UNIT I

1. Give any two postulates of classical free electron theory.

- According to this theory, a metal consists of a very large number of free electrons. These free electrons move freely throughout the volume of the metal. They are fully responsible for the electrical conduction in the metal.

- Drude assumed that the free electrons in a metal form an electron gas. These free electrons move randomly in all possible directions just like the gas molecules move in a container.

2. Define mean free path.

The average distance travelled by a free electron between any two successive collisions in the presence of an applied field is known as **mean free path**.

It is the product of drift velocity of electrons (v_d) and collision time (τ_c).

$$\lambda = v_d \times \tau_c$$

3. Define relaxation time of an electron.

The average time taken by a free electron to reach its equilibrium state from its disturbed state due to application of an external electrical field is called **relaxation time.**

4. Define drift velocity of electron. How is it different from the thermal velocity of an electron?

(A.U. May 2008, Dec 2012)

The average velocity acquired by a free electron in a particular direction after a steady state is reached on the application of an electrical field is called **drift velocity**. It is denoted as v_d and its value is very small (50 cm / s).

The thermal velocity is random in nature and its value is very high (10^5 m/s),

5. Define mobility of electrons. *(A.U. May 2009)*

The magnitude of the drift velocity acquired by the electrons per unit electric field is defined as the mobility of electrons (μ)

$$\text{i.e.,} \quad \boxed{\mu = \frac{v_d}{E}}$$

where $v_d \rightarrow$ Drift velocity of electrons

$E \rightarrow$ Electrical field.

6. Define electrical conductivity. What is its unit.

(A.U. April 2010, Dec 2010)

The amount of electrical charges (q) conducted per unit time (t) across unit area (A) of the conductor for unit applied electrical field (E) is defined as electrical conductivity.

$$\boxed{\sigma = \frac{q}{t\,A\,E}}$$

Its unit is ohm^{-1} m^{-1} or mho m^{-1}

7. What are the merits of classical free electron theory?
(A.U. May 2012)

- It is used to verify Ohm's law.
- It is used to explain electrical and thermal conductivities of metals.
- It is used to derive Wiedemann - Franz law.
- It is used to explain the optical properties of metal.

8. What are the drawbacks of classical free electron theory?
(A.U. May 2009, June 2010, Dec 2012)

- Classical theory states that all free electrons will absorb the supplied energy; on the contrary, quantum theory states that only a few electrons will absorb the supplied energy.
- Electrical conductivity of semiconductors and insulators (non-metals) can not be explained.
- The phenomena such as photo-electric effect, Compton effect and black body radiation can not be explained on the basis of this theory because these phenomena are based on quantum theory.

9. State Wiedemann - F

10. What is Lorentz number? *(A.U. June 2012)*

The ratio between thermal conductivity (K) of a metal to the product of electrical conductivity (σ) of a metal and absolute temperature (T) of the metal is a constant. It is called Lorentz number and it is given by

$$\boxed{L = \frac{K}{\sigma T}}$$

11. Define Fermi distribution function. *(A.U. May 2010)*

The probability $F(E)$ of an electron occupancy for a given energy level at temperature T is known as Fermi distribution function. It is given by

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

$E_F \rightarrow$ Fermi level

$k \rightarrow$ Boltzmann's constant

$T \rightarrow$ Absolute temperature

$E \rightarrow$ Energy of the level whose occupancy is being considered.

12. Write down the expression for the Fermi distribution law and explain for the electrons in a metal.

(A.U. May 2008)

Fermi distribution function is given by

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

where E_F is called Fermi energy

if $E < E_F$, all levels are filled with electrons

i.e., $F(E) = 1$

if $E > E_F$, all levels are empty

i.e., $F(E) = 0$

if $T > 0\,K$ at E_F, $F(E) = \frac{1}{2}$

13. Define Fermi level and Fermi energy with its importance. *(A.U. Dec. 2008, May 2009, Dec 2010, June 2012, Dec 2012)*

Fermi level: It is the energy level at finite temperature above 0 K in which the probability of the electron occupation is 1/2 and it is also the level of maximum energy of the filled states at 0 K.

Fermi energy: It is the energy of the state at which the probability of the electron occupation is 1/2 at any temperature above 0K. It is also the maximum energy of filled states at 0 K.

Importance: Fermi level and Fermi energy determine the probability of an electron occupation for a given energy level at a given temperature.

14. Draw the Fermi distribution curve at 0 K and at any temperature *TK*. *(A.U. May 2010)*

(or)

How does the Fermi function varies with temperature.

Fermi function varies with respect to the temperature as shown in fig.1. At 0 K, all the energy states below E_F are filled and all those above it are empty. When the temperature is increased, the electron takes an energy kT and hence Fermi function falls to zero.

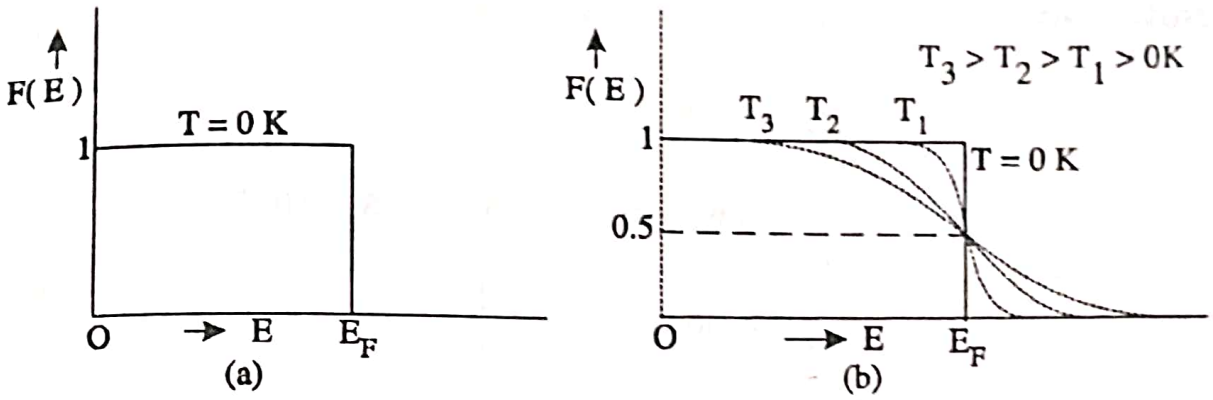


Fig. Variation of Fermi distribution function with E at different temperatures

15. Define density of states. What is its use?

(A.U. June 2011, Dec 2012, June 2013)

It is defined as the number of available electron states per unit volume in an energy interval E and $E + dE$. It is denoted by $Z(E)$.

It is used to determine Fermi energy at any temperature.

16. Mention any two important features of quantum free electron theory of metals. *(AU April 2009)*

- It shows that the energy levels of an electron are discrete
- Maximum energy level upto which the electrons can be filled is denoted by Fermi energy level.

17. Calculate the drift velocity of the free electrons with a mobility of 3.5×10^{-3} $m^2 V^{-1} s^{-1}$ in copper for an electric field strength of 0.5 V/m *(A.U. June 2008)*

Given data

Mobility of free electrons $(\mu) = 3.5 \times 10^{-3}$ $m^2 V^{-1} s^{-1}$

Electric field strength of copper $(E) = 0.5$ Vm^{-1}

i) Electrical conductivity of a metal

$$\sigma = \frac{ne^2\tau}{m}$$

ii) Thermal conductivity of a metal

$$K = \frac{1}{2} n v^2 k \tau$$

iii) Fermi distribution function

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

iv) Density of energy states (No. of available energy states per unit volume)

$$Z(E)\,dE = \frac{N(E)\,dE}{V}$$

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

Intrinsic Semiconductor

(i) Density of electrons in conduction band

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

(ii) Density of holes in valence band

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

(iii) Intrinsic carrier concentration:

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

(iv) Fermi level and its variation with temperature

$$E_F = \frac{E_V + E_C}{2}$$

Extrinsic Semiconductor

(i) Carrier concentration in n-type semiconductor:

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

Variation of Fermi level with temperature and impurity concentration:

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

(ii) Carrier concentration in p-type semiconductor

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

Variation of Fermi level with temperature & impurity concentration

$$\boxed{E_F = \frac{E_a + E_V}{2}}$$

Hall effect 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 current and magnetic field. This phenomenon is known as "Hall effect". The voltage thus generated is called Hall voltage.

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

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

p-type $$R_H = +\frac{1}{pe}$$

$$E_H = R_H JB$$

Hall coefficient in terms of Hall voltage

$$R_H = \frac{V_H b}{IB}$$

Applications

(i) Determination of semiconductor type (n type or p-type)

(ii) Calculation of carrier concentration

(iii) Determination of mobility

(iv) Magnetic field meter

(v) Hall effect multiplier

Nanomaterials

Nanomaterials are newly developed materials with grain size at the nanometer range (10^{-9}m) i.e, in the order of 1–100 nm.

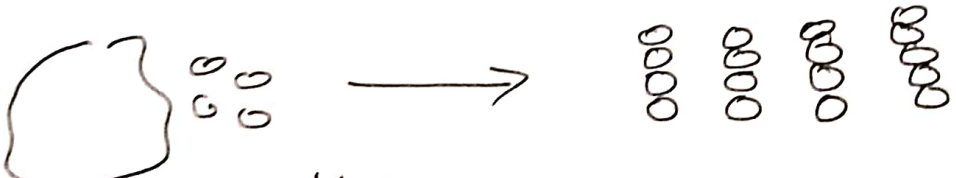
Different forms of nanomaterials

* Nanostructured material
* Nanoparticles
* Nanodots
* Nanorods
* Nanotubes
* Nanowires
* Fullerenes
* Nanocomposites

Synthesis of nanomaterials

- Top-down process
- Bottom-up process

Top-down process The bulk materials are ~~broken~~ broken into nanosized particles.



