UNIT I CONDENSED MATTER PHYSICS

1.1 INTRODUCTION

Atom consists of three basic particles: protons, electrons, and neutrons. The nucleus (center) of the atom contains the protons (positively charged) and the neutrons (no charge). The outermost regions of the atom are called electron shells and contain the electrons (negatively charged). Atoms have different properties based on the arrangement and number of their basic particles.

- **Atom**: The smallest possible amount of matter which still retains its identity as a chemical element, consisting of a nucleus surrounded by electrons.
- **Proton**: Positively charged subatomic particle forming part of the nucleus of an atom and determining the atomic number of an element. It weighs 1 amu.
- **Neutron**: A subatomic particle forming part of the nucleus of an atom. It has no charge. It is equal in mass to a proton or it weighs 1 amu.
- **Electrons**: Electrons have a mass of approximately 0 amu, orbit the nucleus, and have a charge of -1.

1.1.1 THREE STATES OF MATTER:

A matter composed of large number of atoms or molecules or ions. Matter can exist in one of three main states: solid, liquid, or gas.

- **Solid matter** is composed of tightly packed particles. A solid will retain its shape; the particles are not free to move around.
- **Liquid matter** is made of more loosely packed particles. It will take the shape of its container. Particles can move about within a liquid, but they are packed densely enough that volume is maintained.
- **Gaseous matter** is composed of particles packed so loosely that it has neither a defined shape nor a defined volume. A gas can be compressed.

4. SOLIDS

A solid’s particles are packed closely together. The forces between the particles are strong enough that the particles cannot move freely; they can only vibrate. As a result, a solid has a stable, definite shape and a definite volume. Solids can only change shape under force, as when broken or cut.

Example: All metals and non-metals

1.2 TYPES OF SOLIDS

Based on the internal atomic structure, the solids can be classified into two categories namely

1) Crystalline solid
   i) Single crystal
   ii) Poly crystal
2) Non-crystalline (or) Amorphous solids.

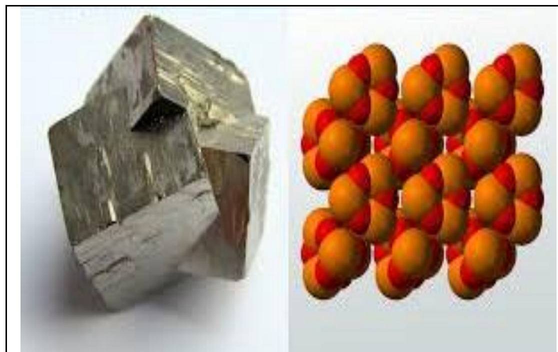


Fig 1. Solids

1.3.1 CRYSTALLINE SOLIDS

The material in which the atoms or molecule are arranged regular and orderly fashions. Since the crystalline solids have directional properties, they are called as **anisotropic substances.** A crystalline solid is again classified into two categories.

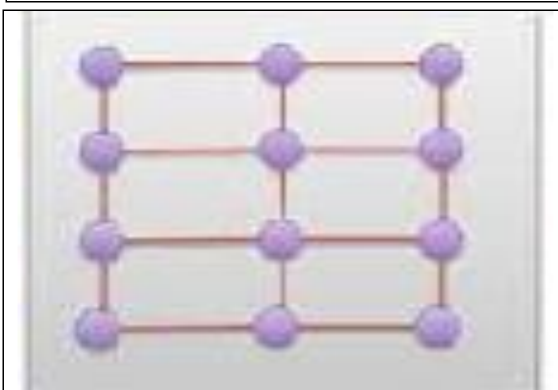


Fig 2. Crystalline Solids

1) **Single crystals:** The entire solid consists of only one crystal.
2) **Poly crystal:** It has an aggregate of many small crystals that are separated by defined boundaries.

Examples: silver, gold, platinum, diamond etc.

1.3.2 AMORPHOUS SOLIDS (OR) NON-CRYSTALLINE SOLIDS

The materials in which the atoms in solid are arranged in an irregular pattern are known as **Non-crystalline solids.**

Since the arrangements of atoms are random, it does not have regular structure or directional property. These types of substance are called **isotropic substances.**

Examples: Glass, Plastic and Rubber.

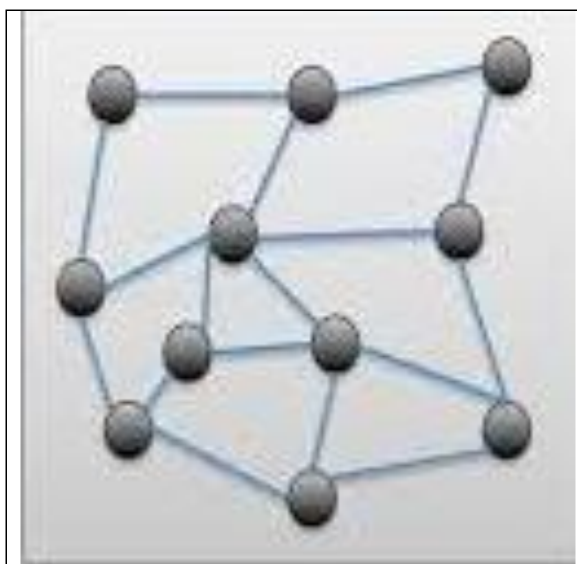


Fig 3. Amorphous Solids

Crystallography: The branch of physics which deals with internal structure of crystals and the physical properties like, thermal, electrical, magnetic properties of crystalline solids by using X-ray, electron beams, neutron beams etc., constitute the science of **crystallography.**

DIFFERENCES BETWEEN CRYSTALLINE AND NON-CRYSTALLINE MATERIAL

S.No	Crystalline material	Non-crystalline material
1	They have regular arrangement of atoms (or) molecules.	They do not have regular arrangement of atoms (or) molecules.
2	They have directional property (anisotropic).	They do not have directional property (isotropic).
3	They are more stable.	They are less stable.
4	They have sharp melting point.	They do not have sharp melting point.
5	Examples: silver, gold, diamond, etc.	Examples: glass, plastics and rubber

1.4 FUNDAMENTALS TERMS OF CRYSTALLOGRAPHY

1.4.1 Lattice:

A lattice is defined as a regular periodic array of point in space. Each point in a lattice has identical surrounding everywhere. Lattice is basically imaginary points on space with a periodic manner.

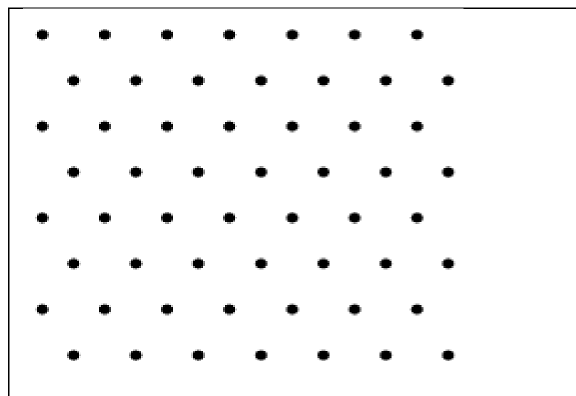


Fig 4. Lattice and Lattice Point

1.4.2 Lattice point:

Every point within the primitive unit cell is unique, but within the macroscopic crystal each point is repeated many times. Choose one point within the primitive unit cell and call it a lattice point. Lattice points are the points representing the locations of atoms in the crystal.

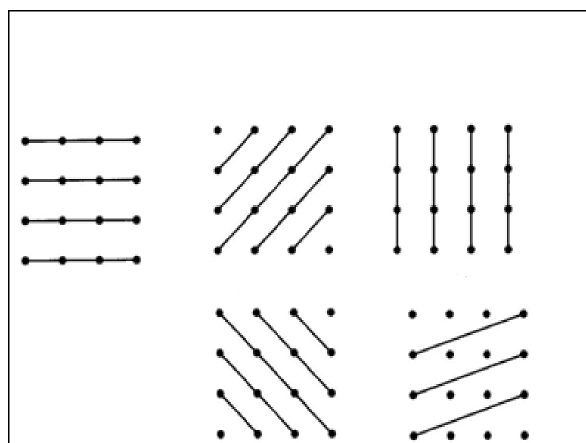


Fig 5. Lattice lines and Lattice plane

1.4.3 Lattice lines:

We can join all the lattice points through a line. The line drawn over lattice point is known as lattice point or the line joining of the lattice points are called a lattice line.

1.4.4 Lattice planes:

A set of parallel and equally spaced planes in a space lattice, which are formed with respect to the lattice point are called lattice planes.

1.4.5 Space lattice or crystal lattice:

Crystal lattice or space lattice is defined as an array of points in three dimensions and have identical surroundings to that of every other point. A space lattice represents the geometrical pattern of crystal in which the surroundings of each lattice point is the same.

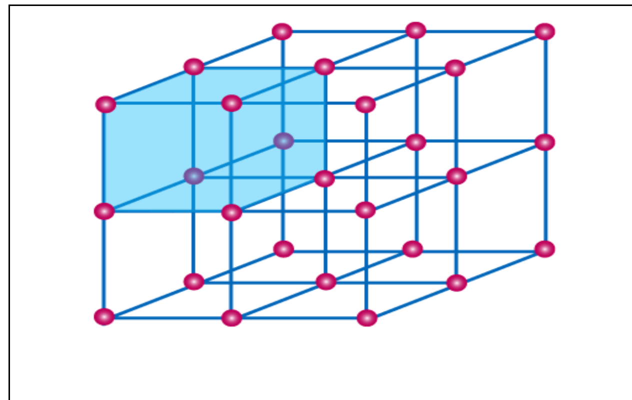


Fig 6. Space Lattice and Unit cell

1.4.6 Unit cell:

A unit cell is the smallest portion of a crystal lattice that shows the three-dimensional pattern of the entire crystal. A crystal can be thought of as the same unit cell repeated over and over in three dimensions.

1.4.7 Basis or motif:

A lattice point is known as a motif or basis. We can obtain a crystal structure by combining the lattice with the motif (i.e., crystal structure = lattice + motif). Figure shows a periodic pattern consisting of a two-dimensional (2-D) net and a motif. The motif is arranged symmetrically and is repeated at each point of the 2-D net to create the periodic pattern, and thus the lattice structure is also symmetric.

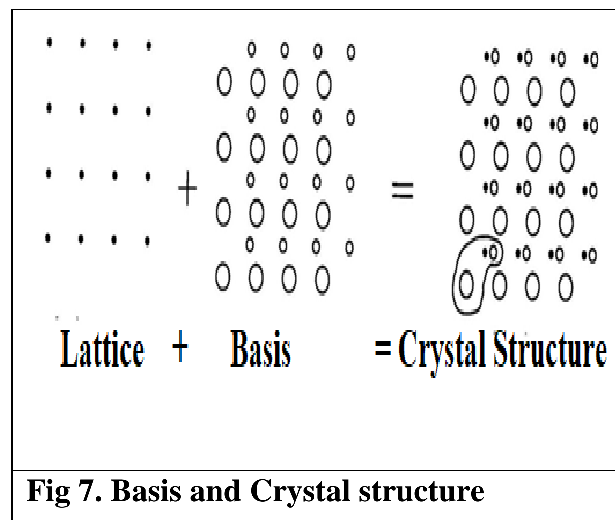


Fig 7. Basis and Crystal structure

The basis representing each lattice point as shown in fig (7), in which two atoms represented by circle with different radii, are associated with one lattice point. Generally, the number of atoms in the basis is one for many metals. But Nacl, KCl basis will have two atoms and CaF_2 basis has three atoms and so on.

