E \rightarrow E_C - E_d =$ Ionisation energy of the donor

$N_d \rightarrow$ Number of donor atoms per unit volume of the material.

$m_e^* \rightarrow$ Effective mass of an electron.

$T \rightarrow$ Absolute temperature

10. Write an expression for carrier concentration of holes in the valence band of p-type semiconductor.

(A.U. Jan 2014)

The carrier concentration in p-type is given by

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

where

$\Delta E = (E_v - E_a) \rightarrow$ ionisation energy of acceptor level

$m_h^* \rightarrow$ Effective mass of hole

$N_a \rightarrow$ Number of acceptor atoms per unit volume of the material.

$T \rightarrow$ Absolute temperature.

11. Define Hall-effect and Hall voltage.

(A.U. May 2015, Dec 2016)

When a conductor carrying a current (I) is placed in a transverse magnetic field (B), a potential difference is produced inside the conductor in a direction normal to the directions of the current and magnetic field.

This phenomenon is known as Hall-effect and the generated voltage is called Hall-voltage.

12. Mention the uses of Hall effect.

(A.U. May 2013, June 2014)

- It is used to find type of semiconductor.
- It is used to measure carrier concentration.
- It is used to find mobility of charge carrier.
- It it used to measure the magnetic flux density using a semiconductor sample of known Hall coefficient.

13. What are the differences between intrinsic and extrinsic semiconductor? ***(A.U 2008, June 2009, 2012)***

S.No.	Intrinsic semiconductor	Extrinsic semiconductor
1.	Semiconductor in a pure form is called intrinsic semi conductor.	Semiconductors which are doped with impurity is called extrinsic semiconductor.
2.	Here, the charge carriers are produced only due to thermal agitation.	Here, the charge carriers are produced due to impurities.
3.	Examples: Si, Ge, etc.	Examples: Si and Ge doped with Al, In, P, As etc.

14. What are the differences between *n*-type and *p*-type semiconductor?

Differences between
***n* - type and *p* - type semiconductors**

S.No.	*n*-type semiconductor	*p*-type semiconductor
1.	When pentavalent impurity is doped to intrinsic semiconductor, n - type semiconductor is formed.	When trivalent impurity is doped to intrinsic semiconductor, p - type semiconductor is formed.

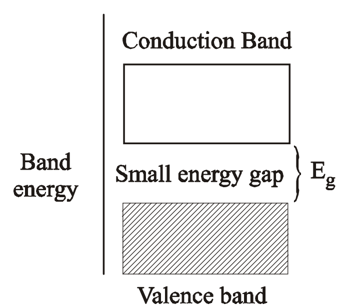
S.No.	*n*-type semiconductor	*p*-type semiconductor
2.	The impurity is called donor impurity since it donates electron.	The impurity is called acceptor impurity since it accepts electron.
3.	Majority charge carriers are electrons.	Majority charge carriers are holes.
4.	Minority charge carriers are holes.	Minority charge carriers are electrons.

ADDITIONAL Q&A

1. What is a semiconductor?

Semiconductor is a special class of material which behaves like an insulator at 0 K and acts conductor at temperature other than 0 K. Its resistivity lies in between a conductor and an insulator.

2. Draw the energy level diagram of a semiconductor.



Energy band diagram of a semiconductor

3. What is an intrinsic semiconductor?

Semiconductor in an extremely pure form (without impurities) is known as intrinsic semiconductor.

4. What is an extrinsic semiconductor?

A semiconducting material in which impurity atoms added (doped) to the material to modify its conductivity is known as extrinsic semiconductor or impurity semiconductor.

5. What is an n-type semiconductor?

When a small amount of pentavalent impurity is added to a pure semiconductor, it becomes extrinsic or impure semiconductor and it is known as n-type semiconductor.

6. What is a p-type semiconductor?

When a small amount of trivalent impurity is added to a pure semiconductor, it becomes extrinsic semiconductor or impure semiconductor and it is called p-type semiconductor.

7. What is meant by doping and doping agent?

The technique of adding impurities to a pure semiconductor is known as **doping** and the added impurity is called **doping agent**.

8. Explain the concept of hole in semiconductor.

In intrinsic semiconductor, charge carriers are created due to breaking of covalent bonds. When a covalent bond is broken, an electron escapes to the conduction band leaving behind an empty space in the valence band. This missing electron is called a hole.

9. What is meant by donor energy level?

A pentavalent impurity when doped with an intrinsic semiconductor donates one electron which produces an energy level called **donor energy level**.

10. What is meant by acceptor energy level?

A trivalent impurity when doped with an intrinsic semiconductor accepts one electron which produces an energy level called acceptor energy level.

11. Mention the uses of compound semiconductor.

They are used as photovoltaic materials, photoconductive cell, laser materials and for making LED [Light Emitting Diode].

12. Define drift velocity.

When an electrical 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 attained by the carriers is proportional to the electrical field strength E.

$$\text{i.e.,} \quad v_d \propto E$$

$$v_d = \mu E \qquad \text{...(1)}$$

where μ is a proportionality constant and it is known as the mobility of the charge carrier.

13. 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.

14. Define diffusion current.

The non-uniform distribution of charge carriers creates the regions of uneven concentrations in the semiconductor.

The charge carriers move from the regions of higher concentration to the regions of lower concentration. This process is known as diffusion. The current is known as diffusion current.

15. What is a Hall device?

The device which uses the hall effect for its application is known as Hall device.

16. What are different types of Hall devices?

There are three types of Hall devices.