E.g Ball milling

Bottom-up process Nanomaterials are produced by building of atom by an atom

E.g Chemical vapour deposition

preparation of Nanomaterials

* Ball milling
* plasma arcing
* Sol-gel
* Hydrothermal
* Co-precipitation
* Solvothermal
* Laser synthesis

Properties of Nanomaterials

I. physical properties :- (a) Variation of physical properties with geometry
(b) Melting point reduces with decreases in cluster size.
(c) The large surface to volume ratio

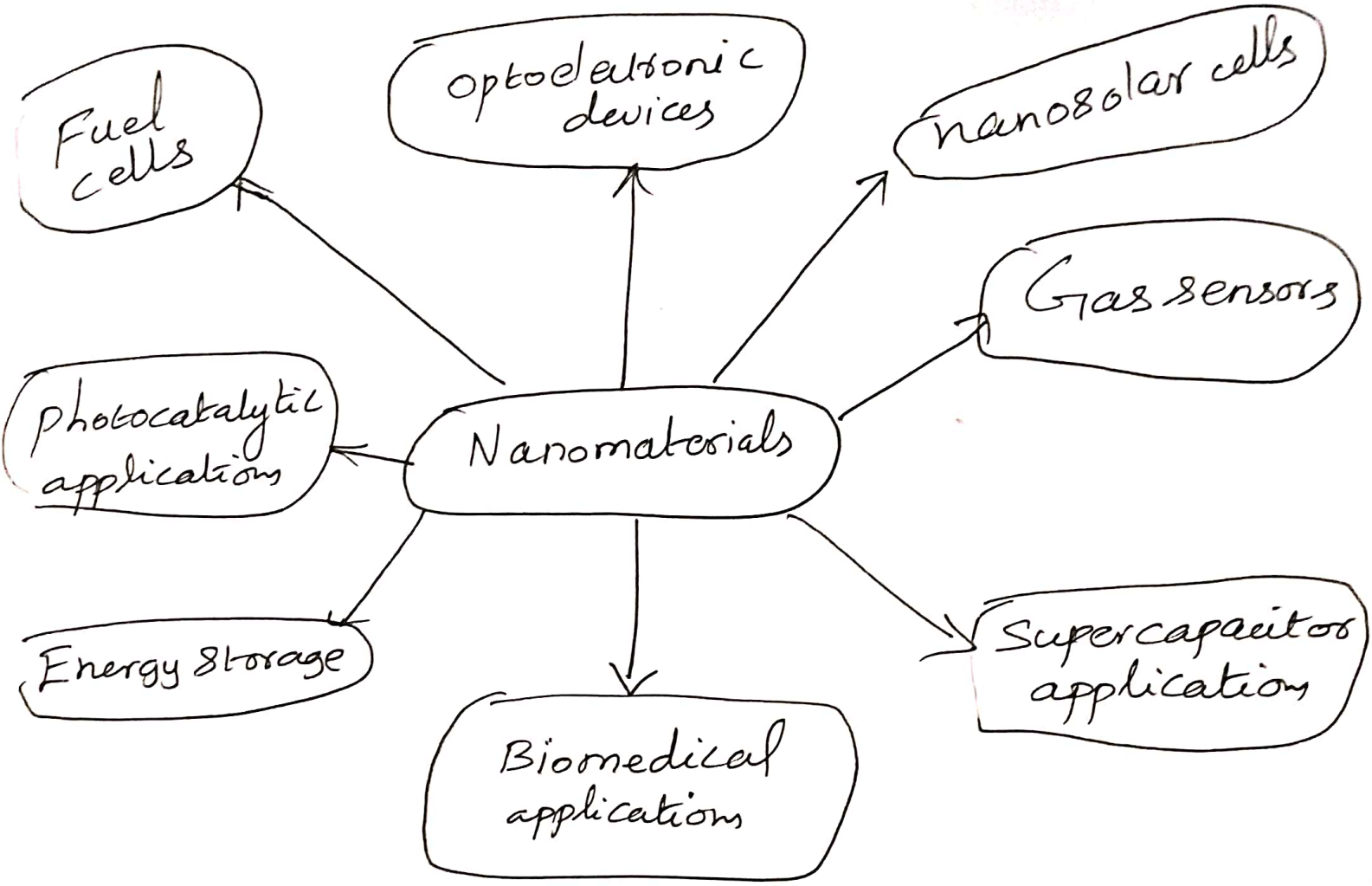
Magnetic properties

metal	Bulk	Nanophase
Na, K	paramagnetic	ferromagnetic
Fe, Co, Ni	ferromagnetic	superparamagnetic

Mechanical properties * Elastic strength is low however, its plastic behaviour is high

Applications

(i) Materials Technology
(ii) Information Technology
(iii) Biomedicals
(iv) Energy Storage
(v) optical devices
(vi) Transmission lines
(vii) Nano & MEMS
(viii) Molecular nanotechnology
(ix) Underwater nanosensor networks



11

"Applications of Nanomaterials"

27.18 KRONIG-PENNEY MODEL

This model illustrates the behaviour of electrons in a periodic potential. It assumes a one-dimensional model of periodic potential (Fig. 27.33).

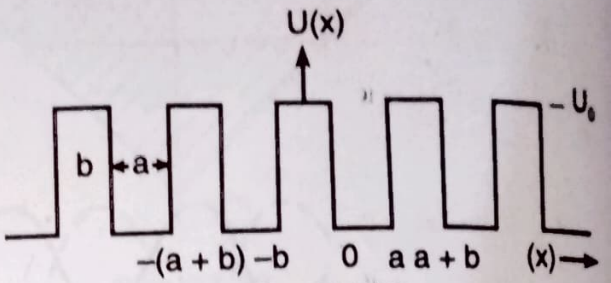


Fig. 27.33

The wave equation can be solved in terms of elementary functions for the square-well array.

The wave functions associated with this model are calculated by solving the Schrodinger equation

$$-\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2} + U(x)\psi = \varepsilon\psi \qquad ...(1)$$

Here, $U(x)$ is the potential energy and ε is the energy eigenvalue.

In the region $0 < x < a$, $U = 0$. Eq. (1) becomes

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2}\varepsilon\psi = 0 \qquad ...(2)$$

The eigenfunction is

$$\psi = Ae^{iKx} + Be^{-iKx}, \qquad ...(3)$$

It represents plane waves travelling to the right and to the left, with energy

$$\varepsilon = \hbar^2 K^2/2m \qquad ...(4)$$

In the region $-b < x < 0$, the Schrodinger wave equation is

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2}[\varepsilon - U_0]\psi = 0 \qquad ...(5)$$

The eigenfunction is

$$\psi = Ce^{Qx} + De^{-Qx}, \qquad ...(6)$$

and

$$U_0 - \varepsilon = \hbar^2 Q^2/2m \qquad ...(7)$$

Since the potential is periodic, the wave functions must be of the form of Bloch function, *i.e.*,

$$\psi(x) = u_k(x)\, e^{ikx} \qquad ...(8)$$

Thus the solution in the region $a < x < a + b$ must be related to the solution (6) in the region $-b < x < 0$ by the Bloch theorem:

$$\psi(a < x < a + b) = \psi(-b < x < 0)\, e^{ik(a+b)}, \qquad ...(9)$$

The constants A, B, C, D are chosen so that ψ and $d\psi/dx$ are continuous at $x = 0$ and $x = a$.

At $x = 0$.

$$A + B = C + D; \qquad ...(10)$$

$$iK(A - B) = Q(C - D). \quad ...(11)$$

At $x = a$, with the use of (9) for $\psi(a)$ under the barrier in terms of $\psi(-b)$,

$$Ae^{ika} + Be^{-ika} = (Ce^{-Qb} + De^{Qb})\, e^{ik(a+b)}; \quad ...(12)$$

$$iK(Ae^{ika} - Be^{-ika}) = Q(Ce^{-Qb} - De^{Qb})\, e^{ik(a+b)}. \quad ...(13)$$

The four equations (10), (11), (12), (13) have a solution only if the determinant of the coefficients of A, B, C, D vanishes. This leads to the following equation:

$$[(Q^2 - K^2)/2QK] \sinh Qb \sin Ka + \cosh Qb \cos Ka = \cos k(a + b) \quad ...(14)$$

The result is simplified if we represent the potential by the periodic delta function obtained when we pass to the limit $b = 0$ and $U_0 = \infty$ in such a way that $Q^2 ba/2 = P$, a finite quantity. In this limit $Q >> K$ and $Qb << 1$. Then (14) reduces to

$$(P/Ka) \sin Ka + \cos Ka = \cos ka \quad ...(15)$$

This is the condition for the solutions of the wave equation to exist.

Figure 27.34 shows a plot of the function $(P/Ka) \sin Ka + \cos Ka$ versus Ka for $P = 3\pi/2$.

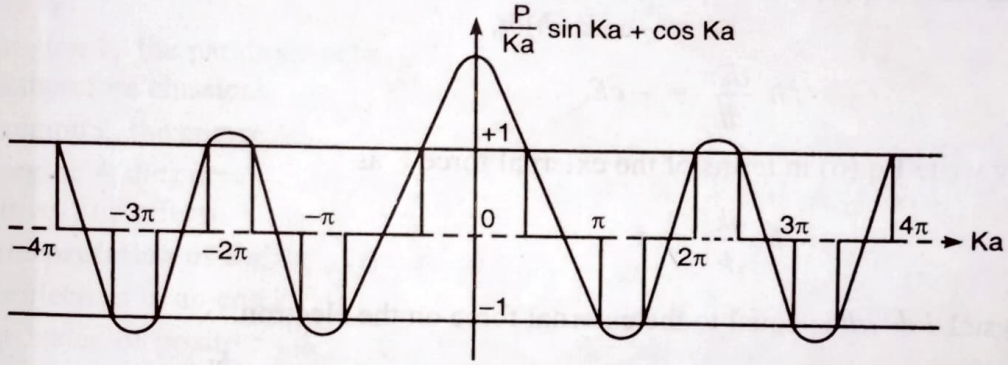


Fig. 27.34

The allowed values of the energy ε are given by those ranges of

$$Ka = \left(\frac{2m\varepsilon}{\hbar^2}\right)^{1/2} a \quad ...(16)$$

for which the function lies between + 1 and − 1.

Clearly there are regions for Ka where the value of $\left[\frac{P \sin Ka}{Ka} + \cos Ka\right]$ does not lie between − 1 and + 1. For these values of Ka and hence of energy ε, no solutions exist. Such regions of energy are prohibited and are called *forbidden bands.*

Thus, *the energy spectrum of the electron consists of alternate regions of allowed energy* (continuous) and *forbidden energy* (dotted). These regions are usually referred as the allowed and forbidden energy bands.

Fig. 27.35 shows plot of energy vs. wavenumber for the Kronig-Penney potential, with $P = 3\pi/2$. Notice the energy gaps at $ka = \pi, 2\pi, 3\pi$ ... The figure shows the periodic dependence of ε on k and demonstrates the existence of forbidden energy gaps

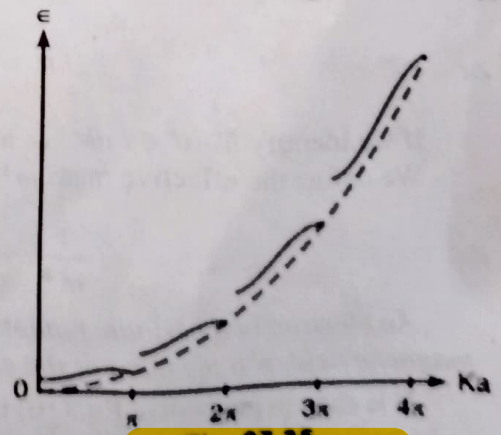


Fig. 27.35

2. Semiconducting Materials

Intrinsic semiconductor - carrier concentration derivation - Fermi level - Variation of Fermi level with temperature - electrical conductivity - band gap determination - compound semiconductors - direct and indirect band gap - derivation of carrier concentration in n-type and p-type semicondfetor - variation of Fermi level with temperature and impurity concentration - Hall effect - Determination of Hall coefficient - Applications.

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.

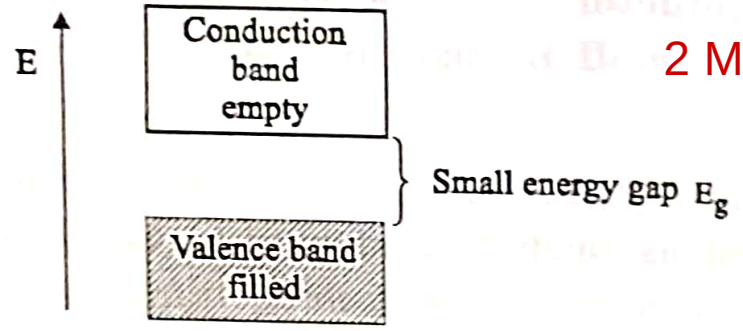
Definition

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)



2 MARK

Fig. 2.1 Energy band diagram of a semiconductor

General properties of the semiconductors

2 MARK

- 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.