1.4.8 Crystal structure:

The space lattice (or) lattice is combined with a basis to generate a crystal structure as shown in fig (7).

1.4.9 Lattice parameters of a Unit cell:

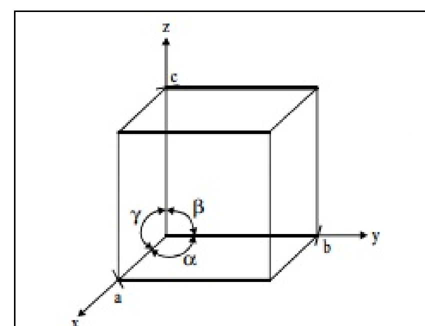


Fig 8. Lattice Parameters

The lines drawn parallel to the lines of interaction of any three faces of the unit cell which do not lie in the same plane are called crystallographic axis as shown in fig (4).

The angles between the three crystallographic axes are known as interfacial angles or interaxial angles.

The angle between the axes y and z = α

The angle between the axes z and x = β

The angle between the axes x and y = γ

The intercepts a, b, and c are known as it's primitive or characteristic intercepts on the axes or axial lengths.

i.e. a is an axial length of the crystal system along x axis

b is an axial length of the crystal system along y axis

c is an axial length of the crystal system along z axis

1.5 THE CRYSTAL SYSTEMS

Crystals are classified into general categories based on their shapes. A crystal is defined by its faces, which intersect with one another at specific angles, which are characteristic of the given substance. The seven **crystal systems** are shown below, along with an example of each. The edge lengths of a crystal are represented by the letters a, b, and c. The angles at which the faces intersect are represented by the Greek letters α, β, and γ. Each of the seven crystal systems differs in terms of the angles between the faces and in the number of edges of equal length on each face.

They are

1. Triclinic
2. Monoclinic
3. Orthorhombic
4. Trigonal
5. Hexagonal
6. Tetragonal and
7. Cubic

We will discuss about all seven types of crystals in detailed manner.

Triclinic System:

In triclinic crystal system, all the axial lengths are differ from another. The interfacial angles are differ from one another and also angle between axis are not perpendicular each other.

i.e. $a \neq b \neq c$

$\alpha \neq \beta \neq \gamma \neq 90^o$

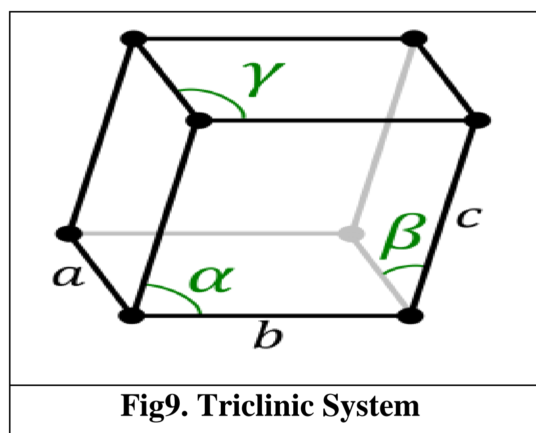


Fig9. Triclinic System

Some standard Triclinic Systems include Labradorite, Amazonite, Kyanite, Rhodonite, Aventurine Feldspar, and Turquoise.

Monoclinic System:

In monoclinic crystal system, all the axial lengths are different in length. The interfacial angles α and β are perpendicular to each other but γ is not perpendicular to both α and β.

i.e. $a \neq b \neq c$

$\alpha = \beta = 90^o, \gamma \neq 90^o$

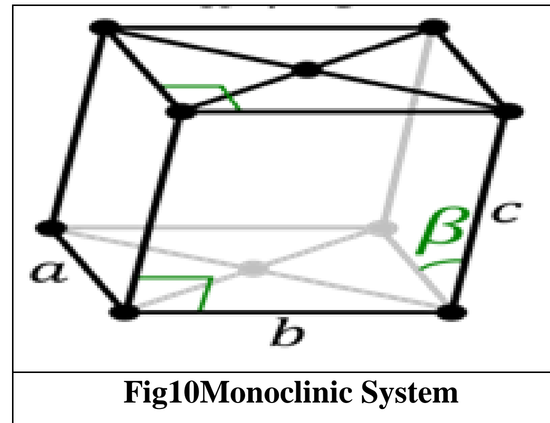


Fig10Monoclinic System

Some examples include Diopside, Petalite, Kunzite, Gypsum, Hiddenite, Howlite, Vivianite and more.

Orthorhombic System:

In orthorhombic crystal system, all the axial lengths are differ from another and angle between axis are perpendicular each other.

i.e. $a \neq b \neq c$

$\alpha = \beta = \gamma = 90^o$

Some common orthorhombic crystals include Topaz, Tanzanite, Iolite, Zoisite, Danburite and more.

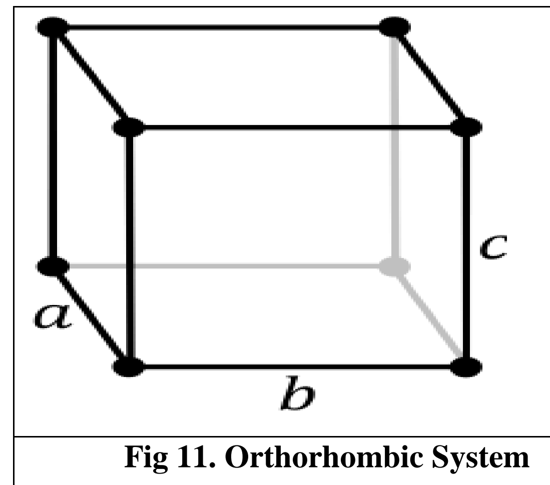


Fig 11. Orthorhombic System

Trigonal System:

In trigonal or rhombohedral system, all the axial lengths are equal and all the interfacial angles are equal. But the angle between the axis are not perpendicular to each other.

i.e. $a = b = c$

$\alpha = \beta = \gamma \neq 90^o$

Some typical examples include Ruby, Quartz,Calcite

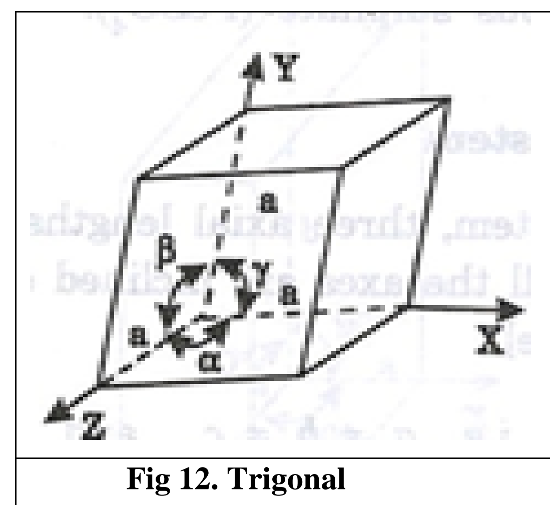


Fig 12. Trigonal

Hexagonal System:

In hexagonal system, the axial length along x and y directions are equal (a=b), but the axial length c is greater than both a and b.

The interfacial angle angles α and β are perpendicular to each other. But the angle $\gamma = 120^o$

i.e.$a = b \neq c$

$\alpha = \beta = 90^o, \gamma = 120^o$

Example: Beryl, Cancrinite, Apatite, Sugilite, etc.

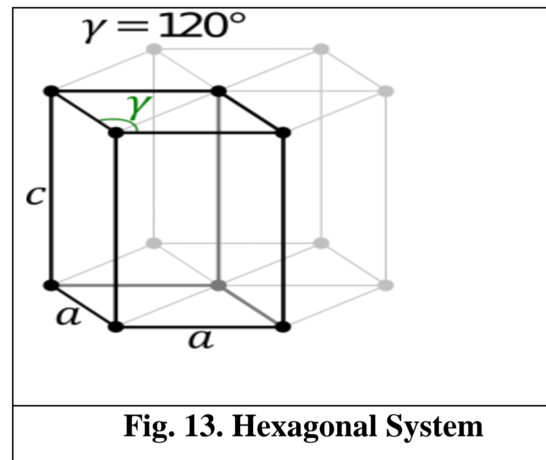


Fig. 13. Hexagonal System

Tetragonal System:

In tetragonal system, the axial length along x and y directions are equal (a=b), but the axial length c is differing from both a and b.

All the interfacial angles are perpendicular to each other.

i.e. $a = b \neq c$

$\alpha = \beta = \gamma = 90^o$

Based on the rectangular inner structure the shapes of crystal in tetragonal include double and eight-sided pyramids, four-sided prism, trapezohedrons, and pyrite.

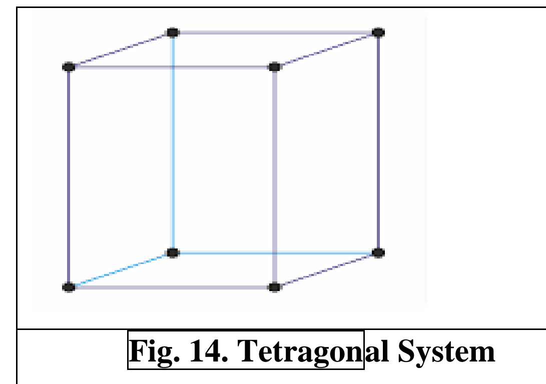


Fig. 14. Tetragonal System

Cubic System:

In cubic system, all the axial lengths are same and interfacial angles are perpendicular to each other.

i.e. a=b=c

$\alpha = \beta = \gamma = 90^o$

Example: Silver, Garnet, Gold, and Diamond.

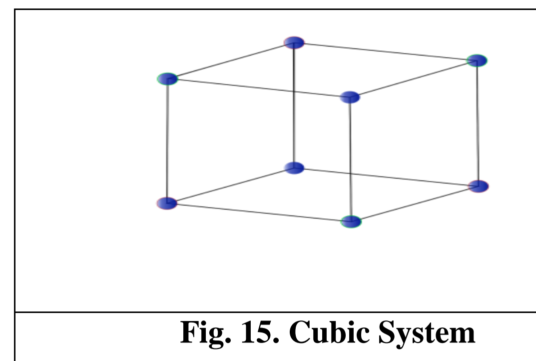


Fig. 15. Cubic System

S.No.	Crystal Systems	Intercepts (a, b, c)	Interfacial angles (α, β, γ)
1.	Triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma \neq 90^o$
2.	Monoclinic	$a \neq b \neq c$	$\alpha = \beta = 90^o, \gamma \neq 90^o$
3.	Orthorhombic	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90^o$
4.	Rhombohedral(Trigonal)	$a = b = c$	$\alpha = \beta = \gamma \neq 90^o$
5.	Hexagoanal	$a = b \neq c$	$\alpha = \beta = 90^o, \gamma = 120^o$
6.	Tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90^o$
7.	Cubic	$a = b = c$	$\alpha = \beta = \gamma = 90^o$

Table shows the differences between axial lengths and interfacial angle for all seven crystal systems.

1.6 PRIMITIVE CELL AND NON-PRIMITIVE CELL:

1.6.1 Primitive cell:

A primitive cell is the simplest type of unit cell which contains only one lattice point per unit cell.