They are

(a) Gauss Meter

(b) Electronic Multiplier

(c) Electronic Wattmeter

17. What is a 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.

18. What are advantages of schottky diodes?

- In schottky diode, stored charges or depletion region is negligible. So a schottky diode has a very low capacitance.
- In schottky diode, the depleting region is negligible. So the schottky diode will immediately switch from ON to OFF state (fast recovery time).
- The depletion region is negligible in schottky diode. So applying a small voltage is enough to produce large current.
- It has high efficiency.
- It operates at high frequencies.
- It produces less noise.

19. What are the application of scholtky diode?

- Schottky diode can be used for rectification of signals of frequencies even exceeding 300 MHz.
- It is commonly used in switching device at frequencies of 20 GHz.
- It is used in radio frequency (RF) applications.
- It is widely used in power supplies.

20. What are the differences between scholtky diode and *p–n* diode?

S.No.	Schottky Diode	*p–n* Diode
1.	Forward current due to thermionic emission (majority carrier transport)	Forward current due to diffusion currents (majority carrier transport)
2.	Reverse current only due to majority carriers that overcome the barrier (less temperature dependent)	Reverse current due to minority carriers diffusing to the depletion layer and drifting to the other side (strong temperature dependence)
3.	Cut-in voltage is small (about 0.3 V)	Cut-in voltage is large (about 0.7V)
4.	High switching speed, because of majority carrier transport. No recombination time needed	Switching speed limited by the recombination time of the injected minority carriers

21. What is 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.

22. What are the uses of ohmic contact?

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

23. What are the differences between scholtky diode and ohmic contacts?

S.No	Schottky Diode	Ohmic contact
1.	It acts as a rectifier	It acts as a resistor
2.	Very low forward resistance but very high reverse biased resistance	Resistance is same in both forward and reverse bias
3.	Work function of metal is greater than that of semiconductor $\phi_m > \phi_{\text{semi}}$	Work function of metal is smaller than that of semiconductor $\phi_m < \phi_{\text{semi}}$

PART - B (16 Marks Questions)

Anna University Questions:

Intrinsic semiconductor

1. Obtain an expression for intrinsic carrier concentration in an intrinsic semiconductor. ***(AU May 2014)***
2. Derive an expression for the density of holes in an intrinsic semiconductor. ***(AU July, Dec. 2015)***
3. Derive an expression for concentration of holes (absence of electrons) in intrinsic semiconductors. ***(AU Nov/Dec 2013)***
4. Obtain an expression for the carrier concentration of electrons in an intrinsic semiconductor. ***(AU May/June 2014)***
5. Assuming the Fermi - Dirac distribution derive an expression for the concentration of electrons per unit volume in the conduction band of an intrinsic semiconductor. ***(AU April/May 2014; Nov/Dec 2015)***

Extrinsic semiconductors

6. Derive the relation for carrier concentration in N - type semiconductor. ***(AU Dec 2014)***

7. Obtain an expression for density of electrons in the conduction band of an n - type and density of holes in the valence band of a p - type extrinsic semiconductor.

   (AU Dec 2015)

8. Obtain an expression for the density of electrons in the conduction band of an n - type semiconductors and show that it is proportional to the square root of the donor concentration at low temperatures. Also state what happens at high temperatures. ***(AU Nov/Dec 2013)***

9. Obtain an expression for the density of holes in the valence band of p - type semiconductors and show that it is proportional to the square root of the acceptor concentration at low temperatures. ***(AU April/May 2012)***

Hall Effect

10. (i) Give the theory of Hall effect.

    (ii) Using that effect how will you determine the electrical conductivity of a semiconductor. ***(AU Oct 2014)***

11. (i) What is Hall effect? Derive an expression of Hall coefficient.

    (ii) Describe an experimental set-up for the measurement of the Hall voltage and give its applications.

    (AU July 2015)

12. (i) What is Hall effect? Show that for a p - type semiconductor the Hall coefficient R_H is given by 1/pe.

    (ii) Mention the applications of Hall effect. ***(AU Dec 2016)***

13. What is Hall effect? Give the theory of Hall effect. Describe the Hall effect experiment to determine the Hall coefficient of semiconductor. ***(AU Dec 2013)***

14. (i) Obtain expression for Hall coefficient.

    (ii) How will you measure Hall coefficient experimentally?

    (iii) Describe any two applications of Hall effect.

    (AU May 2014)

15. (i) Explain Hall effect in p-type and n-type semiconductors.

    (ii) Derive an expression for Hall coefficient.

    (iii) Describe the experimental setup for the measurement of Hall coefficient. ***(AU, Dec 2016)***

16. What is Hall effect? Derive an expression for Hall coefficient. Describe an experiment for the measurement of the Hall coefficient and mention its applications. ***(AU, May / June 2016)***

17. (i) Explain the phenomenon of Hall effect.

    (ii) Derive an expression for Hall coefficient for a n - type semiconductor and for p - type semiconductor. Also state how Hall voltage is related. ***(AU, May / June 2014)***

Additional PART - B (16 Marks Questions)

1. Derive an expression for electrical conductivity of intrinsic semiconductor.
2. Write down expression for drift current and diffusion currents.
3. Explain working of any two Hall devices.
4. Describe construction and working of scholtty diode.
5. Write a note on ohmic contact.

ASSIGNMENT PROBLEMS

1. In an intrinsic semiconductor, the effective mass of the electron is 0.07 m_o and that of the hole is 0.4 m_o where m_o is the rest mass of the electron. Calculate the intrinsic concentration of charge carriers at 300 K. Given $E_g = 0.7$ eV. ***[Ans: 2.3×10^{18} / m^3]***
2. In a Hall experiment, a current of 25 A is passed through a long foil of silver which is 0.1 mm thick and 3 cm wide.