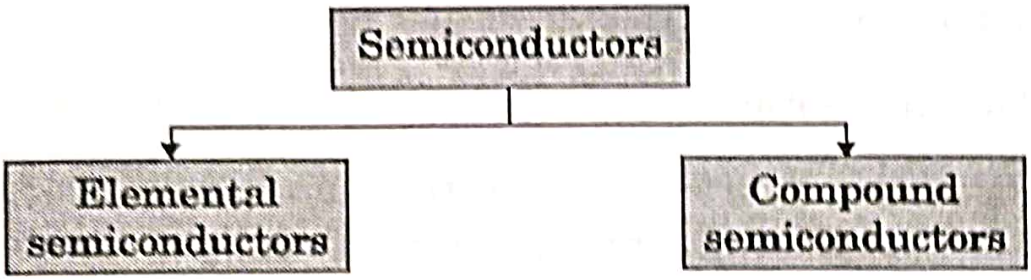
This property is in contrary to that of metals in which if temperature is increased or impurities are added, their electrical conductivity decreases.

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

2.1 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)

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.

2 MARK

Table 2.3

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

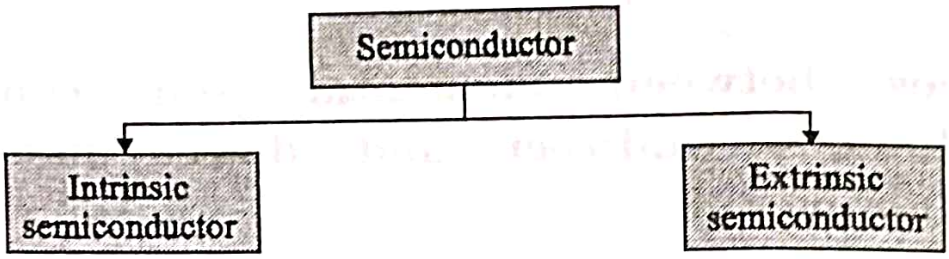
S.No.	Elemental Semiconductors	Compound Semiconductors
1.	They are made of a single element Example: Germanium (Ge), Silicon (Si).	They are made of compounds Example: GaA, GaP, CdS, MgO.
2.	They are known as **indirect band gap semiconductors.**	They are known as **direct band gap semiconductors.**
3.	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.

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 SEMICONDUCTOR

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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**.

Fig. 2.2 shows a two-dimensional crystal structure of germanium and energy band representation of this semiconductor at very low temperature.

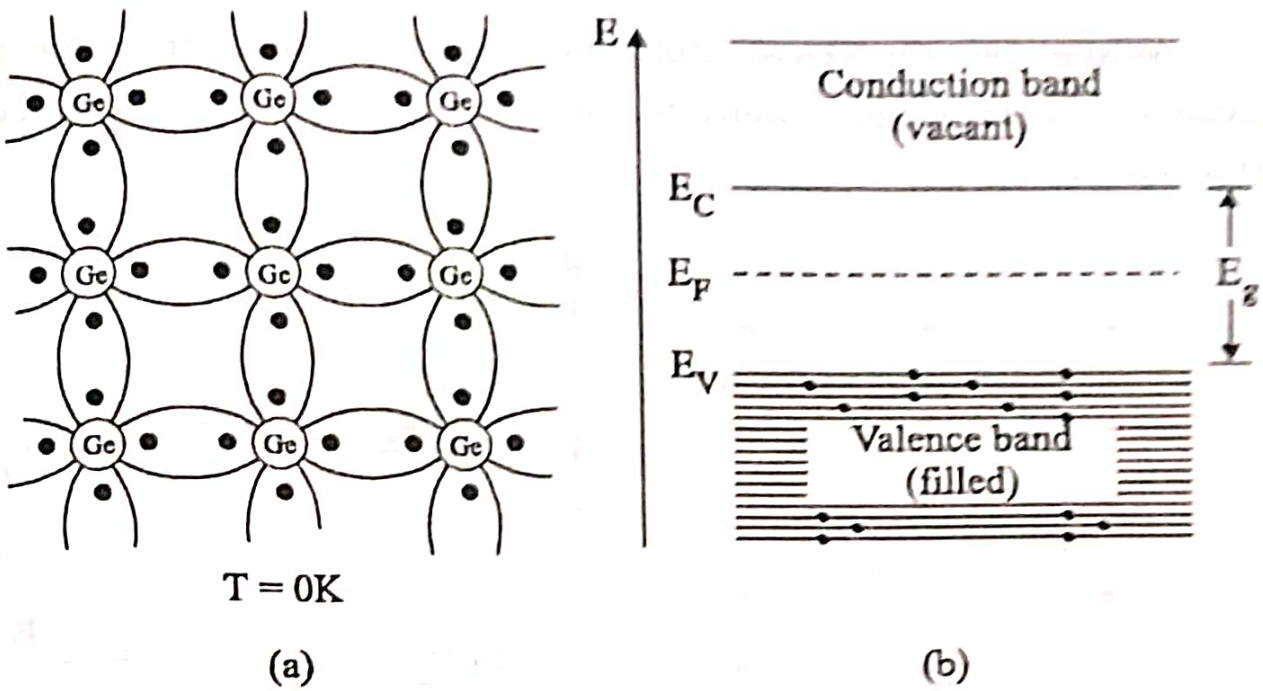


Fig. 2.2 Germanium crystal at 0K

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

(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 an 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. 2.3(a))**

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

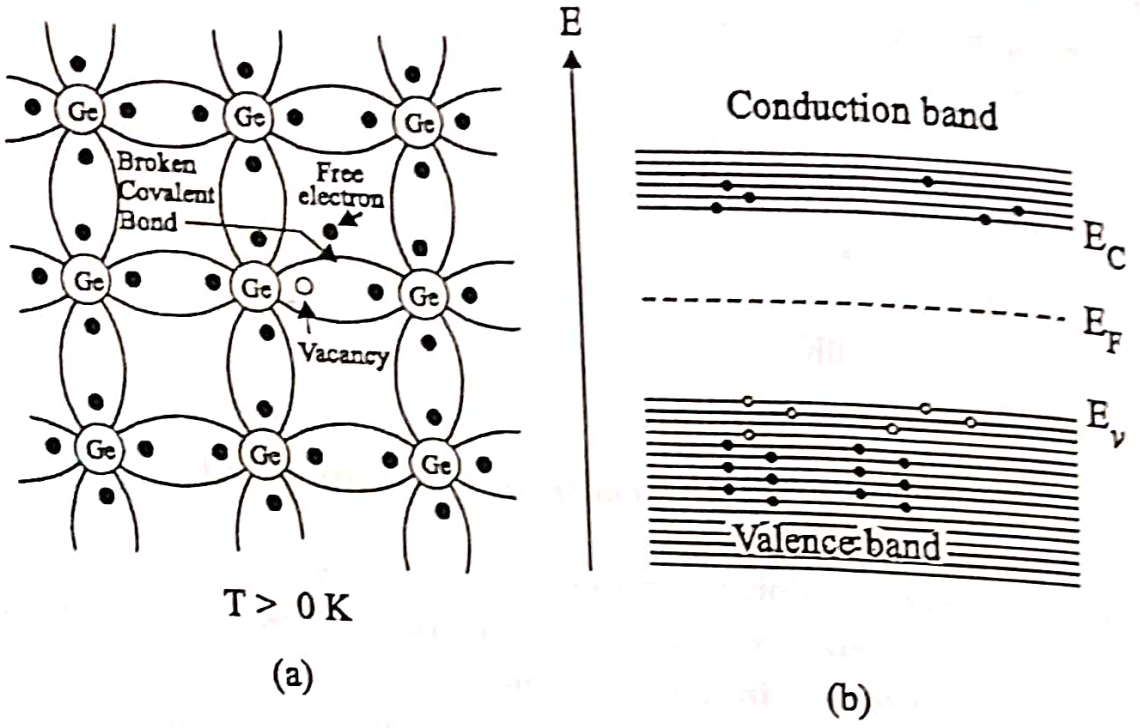


Fig. 2.3 Germanium crystal at temperature above 0K.

(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.

As shown in fig. 2.3 (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**

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 and 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.

2.3 CARRIER CONCENTRATION IN AN INTRINSIC SEMICONDUCTOR

16 MARKS

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.

16 MARK

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

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

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 $+\infty$.

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

E_C is energy corresponding to the bottom most level and $+\infty$ is energy corresponding to the upper most level in conduction band. (Fig 2.4).

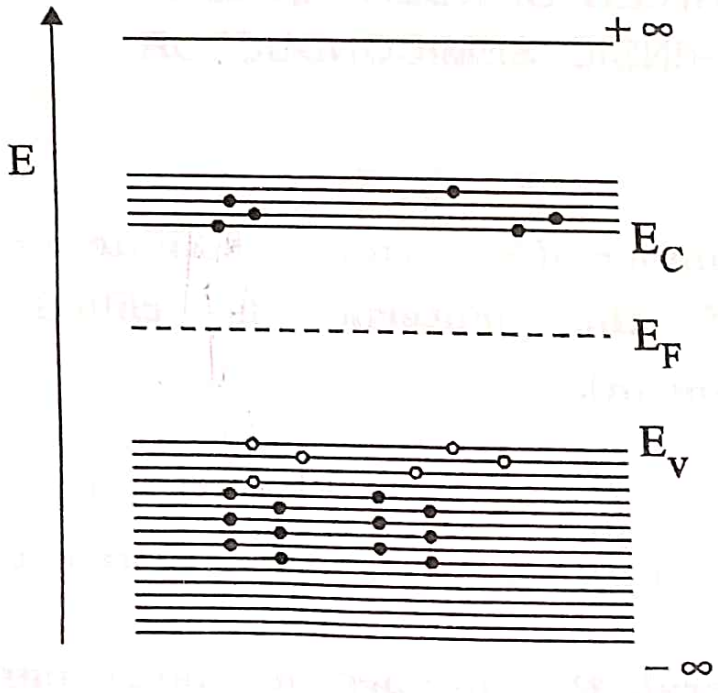


Fig. 2.4 Energy band diagram of intrinsic semiconductor

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

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

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 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 $(E - E_C)$

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

The probability of electron occupation is given by Fermi distribution function

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

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

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

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

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

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

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

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

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

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

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

Substituting above values in eqn (7), we have

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

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

Using the gamma function, it is shown that

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

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

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

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

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

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

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)

16 MARK

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 $E + dE$.

$$dp = Z(E)(1 - F(E))\, dE \quad \ldots (1)$$

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.

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

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

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

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).

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

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

Density of states in valence band,

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

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 $(E_v - E)$.