Eg: simple cubic (SC)

1.6.2 Non-Primitive Cell

If there are more than one lattice points in a unit cell, it is called a Non-Primitive cell.
Eg: BCC and FCC

1.7 BRAVAI'S LATTICE

The Bravai's lattice is the basic building block from which all crystals can be constructed. The concept originated as a topological problem of finding the number of different ways to arrange points in space where each point would have an identical "atmosphere". That is each point would be surrounded by an identical set of points as any other point, so that all points would be indistinguishable from each other.

French Mathematician Auguste Bravais discovered that **there were 14 different collections of the groups of points, which are known as Bravai's lattices**.

In Bravai's lattice, the four types of unit cells are primitive, body centered, face centered and base centered unit cell.

Primitive or simple unit cell: It contains only corner atoms. It is denoted by the symbol **P.**

S.No.	Crystal Systems	Intercepts (a, b, c)	Interfacial angles (α, β, γ)	Bravais Lattices	No. of lattices
1.	Cubic	$a = b = c$	$\alpha = \beta = \gamma = 90^o$	P, I, F	3
2.	Tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90^o$	P, I	2
3.	Orthorhombic	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90^o$	P, I, F, C	4
4.	Monoclinic	$a \neq b \neq c$	$\alpha = \beta = 90^o, \gamma \neq 90^o$	P, C	2
5.	Triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma \neq 90^o$	P	1
6.	Rhombohedral (Trigonal)	$a = b = c$	$\alpha = \beta = \gamma \neq 90^o$	P	1
7.	Hexagoanal	$a = b \neq c$	$\alpha = \beta = 90^o, \gamma \neq 120^o$	P	1
Total					**14**

Body centered unit cell: It contains corner atoms and one atom at center of the body. It is denoted by the symbol **I.**

Face centered unit cell: It contains corner atoms and 6 atoms at each faces of the unit cell. It is denoted by the symbol **F.**

Base centered unit cell: It contains corner atoms and some atoms at base of the unit cell. It is denoted by the symbol **C.**

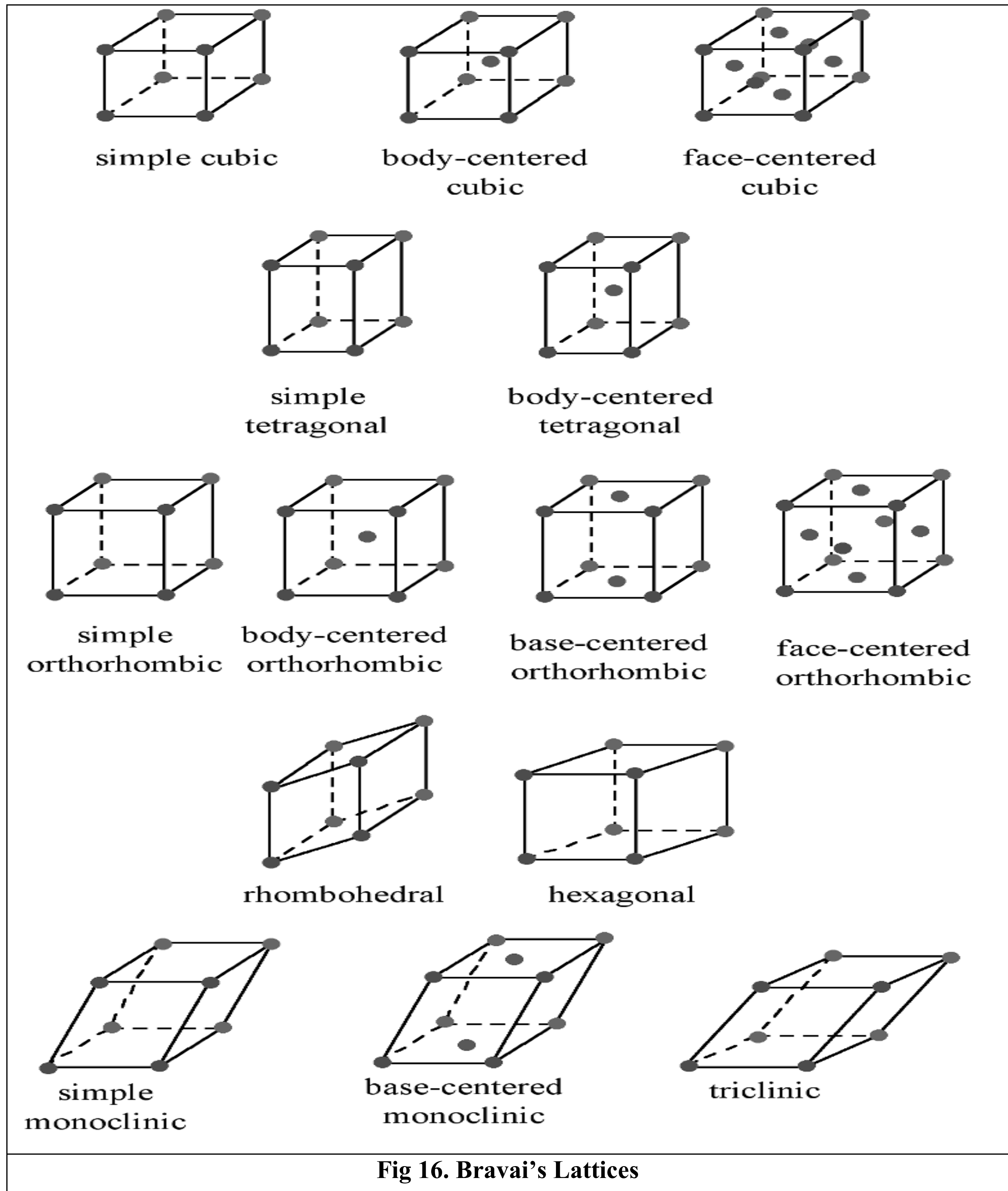


Fig 16. Bravai's Lattices

1.8 CRYSTAL PARAMETERS

1. 8.1 Number of atoms per unit cell:

The total number of atoms possessed or shared by a unit cell is known as number of atoms per unit cell.

No. of atom per unit cell = $\frac{1}{\text{Number of unit cells shared by an atom}}$ **x** No. of particular atom

1.8.2 Atomic radius or Ionic radius

Half of the distance between any two nearest neighbouring atoms is known as Atomic radius. Here those two nearest neighbouring atoms are touch with each other. In crystal physics, the atomic radius expressed in terms of lattice constant “a”.

1.8.3Coordination number

The co-ordination is the numberof nearest neighboring atoms to a particular atom.

1.8.4 Atomic factor or atomic packing density

It is defined as the ratio between the total volumes occupied by atoms to the total volume of the unit cell

$$\text{Atomic packing factor} = \frac{\text{Total volumes occupied by atoms}}{\text{Volume of the unit cell}}$$

$$\text{Atomic packing factor} = \frac{\text{Number of atoms present in unit cell } \times \text{Volume of a atom}}{\text{Volume of the unit cell}}$$

It is very useful to find void space in a unit cell

1.9 CUBIC CRYSTAL SYSTEMS

Now we discuss about simple cubic structure, body centered cubic structure, face centered cubic structure and Hexagonal closely packed structure.

1.9.1 SIMPLE CUBIC STRUCTURE(SC)

- It is a very simplest cubic cell. It contains only corner atoms.
- A simple cubic unit cell consists of 8 corner atoms at 8 corner of the unit cell
- Each and every corner atoms are sheared by 8 adjacent unit cells.
- The corner atoms are touch to each other along the edge of the cube.

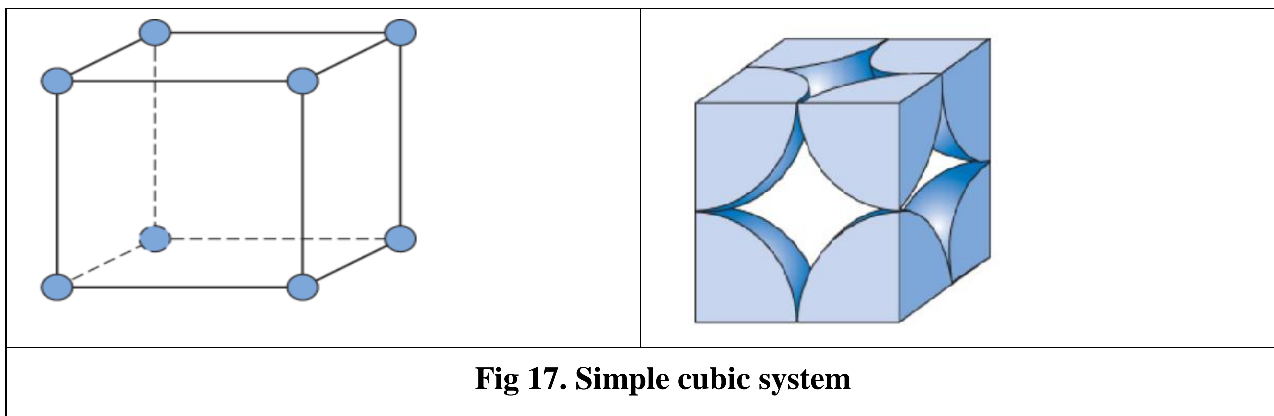


Fig 17. Simple cubic system

Number of atoms per unit cell:

A simple cubic system contains only corner atoms. So no. of atom per unit cell depends on only corner atoms.

No. of corner atom per unit cell, $N_c = \frac{1}{\text{Number of unit cells shared by an atom}}$ **x** No. of particular atom

$N_c = \frac{1}{8} \times 8 = 1\text{atom}$

Hence number of atom per unit cell for SC is 1.

Coordination number

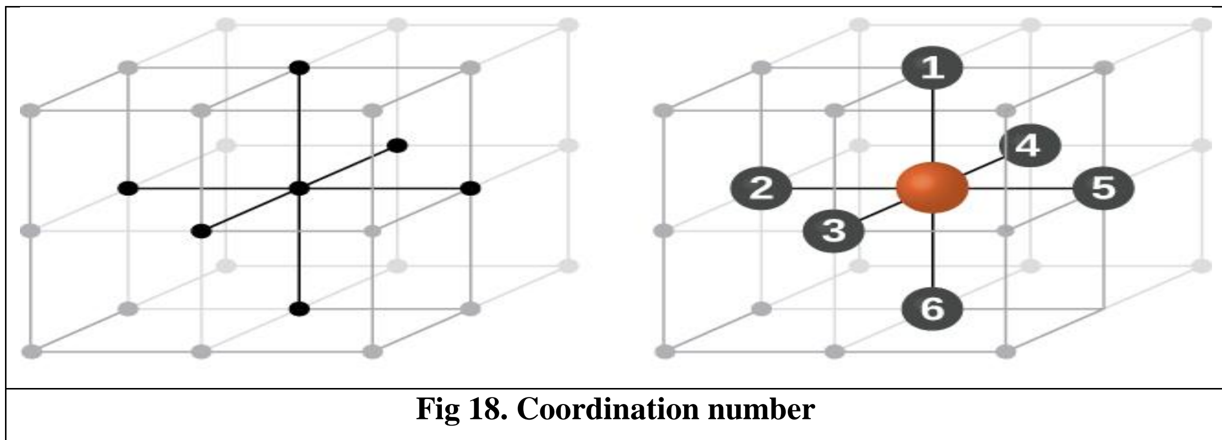


Fig 18. Coordination number

The co-ordination is the number of nearest neighboring atoms to a particular atom. In a simple cubic lattice, the co-ordination number is 6. Because,a particular lattice point co-ordinates with 4 lattice points in a plane, 1 above the plane and 1 below the plane i.e. co-ordinates total 6 lattice points.