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

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

$$dp = \frac{4\pi}{h^3}(2m_h^*)^{3/2}(E_v - E)^{1/2} e^{(E - E_F)/kT}\,dE \qquad \ldots(6)$$

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

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

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

To evaluate the above 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

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

$$p = \frac{4\pi}{h^3}(2m_h^*)^{3/2} e^{(E_v - E_F)/kT} \int_0^\infty x^{1/2} e^{-x/kT} dx \quad \ldots(9)$$

[–ve sign is omitted by interchanging the limits]

Using the gamma function, it is shown that

$$\int_0^\infty x^{1/2} e^{-x/kT} dx = \frac{(kT)^{3/2} \pi^{1/2}}{2} \quad \ldots (10)$$

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

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

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

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

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

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

16 MARK

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

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

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

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

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

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

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

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

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

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

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

The eqn (4) is expression for intrinsic carrier concentration

2.4 FERMI LEVEL AND ITS VARIATION WITH TEMPERATURE

16 MARK

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

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

i.e., $n = p$ ...(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

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

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

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

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

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

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

Taking log on both sides, we get

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

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

$$\left[\because \log_e x^n = n \log_e x \quad \text{and } \log_e e^x = x\right]$$

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

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

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

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

Hence, eqn (4) becomes

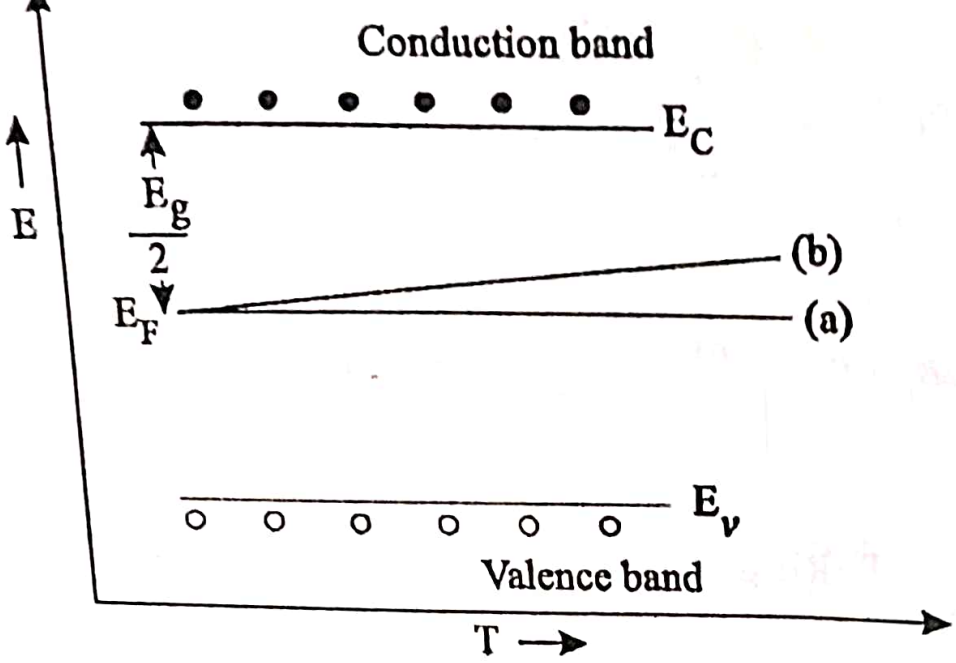


Fig. 2.5 *Positions of Fermi level in intrinsic semiconductor at various temperatures.*

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

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

$$E_F = \frac{E_v + E_C}{2} \quad \ldots (5)$$

Thus, Fermi level is located half way between the top of valence band and bottom of conduction band as shown in fig.2.5 (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.

Mobility

When an electrical field (E) is applied to a semiconductor, the free charge carriers free electrons and holes attain drift velocity v_d.

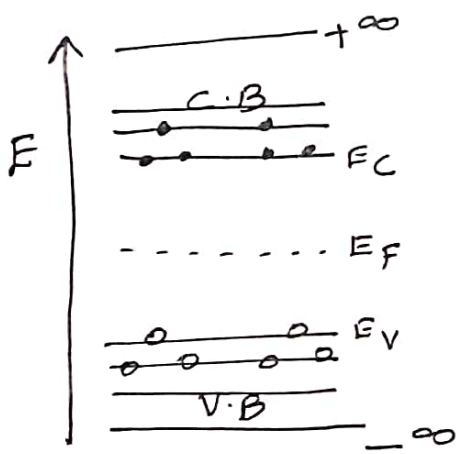
The drift velocity attained by the charge carriers is proportional to the strength of electrical field E. It is different for different semiconducting materials and for different types of charge carriers.

Intrinsic Semiconductor

(i) Density of electrons in Condeution Band

$$dn = Z(E)\, F(E)\, dE$$

$$n = \int_{E_c}^{+\infty} Z(E)\, F(E)\, dE$$



[Density of states,
$Z(E)dE = \frac{4\pi}{h^3}(2m_e^*)^{3/2} E^{1/2} dE$]

[$E = E - E_c$]

[Fermi distribution function,
$F(E) = \frac{1}{1+e^{(E-E_F)/kT}}$]

Here $1 + e^{E-E_F/kT} \simeq e^{E-E_F/kT}$

Subs. we get,

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

To evaluate above integral, let us assume that

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

When $E = E_c$
$E_c - E_c = x$
$x = 0$

When $E = +\infty$
$+\infty - E_c = x$
$x = +\infty$

Sub. above values, we have

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

Using the gamma function,

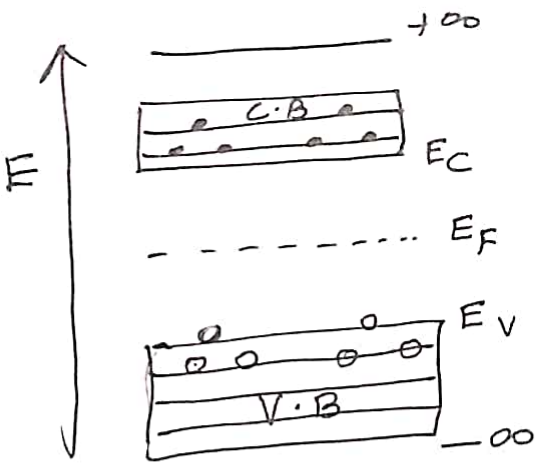
$$\int_0^\infty x^{1/2} e^{-x/kT} dx = \frac{(kT)^{3/2} \pi^{1/2}}{2}$$

We get,

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

(ii) Density of holes in valence band of intrinsic Semiconductor

W.K.T if an electron is transferred from valence band to conduction band, a hole is created in valence band.



$$\boxed{dp = Z(E)\,(1 - F(E))\,dE}$$

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

We get $1 - F(E) = e^{E - E_F/kT}$

Density of states, $Z(E)dE = \frac{4\pi}{h^3} (2m_h^*)^{3/2} E^{1/2} dE$

[Here $E = E_V - E$]

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

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

$E_V - E = x$

$E = E_V - x$

$dE = -dx$

When $E = -\infty$

$E_V - (-\infty) = x$

$E_V + \infty = x$

$x = \infty$

When $E = E_V$

$E_V - E_V = x$

$x = 0$

Subs. we get-

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

Using the gamma function:

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

we get,

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

(iii) Intrinsic carrier concentration

$$\boxed{n_i^2 = n \times p}$$

$$\left\{\text{Here } n = 2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{3/2} e^{E_F - E_C/kT}\right.$$

$$\left. p = 2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{3/2} e^{E_V - E_F/kT}\right\}$$

Subs. & rearranging, we get

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

$E_g = E_C - E_V$ is forbidden energy gap

(iv) Fermi level and its Variation with temperature

$$\boxed{n = p}$$

$$\left[\text{Here } n = 2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{3/2} e^{E_F - E_c/kT}\right.$$

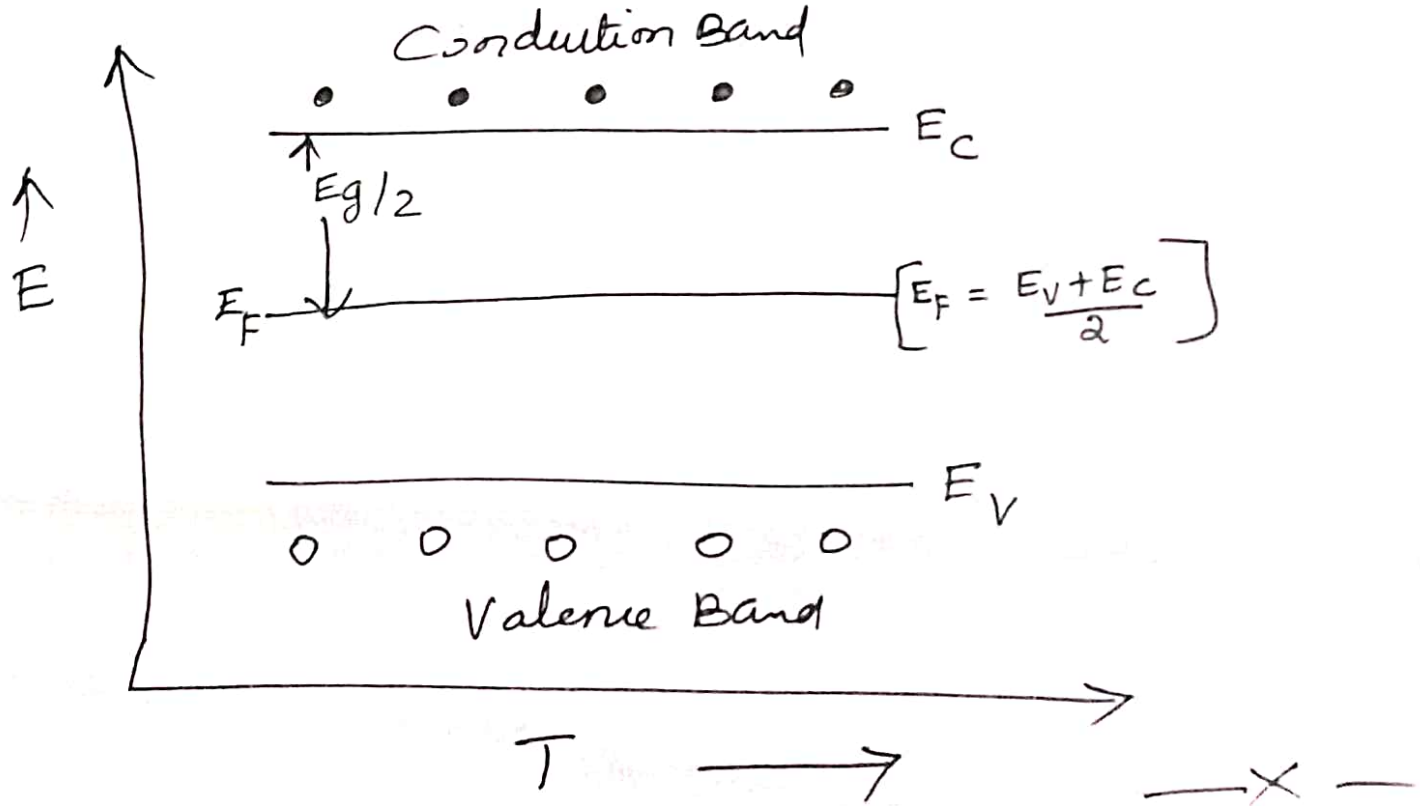
$$\left. p = 2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{3/2} e^{E_v - E_F/kT}\right]$$

Subs. & rearranging we get

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

If $m_h^* = m_e^*$ then $\log_e \frac{m_h^*}{m_h^*} = \log_e 1 = 0$

$$\therefore \quad \boxed{E_F = \frac{E_v + E_c}{2}}$$



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 conductivity measurements do not give any information about the sign of the prominent (p type or n type) charge carriers.

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 current and magnetic field. (Fig. 2.19)

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

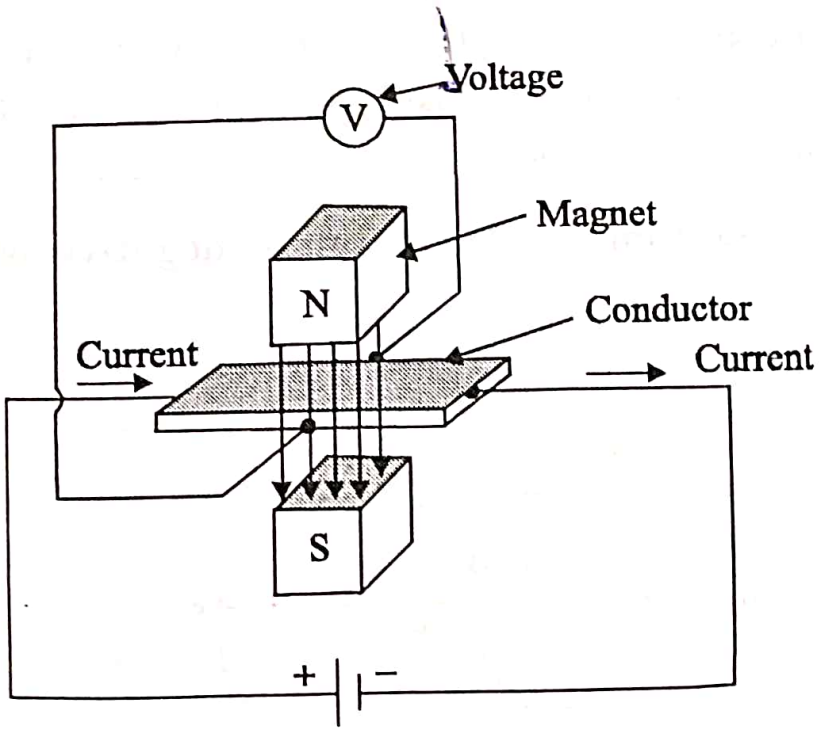


Fig. 2.19 Hall Effect

Hall effect in n - type semiconductor

Consider a *n* - type semiconducting material in the form of a rectangular slab. In this slab, 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. 2.20.

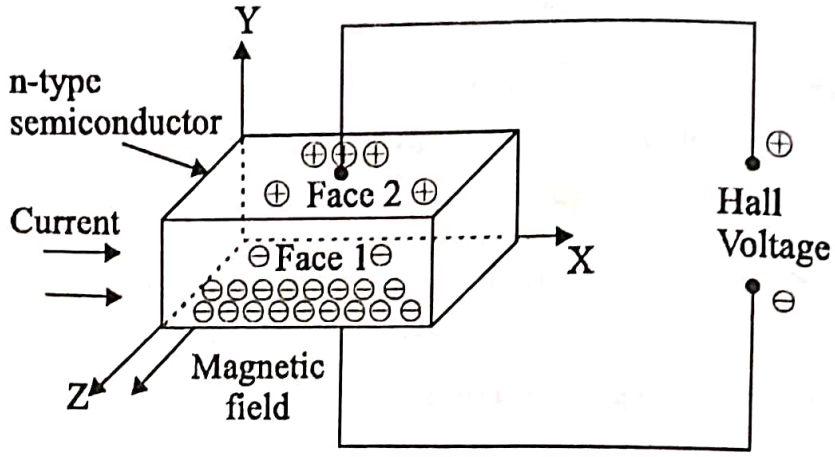


Fig. 2.20 Hall effect

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, 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 2.21).

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

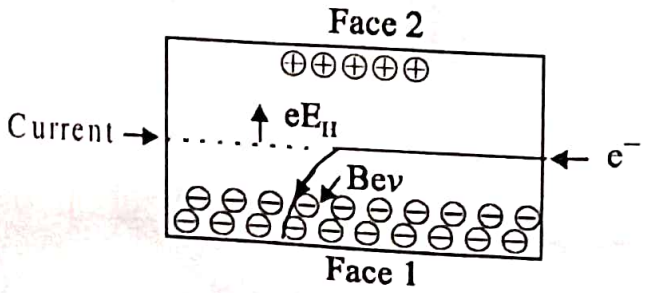


Fig. 2.21 Hall effect in n-type semiconductor

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.**

$$\therefore \quad Bev = eE_H$$

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

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

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

where n is the concentration electrons.

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

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

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

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

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

$$\boxed{R_H = \frac{E_H}{J_x B}}$$

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

Consider a rectangular slab of p - type semiconducting material. The current flow in this material is entirely due to the flow of holes (positive charge) from left to right as shown in fig. 2.22.

The current flow is along X - direction and the magnetic field is applied in the Z - direction. Due to applied magnetic field, charge carrier holes accumulate in the bottom of the slab. Thus a potential difference is developed.

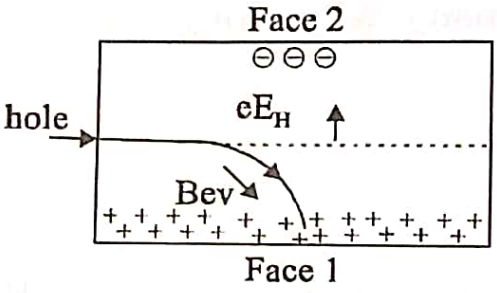


Fig. 2.22 Hall effect in p-type semiconductor

Similar to n-type semiconductor, we can write

$$E_H = R_H J_x B$$

where **Hall coefficient** (R_H) is written as

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

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. ...(8)

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

$$V_H = R_H J_x B t \quad ...(9)$$

If b is breadth of the sample, then

Cross sectional area

of the sample (A) = Breadth $(b) \times$ Thickness (t)

$$= bt$$

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

$$= \frac{I_x}{bt} \quad ...(10)$$

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

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

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

$$\text{Hall coefficient } R_H = \frac{V_H b}{I_x B} \quad ...(11)$$

Note:

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

lobility of charge carriers

We know that Hall coefficient

$$R_H = -\frac{1}{ne}$$

This expression is correct only when the charge carrier re free from any type of attractive forces in energy band and lso they are moving with a constant drift velocity v. But, this not true in the case of semiconductors.

Considering the average speed, it is shown that

$$R_H = \frac{1.18}{ne} \qquad \textbf{for electrons}$$

$$ne = \frac{1.18}{R_H} \qquad \ldots (1)$$

$$R_H = \frac{1.18}{pe} \qquad \textbf{for holes}$$

$$pe = \frac{1.18}{R_H} \qquad \ldots (2)$$

Electrical conductivity of n-type semiconductor,

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

$$\mu_e = \frac{\sigma_e}{ne} \text{ where } \mu_e \text{ is the mobility of electrons} \qquad \ldots(3)$$

Substituting eqn (1) in eqn (3), we have

$$\mu_e = \frac{\sigma_e}{-\frac{1.18}{R_H}}$$

Mobility of electron $\boxed{\mu_e = -\frac{\sigma_e R_H}{1.18}}$ $\ldots (4)$

Electrical conductivity of p - type semiconductor,

$$\sigma_h = pe\,\mu_h$$

$$\mu_h = \frac{\sigma_h}{pe} \qquad \ldots (5)$$

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

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

Mobility of the hole $\boxed{\mu_h = \frac{\sigma_h R_H}{1.18}}$

2.14 DETERMINATION OF HALL COEFFICIENT

The experimental set up to measure Hall-coefficient is shown in fig. 2.23.

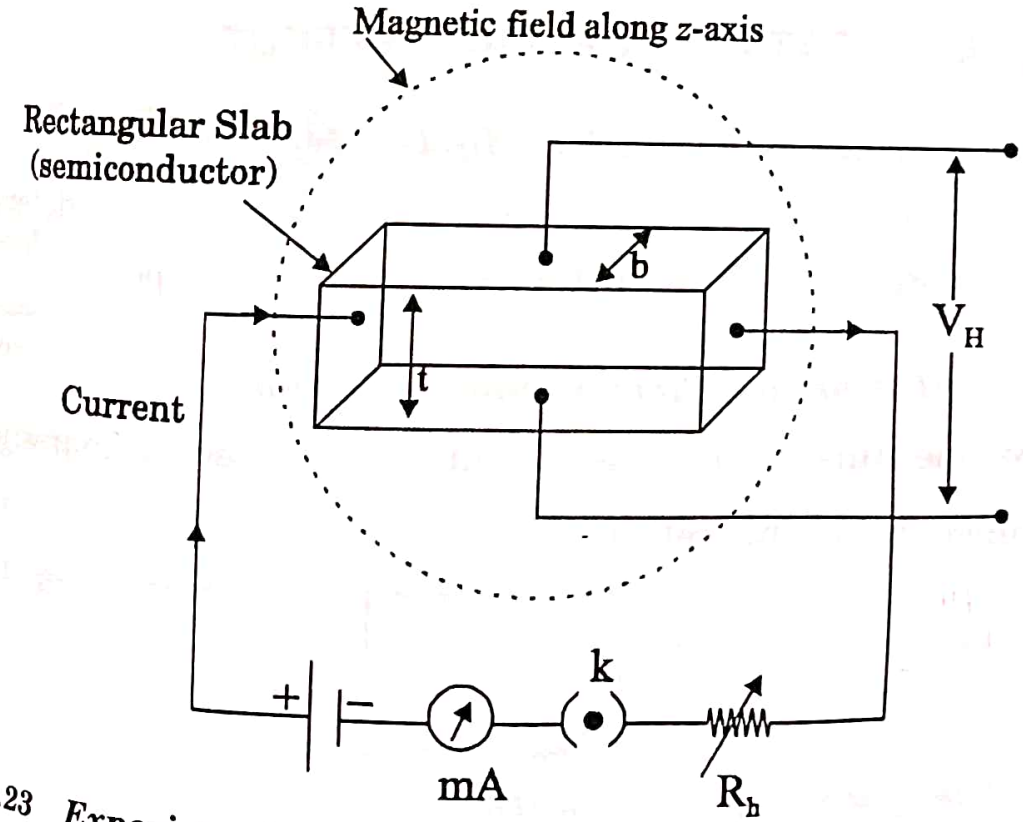


Fig. 2.23 ***Experimental arrangement to measure Hall coefficient***

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

This material is placed between north and south poles of an electromagnet. The magnetic field is applied along Z-axis.

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

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

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

2.15 APPLICATIONS OF HALL EFFECT

(i) Determination of semiconductor type

The sign of the Hall coefficient is used to determine 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

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

(iii) Determination of mobility

We know that electrical conductivity,

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

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

$$\mu_e = \sigma_e R_H$$

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

(iv) *Magnetic field meter*

The Hall voltage V_H for a given current is proportional to B. Hence, V_H measures the magnetic field B.