Atomic radius or Ionic radius

In simple cubic crystal structure, the corner atoms are contacted along edge of the cube. So we can find out atomic radius directly.

In figure, the nearest neighbour distance is the lattice constant a=2r.

$\therefore \text{atomic radius } \ r = \frac{a}{2}$

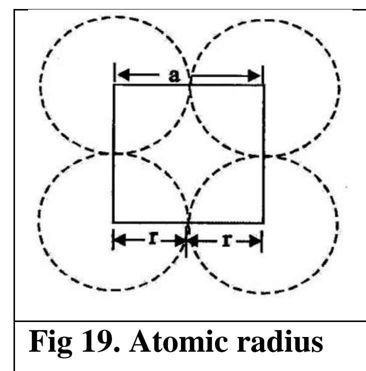


Fig 19. Atomic radius

Atomic packing factor or atomic packing density

It is defined as the ratio between the total volumes occupied by atoms to the total volume of the unit cell

$$\text{Atomic packing factor} = \frac{\text{Total volumes occupied by atoms}}{\text{Volume of the unit cell}}$$

$$\text{Atomic packing factor} = \frac{\text{Number of atoms present in unit cell } \times \text{Volume of a atom}}{\text{Volume of the unit cell}}$$

$$APF = \frac{1 \times (\frac{4}{3})\pi r^3}{a^3}$$

We know, $r = \frac{a}{2}$, therefore,

$$\text{Packing factor} = \frac{(\frac{4}{3})\pi a^3}{8 \times a^3} = \frac{\pi}{6} = 0.52 = 52\%$$

Thus, 52% volume of unit cells are filled with atoms and rest of 48% volume of unit cells are empty.

1.9.2 BODY CENTERED CUBIC STRUCTURE (BCC)

- In BCC structure consists of 8 corner atoms as shown in fig (20).
- Each and every corner atoms are sheared by 8 adjacent unit cells.
- In addition, one atom is located at exact center of the body of the cube.
- One corner atom not touch with other corner atom directly. But one corner atom touch with another corner atom through body centered atom along body diagonal.

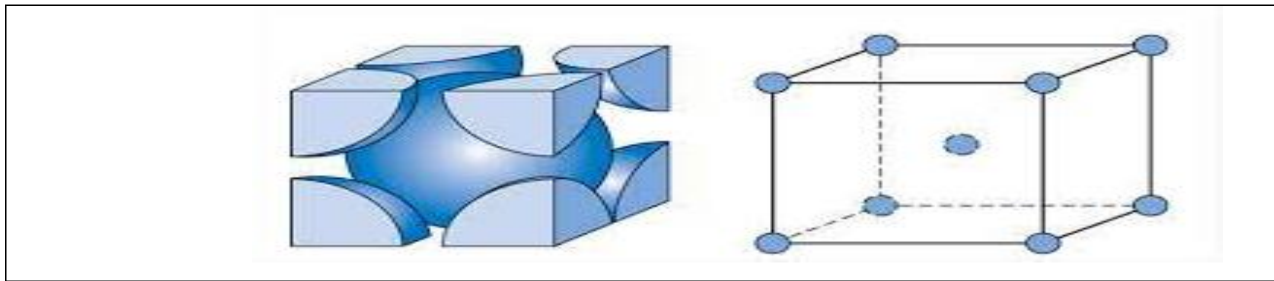


Fig 20. Body centered cubic system

Number of atoms per unit cell:

Here, total number of atom in BCC depending upon both corner atom and body centered atom.

a) No. of corner atom/ unit cell:

No. of corner atom per unit cell, $N_c = \frac{1}{\text{Number of unit cells shared by an atom}}$ **x** No. of particular atom

$$N_c = \frac{1}{8} \times 8 = 1\text{atom}$$

b) No. of body centered atom/ unit cell:

In BCC, body centered atoms are not shared by any other unit cells. Because, it is located at center of the unit cell exactly. So we take whole atom

No. of BC atom, $N_b = 1$

Total no. of atom in BCC= $N_c + N_b$ = 1+1=2 atoms

Coordination number:

A body centered atom is surrounded by 8 corner atoms. Therefore the co-ordination number of a BCC unit cell is 8 as shown in fig (21).

The co-ordination number is 8.

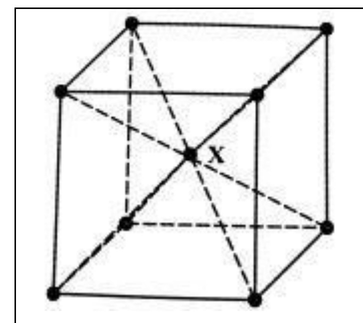


Fig 21. Coordination number of BCC

Atomic radius:

We can calculate the atomic radius of BCC using Phythagoras theorem.

In the triangle ACD

$AD^2 = AC^2 + CD^2$

$= AB^2 + BC^2 + CD^2$

$(4r)^2 = a^2+a^2+a^2$

$16r^2 = 3a^2$

$r^2 = \frac{3a^2}{16}$

Atomic radius $r = a\frac{\sqrt{3}}{4}$

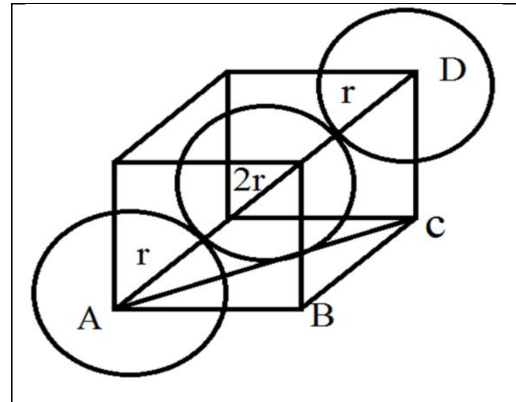


Fig 22. Atomic radius

Atomic packing factor:

$$\text{Packingfactor} = \frac{\text{Number of atoms present in unitcell} \times \text{Volume of atom}}{\text{Volume of the unitcell}}$$

We know, $r = \frac{\sqrt{3}}{4}a$,

No. of atom / unit cell = 2

$$= \frac{2 \times (\frac{4}{3})\pi r^3}{a^3}$$

$$\text{Packing factor} = \frac{2\times(\frac{4}{3})\pi\left(\frac{\sqrt{3}}{4}\right)^3}{a^3}$$

$$= \frac{2\times(\frac{4}{3})\pi\left(\frac{\sqrt{3}}{4}\right)^3}{a^3} = \frac{\sqrt{3}\pi}{8} = 0.68 = 68\%$$

Therefore 68% volume of unit cells are filled with atoms and 32% volume of unit cells are empty.

1.9.3 FACE CENTERED CUBIC STRUCTURE (FCC)

- In FCC structure consists of 8 corner atoms as shown in fig (23).
- Each and every corner atoms are sheared by 8 adjacent unit cells.
- In addition, 6 atoms are placed in six faces of cubic unit cell.
- One corner atom not touch with other corner atom directly. But one corner atom touch with another corner atom through face centered atom along face diagonal.

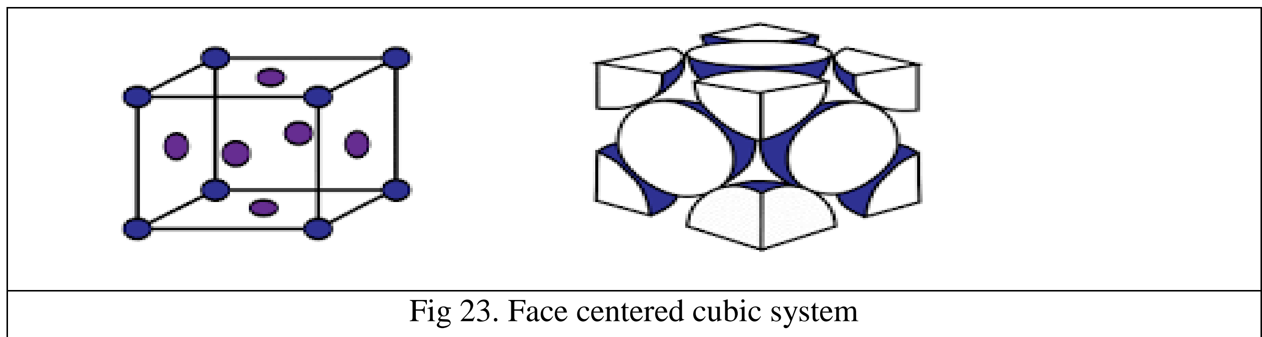


Fig 23. Face centered cubic system

Number of atoms per unit cell:

Here, total number of atom in FCC depending upon both corner atom and face centered atom.

a) No. of corner atom/ unit cell:

No. of corner atom per unit cell, $N_c = \frac{1}{\text{Number of unit cells shared by an atom}}$ **x** No. of particular atom

$$N_c = \frac{1}{8} \times 8 = 1\text{atom}$$

b) No. of face centered atom/ unit cell:

In FCC, one face centered atom is shared by 2 unit cells.

No. of face centered atom / unit cell, $N_f = \frac{1}{\text{Number of unit cells shared by an atom}}$ **x** No. of particular atom

$$N_f = \frac{1}{2} \times 6 = 3\text{atom}$$

Total no. of atom in FCC $= N_c + N_f$

$= 1+3$

$= 4$ atom

Coordination number:

The coordination number for FCC as shown in fig (24). For any corner atom 'x' of the unit cell, the nearest atom are four face center atoms in its plane and four above its plane and four below its plane as shown in fig (24).

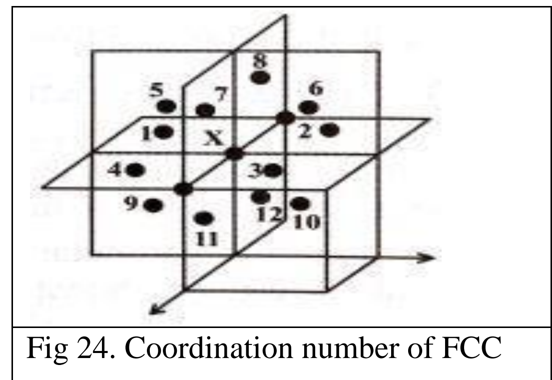


Fig 24. Coordination number of FCC

Thus, the co-ordination number is equal to 4+4+4=12 atoms.

Atomic radius:

We can calculate the atomic radius of FCC using Phythagoras theorem.

In the triangle ABC

$$AC^2 = AB^2 + BC^2$$

$$(4r)^2 = a^2+a^2$$

$$16r^2= 2a^2$$

$$r^2 = \frac{2a^2}{16}$$

Atomic radius, $r = a\frac{\sqrt{2}}{4}$

Or Atomic radius, $r = \frac{a}{2\sqrt{2}}$

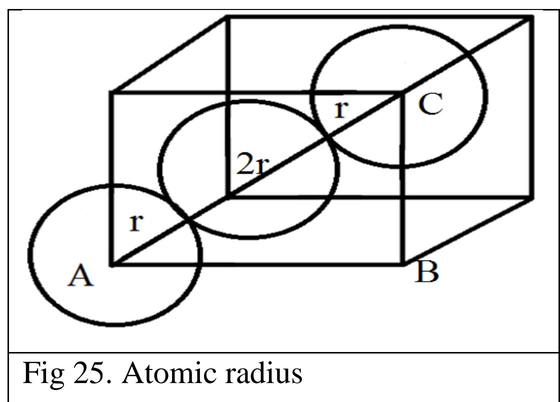


Fig 25. Atomic radius

Atomic Packing factor:x

$$\text{Packingfactor} = \frac{\text{Number of atoms present in unitcell} \times \text{Volume ofatom}}{\text{Volume of the unitcell}}$$

$$= \frac{4\text{X}\left(\left(\frac{4}{3}\right)\pi r^3\right)}{a^3}$$

We know, atomic radius,r = $\frac{a}{2\sqrt{2}}$

$$= \frac{4\times\left(\frac{4}{3}\right)\pi\left(\frac{a}{2\sqrt{2}}\right)^3}{a^3} = \frac{\pi}{3\sqrt{2}} = 0.74 = 74\%$$

Thus, 74% volume of unit cells are filled with atoms and rest of 26 % volume of unit cell is empty.

1.9.4 HEXAHONAL CLOSELY PACKED STRUCTURE (HCP)

The HCP structure, contains three types of atoms

- 12-Corner atoms: One at each and every corner of the hexagon.
- 2 -Base atom: One at the top face of the hexagon and another at the bottom face of the hexagon.
- Middle atom: 3 atoms are placed at middle of the HCP structure in alternate vertical faces with the height of c/2.

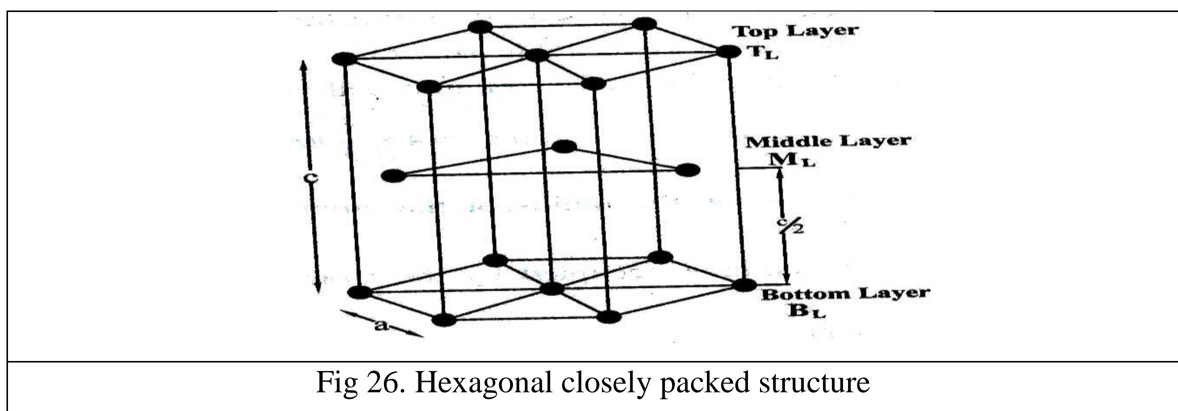


Fig 26. Hexagonal closely packed structure

Number of atoms per unit cell:

Here, total number of atom in HCP depending upon corner atom, base atom and middle layer atom. A corner atom shared by 6 unit cells.

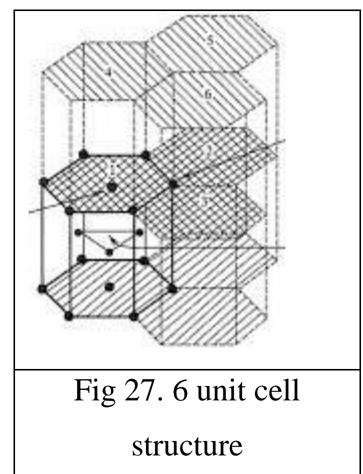


Fig 27. 6 unit cell structure

a) No. of corner atom/ unit cell:

No. of corner atom per unit cell,

$$N_c = \frac{1}{\text{Number of unit cells shared by an atom}} \textbf{ x } \text{No. of particular atom}$$

$$N_c = \frac{1}{6} \times 12 = 2 \text{ atoms}$$

b) No. of base atom/ unit cell:

In HCP, one base atom is shared by 2 other unit cells.

No. of face centered atom / unit cell, $N_b = \frac{1}{\text{Number of unit cells shared by an atom}}$ **x** No. of particular atom

$$N_f = \frac{1}{2} \times 2 = 1 \text{ atom}$$

c) Middle layer atom:

All the three middle layer atoms are placed completely inside the unit cell. So we take full atom.

Middle layer atom, $N_m = 3$

Total no. of atom in FCC= $N_c + N_b + N_m = 2+1+3=$ 6 atoms

Coordination number:

Let us consider two unit cells as shown in fig (28). A central atom in B layer has 6 neighbouring atoms in its own plane. Further at a distance of C/2, it has 3 atoms in the middle layer of the unit cell-1 and 3 more atoms in the middle layer of unit cell-2.

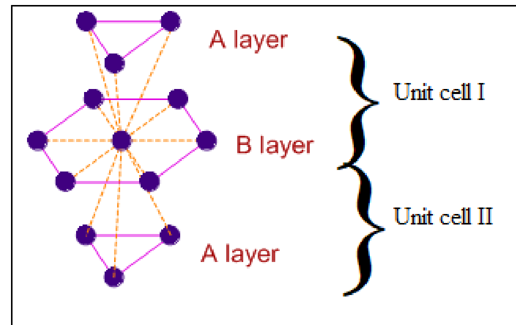


Fig 28. Coordination number

Thus, the coordination number is 3+6+3 = 12.

Atomic radius:

In HCP all the corner atoms are touch with another corner atom and also touch with base atom.

From atomic radius 2r = a

$$\text{Or } r = \frac{a}{2}$$

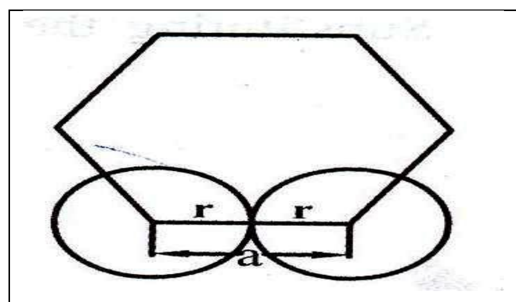


Fig 29. Atomic radius

Relation between 'c' and 'a'(c/a ratio)

In HCP structure, 'c' is the height of the unit cell and 'a' is the distance between two nearest atoms.

- Here, I, J, K, L, M, N are corner atoms and O be the base atom of HCP.
- P, Q, T are the middle atoms as shown in fig (18).
- Now, let us draw the normal line OR from O to line IN.

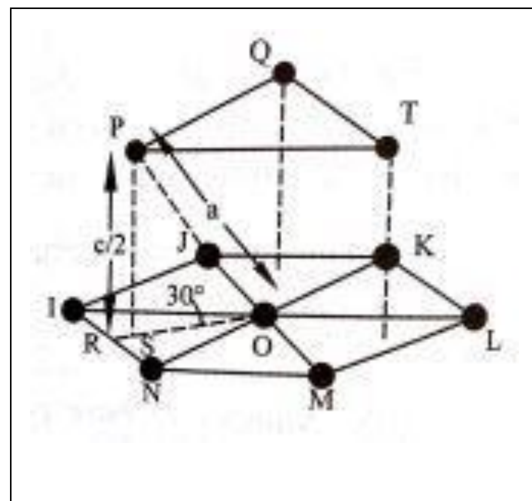


Fig 30. c/a ratio

In the triangle IRO,

$$\cos 30^o = OR/OI$$

$$OR = OI \cos 30^o$$

Since OI = a and $\cos 30^o = \sqrt{3}/2$

We can write

$$OR = \frac{a\sqrt{3}}{2}$$

OS is an ortho center of triangle. The length OS is 2/3 times of OR.

So, $OS = \frac{2}{3} OR$

Substituting the value of 'OR' from equation (1) we get

$$OS = \frac{2}{3} a \frac{\sqrt{3}}{2}$$

$$OS = \frac{a}{\sqrt{3}}$$

In the triangle SOP,

$$OP^2 = OS^2 + SP^2$$

Here, SP = c/2 and OP = a

Substituting the values of OP, OS and SP in equation (3) we get

$$a^2 = \left(\frac{a}{\sqrt{3}}\right)^2 + \left(\frac{c}{2}\right)^2$$

$$a^2 = \frac{a^2}{3} + \frac{c^2}{4}$$

Rearranging we get,

$$\frac{c^2}{4} = a^2 - \frac{a^2}{3}$$

$$\frac{c^2}{4} = \frac{3a^2 - a^2}{3} = \frac{2a^2}{3}$$

$$\frac{c^2}{a^2} = \frac{8}{3}$$

$$\frac{c}{a} = \sqrt{\frac{8}{3}} = 1.633$$

Atomic packing factor (APF):

Area of the base = 6 x area of the triangle ONI

Area of the triangle ONI = (1/2) (IN) (OR)

Substituting the value of OR (from equation (1)) and IN

$$= \frac{1}{2} a \times \frac{a\sqrt{3}}{2}$$

Thus, the area of the base $= 6 \times \frac{a^2}{2}\frac{\sqrt{3}}{2}$

$$= \frac{3}{2}\sqrt{3}a^2$$

Hence, the volume of the HCP unit cell = area of base x c (height)

$$= \frac{3}{2}\sqrt{3}a^2\ c$$

The number of atoms present in a unit cell = 6 atoms

$$\text{Packingfactor} = \frac{\text{Numberofatomspresentinunitcell} \times \text{Volumeofaatom}}{\text{Volumeoftheunitcell}}$$

$$= \frac{6 \times \left(\left(\frac{4}{3}\right)\pi r^3\right)}{\frac{3}{2}\sqrt{3}a^2 C}$$

$$= \frac{6 \times \left(\left(\frac{4}{3}\right)\pi\left[\frac{a}{2}\right]^3\right)}{\frac{3}{2}\sqrt{3}a^2 C} = \frac{\pi a^3}{\frac{3}{2}\sqrt{3}a^2 C} \qquad \left(r = \frac{a}{2}\right)$$

$$= \frac{2\pi}{3\sqrt{3}}\left(\frac{a}{c}\right)$$

$$= \frac{2\pi}{3\sqrt{3}}\left(\frac{3}{8}\right)^{1/2} = \frac{\sqrt{2}\pi}{6} = \frac{\pi}{3\sqrt{2}} = 0.74 = 74\%$$

Thus 74% volume of unit cells are filled with atoms and remaining 26% volume of unit cells are void.

Atomic packing factor for FCC and HCP are same

1.10. MILLER INDICES

Definition:

Miller introduced a system to designate a plane in a crystal. He introduced a set of three numbers to specify a plane a plane in a crystal. This set of three numbers is known as Miller Indices of the concerned plane.

Procedure for finding Miler Indices:

- Determine the intercepts of the plane along the axes X, Y and Z in terms of the Lattice Constant a, b, c.
- Determine the reciprocals of these numbers.
- Find the least common denominator (LCD) and multiply each by this LCD.
- The result is written in the form (hkl) and is called the Miller Indices of the plane.

Example:

- Let the plane have intercepts 4, 1 and 2 on the three axes. The reciprocals are ¼ , 1 and ½. Multiplying each by 4, we get 1, 4 and 2. Hence (1 4 2) are the Miller Indices of the plane.
- Plane ABC (figure 31) has intercepts of 2 axial units on X-axis, 2 axial units on Y-axis and 1 axial unit on Z-axis.