(v) *Hall effect multiplier*

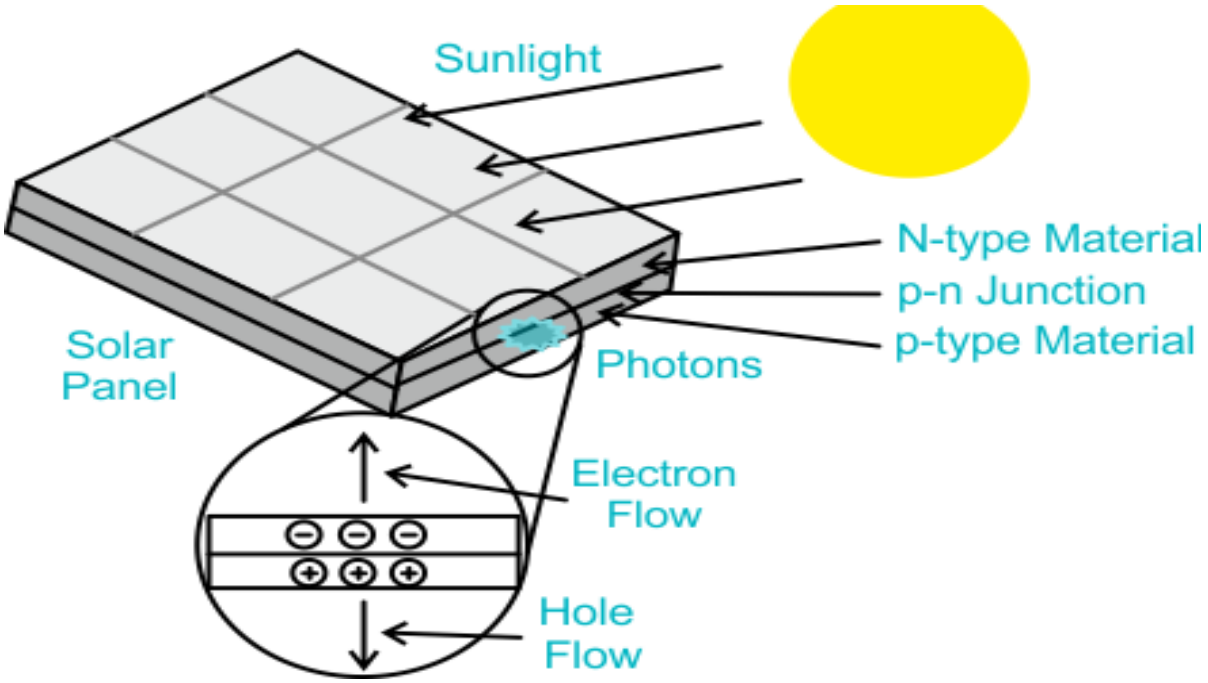
This instrument gives an output proportional to the product of two signals. Thus, if current I is made proportional to one input and magnetic field B is proportional to the second input, then Hall voltage V_H is proportional to the product of two inputs.

Principle, Construction and Working of Photovoltaic cell Advantages, Disadvantages and Applications

Introduction:

- **It is an electronic cell that converts light /photon energy into electrical energy in certain semiconducting materials.**
- **This directly converts light energy to electricity without any intermediate process.**
- **The most common uses of photovoltaic cells are solar panels and thermostats.**
- **The most common element required for the current flow in a photovoltaic cell is silicon.**
- **A photovoltaic cell is a type of PN junction diode which converts light energy into electricity.**
- **They generally work in a reverse bias condition.**
- **It is similar to a solar cell since they belong to similar working principles but have distinct differences.**

Construction and working of Photovoltaic Cell:



The photovoltaic effect occurs in solar cells. These solar cells are composed of **two** different types of **semiconductors**. One is **p-type** and another one is **n-type**. Both are joined together to create a **p-n junction**. By joining these two types of semiconductors, an **electric field** is formed in the region of the junction as **electrons** move to the **positive p-side** and **holes** move to the **negative n-side**. This field causes negatively charged particles to move in one direction and positively charged particles in the other direction.

Light is composed of photons, which are simply **small bundles (hυ)** of electromagnetic radiation or energy. These photons can be absorbed by a photovoltaic cell (i.e) the type of cell that composes solar panels.

When light of a suitable wavelength is incident on these cells, energy from the photon is transferred to an atom of the semiconducting material in the p-n junction. Specifically, the energy is transferred to the electrons in the material.

This causes the electrons to jump to a higher energy state known as the conduction band. This leaves behind a "hole" in the valence band that the electron jumped up from. This movement of the electron because of added energy creates two **charge carriers**, an **electron-hole pair**.

When unexcited, electrons hold the semiconducting material together by forming bonds with surrounding atoms, and thus they cannot move. However, in their excited state in the conduction band, these electrons are free to move through the material. Because of the electric field that exists because of the p-n junction, electrons and holes move in the opposite direction as expected. Instead of being attracted to the p-side, the freed electron tends to move to the n-side. This motion of the electron creates an electric current in the cell. Once the electron moves, there is a "hole" that is left. This hole can also move, but in the opposite direction to the p-side. It is this process which creates a current in the cell.

Advantages, Disadvantages and Applications of Photovoltaic Cell:

Advantages :

- **They generate clean energy and are sustainable for the environment**
- **Low maintenance costs.**
- **It is a renewable energy source and easily available.**
- **They have a lower risk for the loss of efficiency and can be used for a longer time period.**
- **Cancels noise pollution.**
- **They can generate electricity anywhere if there is enough sunlight in a particular area.**
- **Can resolve our world’s energy crisis.**

Disadvantages :

- **The infrastructure for photovoltaic cells is not readily available on a larger scale.**
- **Though maintenance costs are low, the installation is much more expensive.**
- **Currently photovoltaic cells cannot produce electricity at a commercial level, they operate on devices which require less electricity and power.**
- **Long-range transmission is difficult when it comes to photovoltaics.**
- **They are fragile and can be easily damaged.**

Applications :

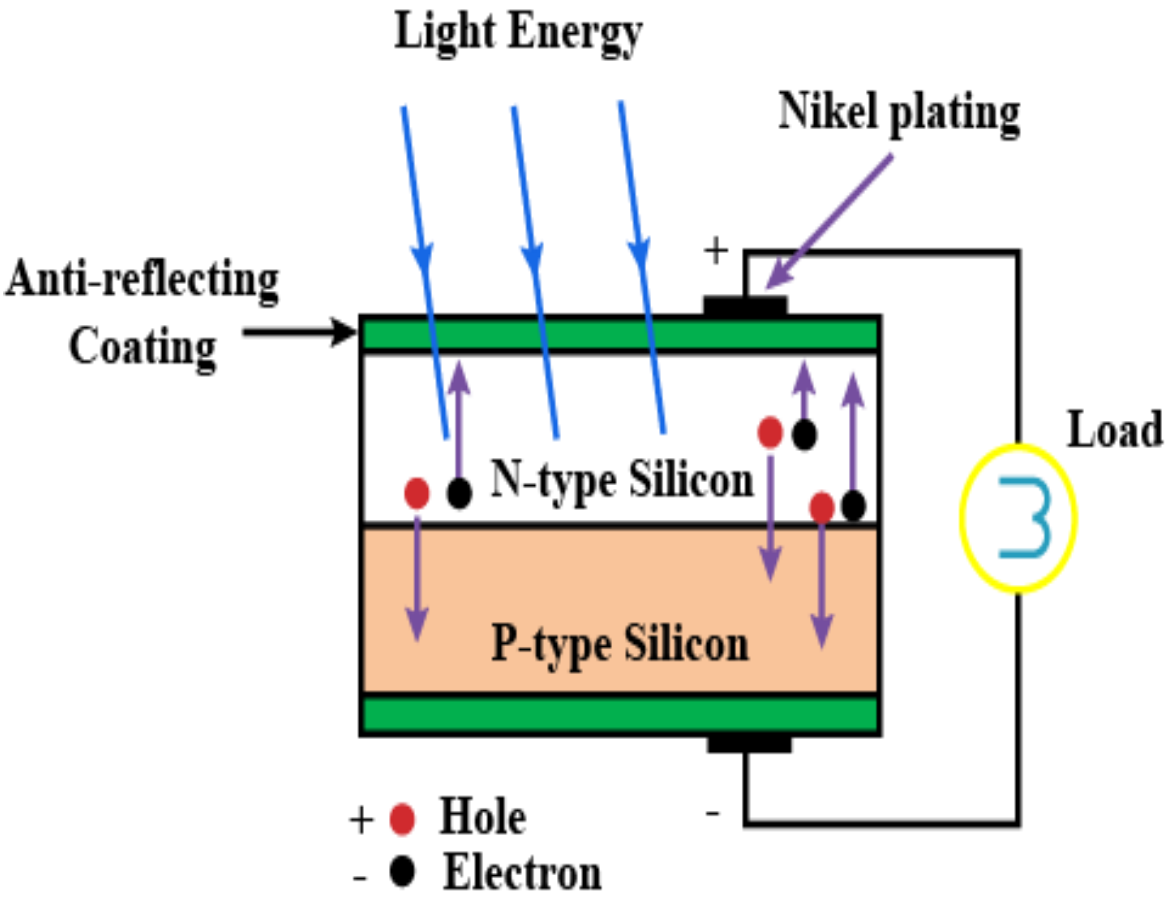
Some main applications of photovoltaic cells are as follows.

- **Can be used in making solar farms, which would generate gigawatts of electricity.**
- **In difficult topographical conditions photovoltaic cells would efficiently deliver electricity than the conventional source.**
- **Primary power source for space explorations and experiments, due to its lightweight.**
- **Navigation aids.**

Difference between Solar cell and Photovoltaic Cell:

Property	Solar Cell	Photovoltaic Cell
Definition	A device that converts sunlight directly into electricity	A device that converts light energy into electricity using the photovoltaic effect
Source of Energy	Sunlight	Any light source (not necessarily sunlight)
Applications	Generate electric power from sunlight, solar calculators, solar panels	Generate electric power from sunlight as well as artificial light, solar photovoltaic modules, building integrated photovoltaics
Examples	Silicon solar cell, Cadmium telluride solar cell, Perovskite solar cell	Crystalline silicon photovoltaic cell, Thin film photovoltaic cell, Dye-sensitized solar cell

Diagram, Construction and Working of a solar cell:



The construction of a solar cell is shown in the figure. The principle layer of this cell includes an anti-reflective cover glass. This glass guards the semi-conductor materials against the sunlight. In this cell, small grid patterns with slight metallic strips are available under the glass. So that the top layer of this cell can be formed by using the glass, metallic strips and anti-reflective coat.

The most important part of the cell is the **middle layer where solar energy can be formed through the effect of photovoltaic.** It **consists of two semiconductor layers which are made up of p-type and n-type materials.**

The base layer of this cell consists of two parts. A rear metallic electrode is situated below the p-type semiconductor and it works with the metallic grid to generate an electric current in the pinnacle layer.

A reflective layer is the last layer in this cell used to decrease the loss of light within the system. Based on the application, solar cells utilize various materials based on their application and cost.

Working:

Once the **solar energy falls** on a solar panel, then it **absorbs**. Each panel in the solar panel includes semiconductor material to **combine the properties of insulators and metal**. So, it makes to convert the light energy into electrical.

Once the energy from the sun falls on the panel then a semiconductor absorbs, the **energy of photons transfers to electrons and allows the flow of electrons through the material like an electric current**. There are different kinds of semiconductor materials used in solar cells like silicon, photovoltaics like Thin-film, organic and concentration Photovoltaics.

Zener diode

The diode which operates in the reverse breakdown region with a sharp breakdown voltage is called a Zener diode.

Zener diode is a heavily doped silicon diode used in reverse biased condition. It is specially designed to be operated in the breakdown region. A typical current-voltage (I-V) characteristic for a Zener diode is shown in Figure.

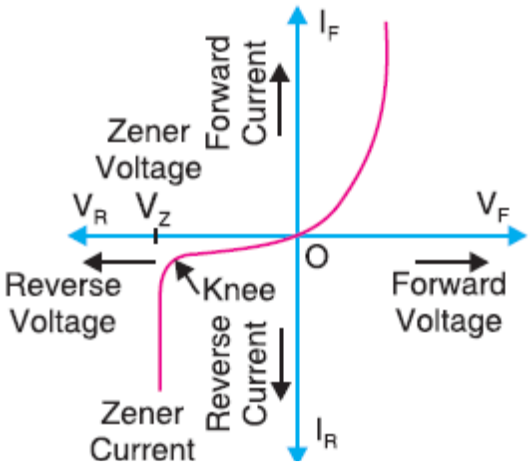


Figure: I-V characteristics of Zener-diode

Applications:

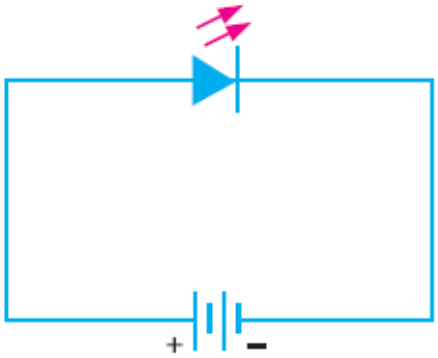
- Zener diode can be used as voltage regulator
- It can be used for calibrating voltages
- It is used to provide fixed reference voltage in a network for biasing
- It is used to protect of any gadget against damage from accidental application of excessive voltage

****

Light emitting Diode (LED)

LED is a p-n junction diode which emits visible or invisible light when it is forward biased. Since electrical energy is converted to light energy, this process is also called electroluminescence.

The circuit symbol of LED is shown in figure. The direction of arrows indicates that light is emitted from the diode.



- The colour of the light is determined by the energy band gap of the material.
- Therefore, LED's are available in a wide range of colours such as blue (SiC), green (AlGaP) and red (GaASP). Nowadays, LED which emits white light (GaInN) is also available.

Applications

- LED's are used in indicator lamps on the front panel of the scientific and laboratory equipments.
- LED can be used as seven-segment displays.
- They are used in traffic signals, emergency vehicle lighting etc.
- They are used in remote control of television, air-conditioner etc.

****

1. Due to their high resistance to corrosion, metallic glasses are ideal materials for making surgical instruments.
2. They are used as prosthetic materials for implantation in human body.

6.5 SHAPE MEMORY ALLOYS

A group of metallic alloys which shows the ability to return to their original shape or size (i.e., alloy appears to have memory) when they are subjected to heating or cooling are called shape memory alloys.

Phases of shape memory alloys

Martensite and **austenite** are two solid phases in SMA as shown in fig. 6.4

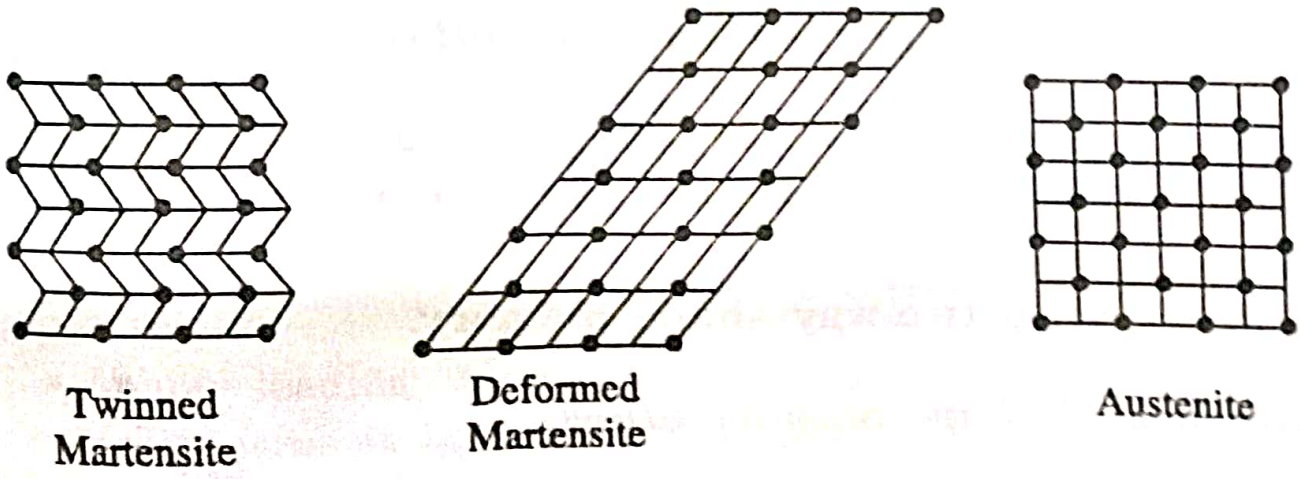


Fig. 6.4 Phases of SMA

(i) **Martensite is relatively soft.** It is easily deformable phase which exists at low temperature (monoclinic) (fig 6.5).

(ii) **Austenite** is a phase that occurs at high temperature having a crystal structure and high degree of symmetry (cubic) (fig 6.5).

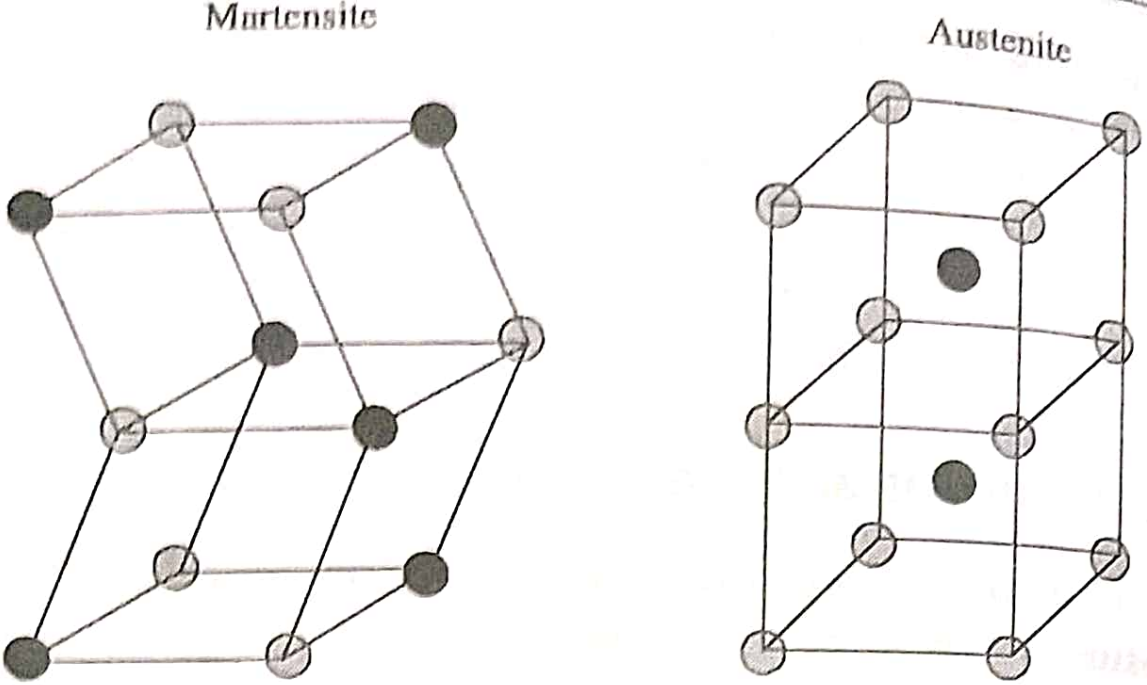


Fig. 6.5 Martensite and austenite phases

Types of Shape memory alloys

There are two types of shape memory alloys

(i) One - way shape memory alloy

(ii) Two - way shape memory alloy

A material which exhibits shape memory effect only upon heating is known as **one-way shape memory**. A material which shows a shape memory effect during both heating and cooling is called **two-way shape memory**.

Examples of shape memory alloys

Generally, shape memory alloys are intermetallic compounds having super lattice structures and metallic - ionic - covalent characteristics. Thus, they have the properties of both metals and ceramics.

- **Ni – Ti alloy (Nitinol)**
- **Cu – Al – Ni alloy**
- **Cu – Zn – Al alloy**
- **Au – Cd alloy**
- **Ni – Mn – Ga** and **Fe based alloys**

Note:

Now a days, shape memory alloys are also available in nanophase structures.

Methods of Processing

The shape memory alloys are generally prepared in vacuum or in an inert gas atmosphere due to the high reactivity of the titanium present in the compound.

The methods such as plasma arc melting, electron beam melting, vacuum induction, etc., are used for the commercial preparations of shape memory alloys.

6.6 CHARACTERISTICS OF SMAS

1. Shape memory effect

The change in shape of a material at low temperature by loading and regaining of original shape by heating it, is known as shape memory effect.

The shape memory effect occurs in alloys due to the change in their crystalline structure with the change in temperature and stress.

- While loading, twinned martensite becomes deformed martensite at low temperature.
- On heating, deformed martensite becomes austenite (shape recovery) and upon cooling it gets transformed to twinned martensite (fig. 6.6).

2. SMAs exhibit changes in electrical resistance, volume and length during the transformation with temperature.

3. The mechanism involved in SMA is reversible (austenite to martensite and vice versa.)

4. Stress and temperature have a great influence on martensite transformation.

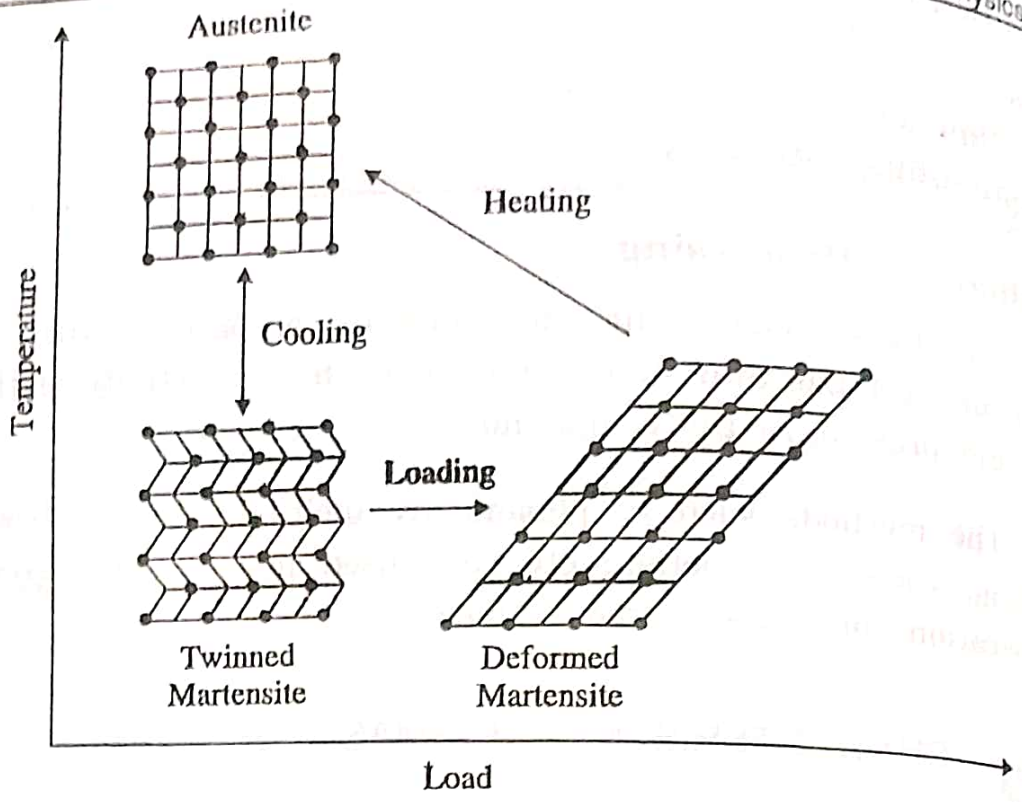


Fig. 6.6 Material crystalline arrangement during shape memory effect

5. Pseudo elasticity

Pseudo - elasticity occurs in shape memory alloys when it is completely in austenite phase (temperature is greater than A_f austenite finish temperature).