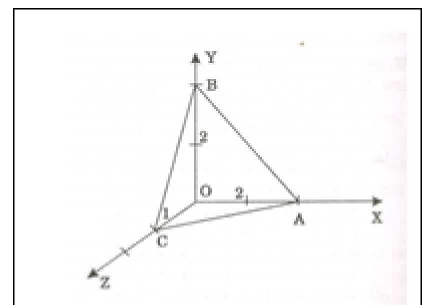


Fig 31. Example

- The reciprocals are 1/2, 1/2 and 1. The LCM is 2.
- Multiplying each by, we get 1, 1, 2. Hence the Miller Indices of the plane are (1 1 2).

Points to ponder

- ✓ The Miller Indices should be enclosed only in this bracket like this ( ).
- ✓ There should not be any commas in between the numbers.
- ✓ If the Miller Indices is say (2 6 3) means it should be read as two six three, and not as two hundred and sixty three.
- ✓ The direction of plane can be represented by enclosing the Miller Indices in a square bracket. For example [2 6 3]
- ✓ Putting a bar over the numbers can represent negative Miller Indices.

  For an example $(\bar{2}\ 6\ \bar{3})$ represents the plane with intercepts on negative X axis, positive Y-axis and negative Z-axis.

1.11. INTERPLANAR SPACING OR "d" SPACING

Definition

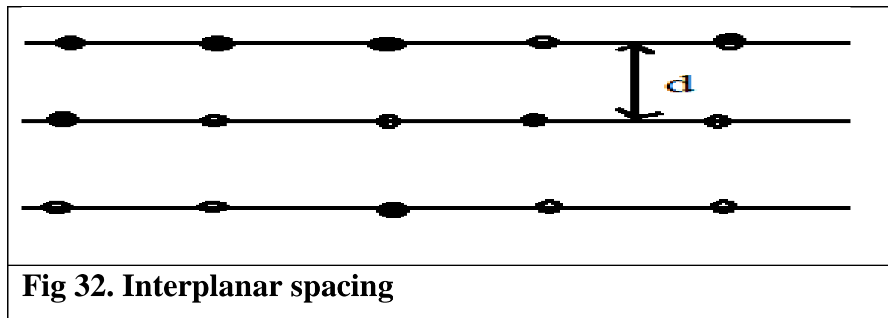


Fig 32. Interplanar spacing

d-spacing or interplanar spacing is the distance between any two successive planes.

i.e. $d = d_2 - d_1$

where, d_1 be the distance of 1st plane from origin O and

d_2 be the distance of 2nd plane from origin O.

Derivation:

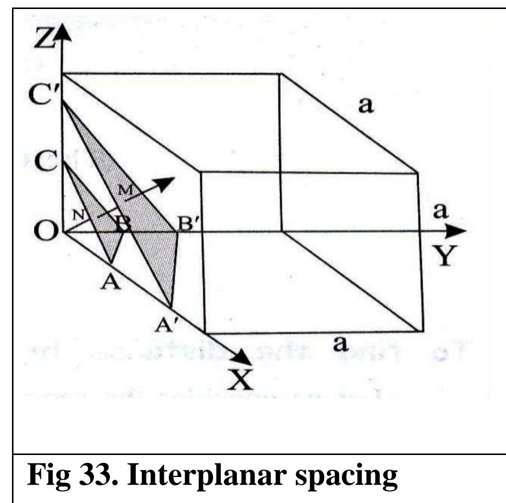


Fig 33. Interplanar spacing

- Consider a cubic lattice.
- ABC&A'B'C' are the two successive planes
- O – Origin
- (hkl) – Miller Indices of the planes
- Draw a perpendicular line from O to Plane ABC. It meets at N.

  $ON = d_1$

- Draw a perpendicular line from O to plane A'B'C'. It meets at M.

  $OM = d_2$

- Let α be the interfacial angle between ON & OA or OM & OA'
- β be the interfacial angle between ON & OB or OM & OB'
- γ be the interfacial angle between ON & OC or OM & OC'
- Interplanar distance $d = d_2 - d_1$ --------(1)

To calculate d1:

The Miller indices along three axes can be written in terms of axial lengths are

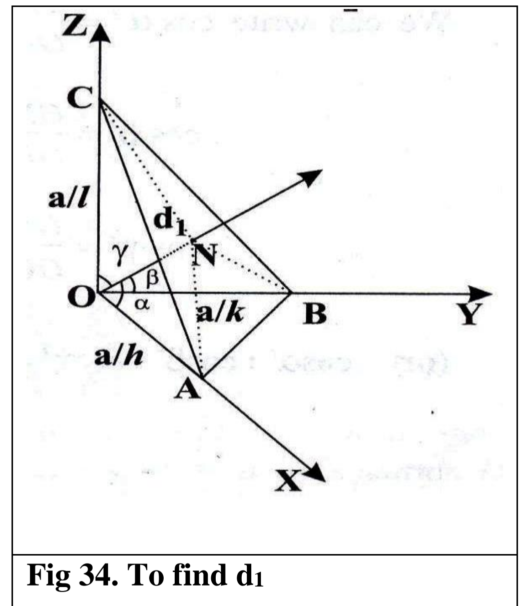


Fig 34. To find d1

$$OA = \frac{a}{h} \;;\; OB = \frac{a}{k} \;;\; OC = \frac{a}{l} \text{-----------------------(2)}$$

$$\Delta ONA,\ \cos\alpha = \frac{ON}{OA} = \frac{d_1}{a/h} = \frac{d_1 h}{a} \text{----------------(3)}$$

$$\Delta ONB,\ \cos\beta = \frac{ON}{OB} = \frac{d_1}{a/k} = \frac{d_1 k}{a} \text{---------------(4)}$$

$$\Delta ONC,\ \cos\gamma = \frac{ON}{OC} = \frac{d_1}{a/l} = \frac{d_1 l}{a} \text{---------------(5)}$$

According to law of direction of cosines,

$$\cos^2\alpha + \cos^2\beta + \cos^2\gamma = 1 \text{--------------------------(6)}$$

Substituting equations 3, 4&5 in equation 6, we get,

$$\left(\frac{d_1 h}{a}\right)^2 + \left(\frac{d_1 k}{a}\right)^2 + \left(\frac{d_1 l}{a}\right)^2 = 1$$

$$\left(\frac{d_1}{a}\right)^2 \left(h^2 + k^2 + l^2\right) = 1$$

$$\left(\frac{d_1}{a}\right)^2 = \frac{1}{\left(h^2 + k^2 + l^2\right)}$$

Taking root on both sides,

$$\left(\frac{d_1}{a}\right) = \frac{1}{\sqrt{h^2 + k^2 + l^2}}$$

Rearranging we get,

$$d_1 = \frac{a}{\sqrt{h^2 + k^2 + l^2}} \text{----------------------------------(7)}$$

To calculate d2:

The Miller indices along three axes can be written in terms of axial lengths are

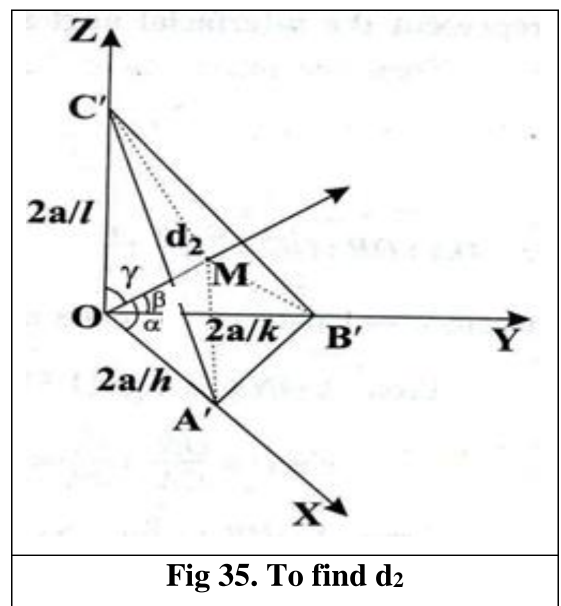


Fig 35. To find d2

$$OA' = \frac{2a}{h} \;;\; OB' = \frac{2a}{k} \;;\; OC' = \frac{2a}{l} \text{--------------(8)}$$

$$\Delta OMA',\ \cos\alpha = \frac{OM}{OA'} = \frac{d_2}{2a/h} = \frac{d_2 h}{2a} \text{------------(9)}$$

$$\Delta OMB',\ \cos\beta = \frac{OM}{OB'} = \frac{d_2}{2a/k} = \frac{d_2 k}{2a} \text{-----------(10)}$$

$$\Delta OMC',\ \cos\gamma = \frac{OM}{OC'} = \frac{d_2}{2a/l} = \frac{d_2 l}{2a} \text{-----------(11)}$$

According to law of direction of cosines,

$$\cos^2\alpha + \cos^2\beta + \cos^2\gamma = 1$$

Substituting equations 9, 10& 11 in equation 6, we get,

$$\left(\frac{d_2 h}{2a}\right)^2 + \left(\frac{d_2 k}{2a}\right)^2 + \left(\frac{d_2 l}{2a}\right)^2 = 1$$

$$\left(\frac{d_2}{2a}\right)^2 \left(h^2 + k^2 + l^2\right) = 1$$

$$\left(\frac{d_2}{2a}\right)^2 = \frac{1}{\left(h^2 + k^2 + l^2\right)}$$

Taking root on both sides,

$$\left(\frac{d_2}{2a}\right) = \frac{1}{\sqrt{h^2 + k^2 + l^2}}$$

Rearranging we get,

$$d_2 = \frac{2a}{\sqrt{h^2 + k^2 + l^2}} \text{------------------------------}(12)$$

To find d:

d = d2 - d1

$$d = \frac{2a}{\sqrt{h^2 + k^2 + l^2}} - \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

$$d = \frac{a}{\sqrt{h^2 + k^2 + l^2}} \text{------------------------------}(13)$$

Equation 13 represents the interplanar spacing or d spacing.

1.11 CRYSTAL GROWTH TECHNIQUES

Crystal growth is a challenging task and the technique followed for crystal growth depends upon the characteristics of the materials under investigation, such as its melting point, Volatile nature, solubility in water or other organic solvents and so on.

The basic growth methods available for crystal growth are broadly. They are

- Growth from melt
- Growth from vapour
- Growth from solution
- Growth from solid

1.11.1 Growth from the melt:

Melt growth is the process of crystallization of fusion and resolidification of the pure material, crystallization from a melt on cooling the liquid below its freezing point. In this

technique apart from possible contamination from crucible materials and surrounding atmosphere, no impurities are introduced in the growth process and the rate or growth is normally much higher than possible by other methods. Melt growth is commercially the most important method of crystal growth.

1.11.2 Bridgmann method:

This technique was named after its inventor Bridgemann in 1925, Stockbarger in 1938.

Principle

The material is heated to a very high temperature until the molten stage is reached. The molt is moved across a temperature gradient so as to solidify and form a seed. Such movements will lead to the crystal growth.

Description (or) Construction

- The material to be grown in the form of a crystal is taken in a crucible inside the vertical cylindrical container.
- A seed crystal is placed at the bottom of the crucible.
- The container is surrounded by two furnaces namely, Furnace 1 & Furnace 2.
- Furnace 1 is kept at hot zone (1237° C) and Furnace 2 is kept at cold zone (620o C).