Unlike the shape memory effect, Pseudo-elasticity occurs due to stress induced phase transformation without a change in

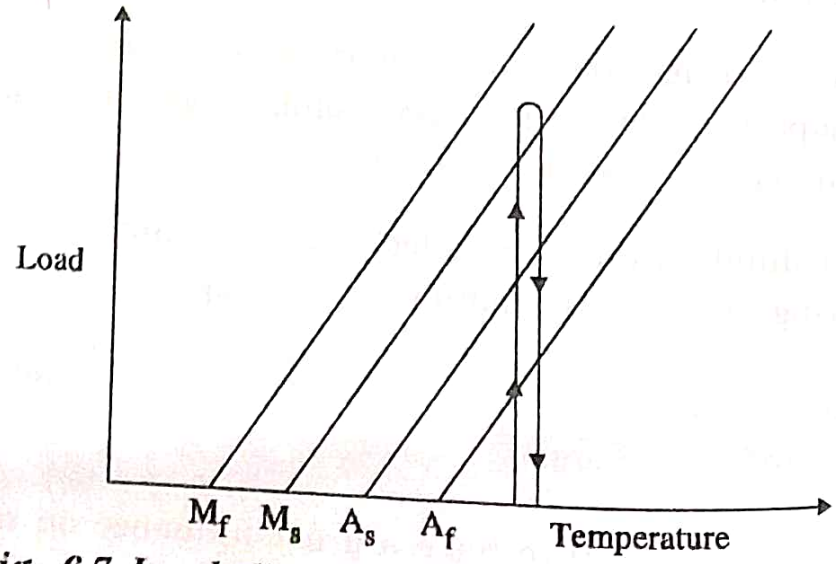


Fig. 6.7 Load diagram of pseudo elastic effect

temperature. The load on the shape memory alloy changes austenite phase into martensite (Fig. 6.7.)

As soon as the loading decreases the martensite begins to transform to austenite results in shape recovery.

This phenomenon of deformation of a SMA on application of large stress and regaining of original shape on removal of the load is known as psuedo elasticity.

This pseudo elasticity is also known as super elasticity.

6. Hysteresis

The temperature range for the martensite to austenite transformation which takes place upon heating is somewhat higher than that for the reverse transformation upon cooling.

The difference between transition temperature upon heating and cooling is called hysteresis. The hysteresis curve for SMAs is shown in fig. 6.8.

The difference of temperature is found to be 20 – 30 °C.

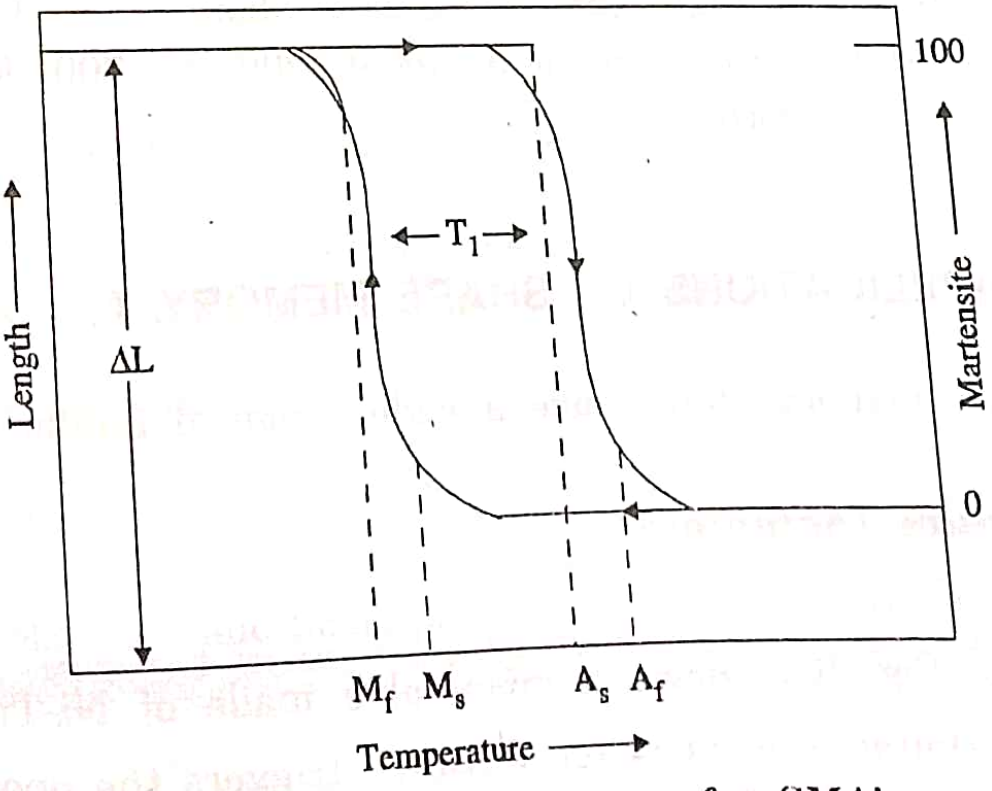


Fig. 6.8 hysteresis curve for SMA's

6.7 PROPERTIES OF Ni - Ti ALLOY

Nickel - Titanium [Ni–Ti] is a type of shape memory alloy which has high shape memory strain.

It has the following properties.

- Ni–Ti alloy has high shape memory strain [8.5%].
- The density of Ni–Ti is 6450 $kg\,m^{-3}$.
- It is more flexible.
- It has high melting point [1300°C].
- The transformation temperature varies between – 200°C and 110°C.
- It has high thermal stability.
- It has high corrosion resistance.
- The thermal conductivity ranges from 8.5 [Martensite] to 18 [Austenite] $WK^{-1}m^{-1}$
- It has very high yield strength of about 70 to 140 MPa in Martensite form and about 200 to 700 MPa in Austenite form.

6.8 APPLICATIONS OF SHAPE MEMORY ALLOYS

Shape memory alloys have a wide range of applications.

1. Microvalve (Actuators)

One of the most common applications of SMAs is microvalves. Fig. 6.9 shows a microvalve made of Ni-Ti alloy actuator. Actuator is a microsensor which triggers the operation of a device. The electrical signal initiates an action.

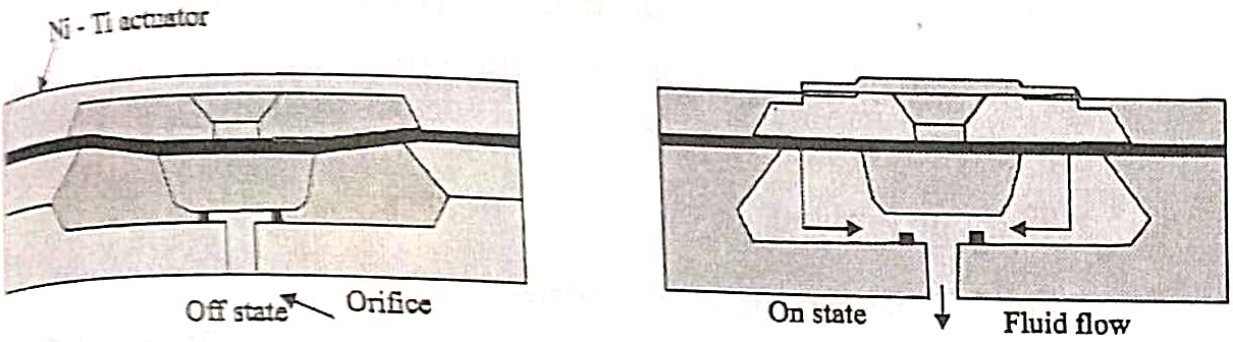


Fig. 6.9 Schematic of microvalves which open and close according to temperature

When an electrical current of 50 to 150 mA flows in Ni - Ti actuator, it contracts and lifts the poppet from the orifice and opens the valve.

2. *Toys and novelties*

Shape memory alloys are used to make toys and ornamental goods.

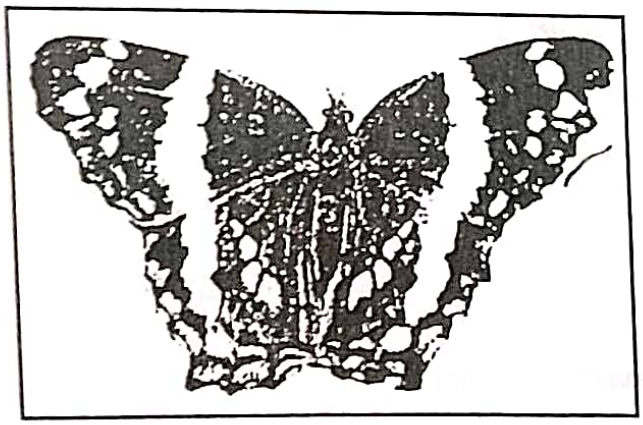


Fig. 6.10 Ni - Ti actuated butterfly

A butterfly using SMA as shown in fig. 6.10. It moves its wings in response to pulses of electricity.

3. *Medical field*

Blood clot filters

(i) Blood clot filters are SMAs, properly shaped and inserted in to veins to stop the passing blood clots.

When the SMA is in contact with the clot at a lower temperature, it expands and stops the clot and blood passes through the veins.

(ii) They are used in artificial hearts.

(iii) **Orthodontic applications**
Ni-Ti wire holds the teeth tight with a constant stress irrespective of the strain produced by the teeth movement. It resists permanent deformation even if it is bent. Ni-Ti is non-toxic and non - corrosive with body fluid.

(iv) SMAs (Ni-Ti) are used to make eye glass frames and medical tools. Sun-glasses made from superelastic Ni-Ti frames provide good comfort and durability.

4. Antenna wires

The flexibility of superelastic Ni - Ti wire makes it ideal for use as retractable antennas.

5. Thermostats

SMAs are used as thermostat to open and close the valves at required temperature.

6. Cryofit hydraulic couplings

SMAs materials are used as couplings for metal pipes.

7. Springs, shock absorbers and valves

Due to the excellent elastic property of the SMAs, springs can be made which have varied industrial applications. Some of them are listed here.

- Engine micro valves
- Medical stents (Stents are internal inplant supports provided for body organs)
- Firesafety valves and

- Aerospace latching mechanisms

8. ***Stepping motors***

Digital SMA stepping motors are used for robotic control.

9. **Titanium-aluminium shape memory alloys** offer excellent strength with less weight and dominate in the aircraft industry. They are high temperature SMAs, for possible use in aircraft engines and other high temperature environments.

6.9 ADVANTAGES OF SHAPE MEMORY ALLOYS

- They are simple, compact and high safe.
- They have good bio - compatibility.
- They have diverse applications and offer clean, silent and spark-free working condition.
- They have good mechanical properties and strong corrosion-resistance.

6.10 DISADVANTAGES OF SHAPE MEMORY ALLOYS

- They have poor fatigue properties.
- They are expensive.
- They have low energy efficiency.