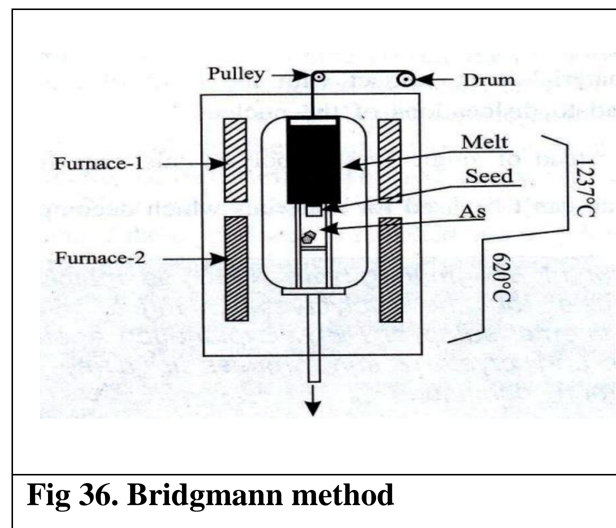


Fig 36. Bridgmann method

- The container is moved up and down during the crystallization process using a pully and drum.
- This movement is used to heat and cool the crystal to be grown (melt).

Working

- Furnace 1 is switched ON and the material is heated to a very high temperature.
- Now the material is changed into molten state.
- The container is moved slowly towards the furnace 2 with the help of the pully and the drum.
- When the container enters into the furnace 2, the crystallization starts in the tip of the seed crystal.
- This movement is very slow in the range of 1 to 30 mm/hour.
- When the container is moved down continuously, the entire molten material will grow into a large crystal.

Advantages

- Cheaper and Easiest method than other techniques.
- Composition can be controlled during the growth.
- Good crystals can be formed.

1.11.3 Czochralski method:

Principle

"Crystal pulling" is the principle used in Czochralski method. Here the material is melted over the monocrystalline seed and is rotated. Further, with the help of pull rod it is slowly drawn upwards and hence the melt freezes on the crystal and thus the crystal grows.

Description (or) Construction

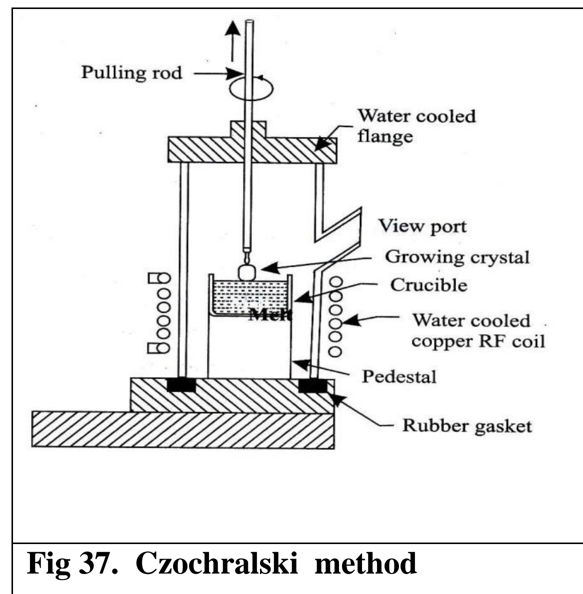


Fig 37. Czochralski method

- The material to be grown in the form of a crystal is taken in a crucible.
- The material is heated by a radiofrequency heater to obtain melt.
- The seed crystal is attached to a pulling rod.
- The seed crystal is just touch on the melt surface.
- Water cooled flange is provided for cooling effect.
- The entire system is covered in a vessel with argon gas.
- Argon gas avoids combustion.
- The growing crystal can be seen through the view point.
- Pedestal and Rubber gasket give strong support to the system.

Working

- The seed crystal is attached to a pulling rod with a specific orientation.
- The heater is switched ON.
- The material in the crucible is melted and free liquid surface will be formed on the top.
- The pulling rod is allowed to rotate and pulled out gradually from the melt.
- The melt freezes on the seed crystal.
- Now a single crystal is grown as the seed crystal orientation.
- The shape of the crystal is initially in the form of a thin neck and then increased. It is known as **necking procedure**.
- By pulling mechanism and necking procedure, bulk crystal can be grown.

- The pulling rate, rotation rate and the power to the heater decide the diameter of the grown crystal.

Advantages

- This technique provides growth of crystal free from crystal defect.
- It can produce large single crystal.
- It allows convenient chemical composition of crystal.
- It enables easy control of atmosphere during growth.

UNIT II PHYSICS OF SEMICONDUCTOR

2.1 INTRODUCTION

A semiconductor has electrical conductivity between that of a conductor and an insulator. Semiconductors differ from metals in their characteristic property of decreasing electrical resistivity with increasing temperature. Semiconductors can also display properties of passing current more easily in one direction than the other, and sensitivity to light.

Because the conductive properties of a semiconductor can be modified by controlled addition of impurities or by the application of electrical fields or light, semiconductors are very useful devices for amplification of signals, switching, and energy conversion. The comprehensive theory of semiconductors relies on the principles of quantum physics to explain the motions of electrons through a lattice of atoms.

Current conduction in a semiconductor occurs via free electrons and holes, collectively known as charge carriers. Adding a small amount of impurity atoms greatly increases the number of charge carriers within it. When a doped semiconductor contains excess holes it is called “p-type,” and when it contains excess free electrons it is known as “n-type”.

The semiconductor material used in devices is doped under highly controlled conditions to precisely control the location and concentration of p- and n-type dopants. A single semiconductor crystal can have multiple p and n type regions; the p-n junctions between these regions have many useful electronic properties.

Semiconductors are the foundation of modern electronics, including radio, computers, and telephones. Semiconductor-based electronic components include transistors, solar cells, many kinds of diodes including the light-emitting diode (LED), the silicon controlled rectifier, photo-diodes, digital analog integrated circuits. Increasing understanding of semiconductor materials and fabrication processes has made possible continuing increases in the complexity and speed of semiconductor devices, an effect known as Moore’s Law.

2.2 PROPERTIES OF SEMICONDUCTOR

- All the semiconductors are crystalline solids
- Atoms in semiconductors are bonded by covalent bond
- They have small energy gap (or) band gap.
- They have an empty conduction band and almost filled valence band 0 K.
- Semiconductor acts like an insulator at Zero Kelvin. On increasing the temperature, it works as a conductor.

- Due to their exceptional electrical properties, semiconductors can be modified by doping to make semiconductor devices suitable for energy conversion, switches, and amplifiers.
- Lesser power losses.
- Semiconductors are smaller in size and possess less weight.
- Their resistivity is higher than conductors but lesser than insulators.
- The resistance of semiconductor materials decreases with the increase in temperature and vice-versa.
- Both electrons and holes are the charge carriers
- The electrical conductivity of semiconductor depends on electrical conductivity due to electrons and holes.

2.3 CLASSIFICATION OF SEMICONDUCTORS

Semiconductors are classified in to two types based on number of elements. They are

1. Elemental semiconductors or indirect band gap semiconductor
2. Compound semiconductor or direct band gap semiconductor

Based on purity, semiconductors are classified as follows:

1. Intrinsic semiconductor
2. Extrinsic semiconductor

The extrinsic semiconductor further classified in to two types based on addition of impurities added. They are

1. N type semiconductor
2. P type semiconductor

2.3.1 Indirect band gap semiconductor or Elemental semiconductors

These are made from single element. They also known as indirect band gap semiconductors. In which the recombination of free electron from the conduction band with the hole in the valence band takes place via traps. During recombination phonons [lattice vibrations] are produced and they heat the crystal lattice (position of the atom). These are the IV group element in the periodic table.

Example: Ge, Si

2.3.2 Direct band gap semiconductor or Compound semiconductors

Compound semiconductors are semiconductors that are made from two or more elements. Silicon is made from a single element, and therefore is not a compound semiconductor.

Most compound semiconductors are from combinations of elements from Group III and Group V of the Periodic Table. Other compound semiconductors are made from Groups II and

VI. It is also possible to use different elements from within the same group (IV), to make compound semiconductors.

Example: GaAs, GaP,

2.3.3 Intrinsic semiconductor

An intrinsic semiconductor is formed from a highly pure semiconductor material. These are basically undoped semiconductors that do not have doped impurity in it.

Example: Si, Ge (Pure form)

At room temperature, intrinsic semiconductors exhibit almost negligible conductivity. As no any other type of element is present in its crystalline structure.

The group IV elements of the periodic table form an intrinsic semiconductor. However, mainly silicon and germanium are widely used. This is so because in their case only small energy is needed in order to break the covalent bond.

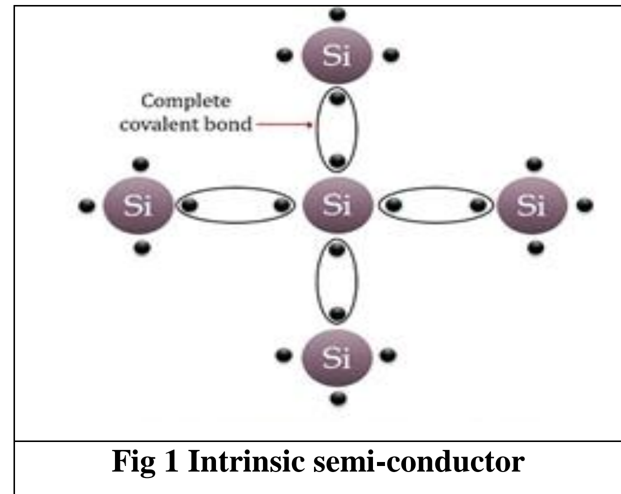


Fig 1 Intrinsic semi-conductor

The figure above clearly shows that silicon consists of 4 electrons in the valence shell. Here, 4 covalent bonds are formed between the electrons of the silicon atom.

When the temperature of the crystal is increased then the electrons in the covalent bond gain kinetic energy and after breaking the covalent bond it gets free. Thus, the movement of free electrons generates current.

The rise in temperature somewhat increases the number for free electrons for conduction.

2.3.4 Extrinsic semiconductor

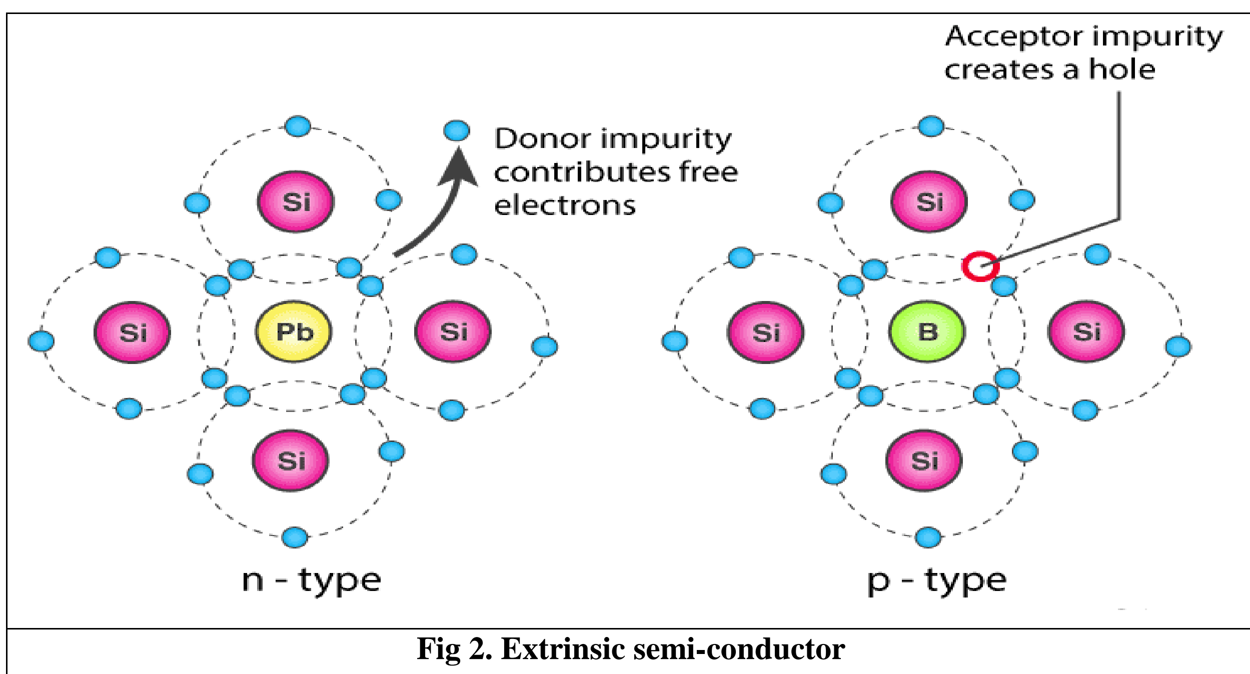


Fig 2. Extrinsic semi-conductor

Extrinsic Semiconductors are those that are the result of adding an impurity to a pure semiconductor. These are basically termed as an impure form of semiconductors.

The process by which certain amount of impurity is provided to a pure semiconductor is known as doping. So, we can say a pure semiconductor is doped to generate an extrinsic semiconductor.

These are highly conductive in nature. However, unlike intrinsic semiconductor, extrinsic semiconductors are of two types p-type and an n-type semiconductor.

It is noteworthy here that the classification of the extrinsic semiconductor depends on the type of element doped to the pure semiconductor.

Doping:

It is the process of addition of foreign atom with pure form of semiconducting materials. In semiconductor, pentavalent or trivalent atom is add with tetravalent to form extrinsic semiconductor.

N type semiconductor

When a small amount of Pentavalent impurity is added to a pure semiconductor providing a large number of free electrons in it, the extrinsic semiconductor thus formed is known as n-Type Semiconductor.

The conduction in the n-type semiconductor is because of the free electrons denoted by the pentavalent impurity atoms. These electrons are the excess free electrons with regards to the number of free electrons required to fill the covalent bonds in the semiconductors.

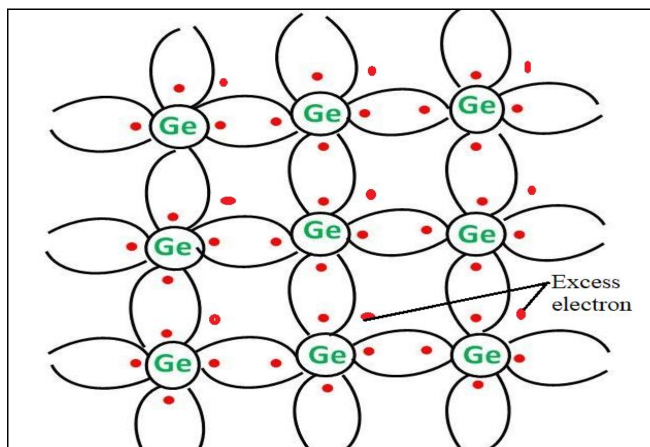


Fig 3. N type semi-conductor

The addition of Pentavalent impurities such as arsenic and antimony provides a large number of free electrons in the semiconductor crystal. Such impurities which produce n-type semiconductors are known as Donor Impurities.

They are called a donor impurity because each atom of them donates one free electron crystal.

When a few Pentavalent impurities such as Arsenic whose atomic number is 33, which is categorised as 2, 8, 15 and 5. It has five valence electrons, which is added to germanium crystal. Each atom of the impurity fits in four germanium atoms as shown in the figure above.

Hence, each Arsenic atom provides one free electron in the Germanium crystal. Since an extremely small amount of arsenic, impurity has a large number of atoms; it provides millions of free electrons for conduction.

P type semiconductor

The extrinsic p-Type Semiconductor is formed when a trivalent impurity is added to a pure semiconductor in a small amount, and as a result, a large number of holes are created in it. A large number of holes are provided in the semiconductor material by the addition of trivalent impurities like Gallium and Indium.

Such types of impurities which produce p-type semiconductor are known as an Acceptor Impurities because each atom of them create one hole which can accept one electron.

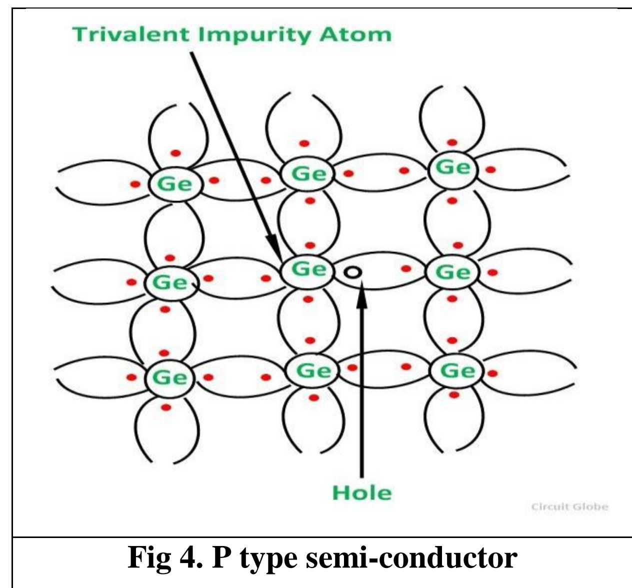


Fig 4. P type semi-conductor

A trivalent impurity like gallium, having three valence electrons is added to germanium crystal in a small amount. Each atom of the impurity fits in the germanium crystal in such a way that its three valence electrons form covalent bonds with the three surrounding germanium atoms.

In the fourth covalent bonds, only the germanium atom contributes one valence electron, while gallium atom has no valence bonds.

Hence, the fourth covalent bond is incomplete, having one electron short. This missing electron is known as a Hole. Thus, each gallium atom provides one hole in the germanium crystal.

As an extremely small amount of Gallium impurity has a large number of atoms, therefore, it provides millions of holes in the semiconductor.

2.3.5 Comparison between intrinsic and extrinsic semiconductor

Parameter	Intrinsic Semiconductor	Extrinsic Semiconductor
Form of semiconductor	Pure form of semiconductor.	Impure form of semiconductor.
Conductivity	It exhibits poor conductivity.	It possesses comparatively better conductivity than intrinsic

Parameter	Intrinsic Semiconductor	Extrinsic Semiconductor
		semiconductor.
Band gap	The band gap between conduction and valence band is small.	The energy gap is higher than intrinsic semiconductor.
Fermi level	It is present in the middle of forbidden energy gap.	The presence of fermi level varies according to the type of extrinsic semiconductor.
Dependency	The conduction relies on temperature.	The conduction depends on the concentration of doped impurity and temperature.
Carrier concentration	Equal amount of electron and holes are present in conduction and valence band.	The majority presence of electrons and holes depends on the type of extrinsic semiconductor.
Type	It is not further classified.	It is classified as p type and n type semiconductor.
Example	Si, Ge etc.	GaAs, GaP etc.

2.4 CARRIER CONCENTRATION IN AN INTRINSIC SEMICONDUCTOR

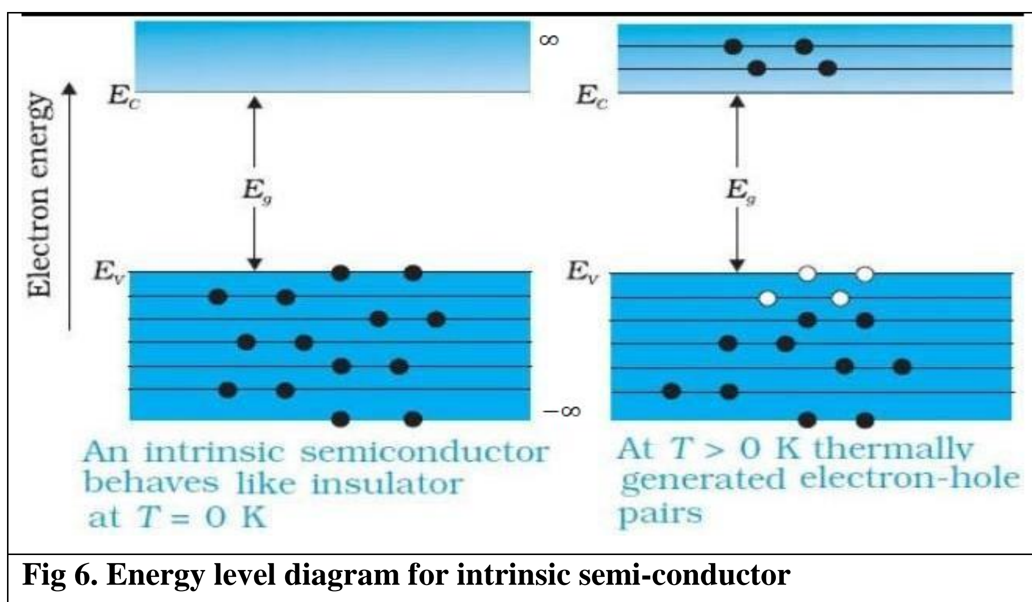


Fig 6. Energy level diagram for intrinsic semi-conductor

In a semiconductor both electrons and holes are charge carriers (know as carrier concentration). A semiconductor in which holes and electrons are created by thermal excitation across the energy gap is called an intrinsic semiconductor.

In an intrinsic semiconductor the number of holes is equal to the number of free electrons.

At T = 0K, valence band is completely filled and conduction band is completely empty. Thus, the intrinsic semiconductor behaves as a perfect insulator. At T > 0K, the electron from the valence band shifted to conduction band across the band gap. Thus, there are number of free electrons and holes in intrinsic semiconductor.

Let E_C be the lower level of conduction band and E_V be the upper level of valence band. The total energy varies from $-\infty$ to ∞.

2.4.1 Density of electron in conduction band

The density of electron in condition band is represented by the symbol N_e.

The density of electron in condition band, N_e=Density of states X Fermi distribution function

$$N_e = N(E)\,dE \times F(E) \text{---1}$$

We know,

$$N(E)dE = \frac{\pi}{2}\left(\frac{8m}{h^2}\right)^{\frac{3}{2}} E^{\frac{1}{2}} dE \text{ and-------------------------------2}$$

$$F(E) = \frac{1}{1+\exp\left[\frac{E-E_F}{KT}\right]} \text{------------------------------------3}$$

Subs. Eqn. 2&3 in eqn. 1, we get

$$N_e = \frac{\pi}{2}\left(\frac{8m}{h^2}\right)^{\frac{3}{2}} E^{\frac{1}{2}} dE.\frac{1}{1+\exp\left[\frac{E-E_F}{KT}\right]}$$

Here mass of the electron (m) is replaced by effective mass of an electron (m_e^*) and energy of conduction band can be calculated as $E=E-E_C$.

$$N_e = \frac{\pi}{2}\left(\frac{8m_e^*}{h^2}\right)^{\frac{3}{2}} (E-E_C)^{\frac{1}{2}} dE.\frac{1}{1+\exp\left[\frac{E-E_F}{KT}\right]} \text{-----------4}$$

Total electron in conduction band can be calculated by integrating eqn. 4 with in the limit E_C to ∞

$$N_e = \int_{E_C}^{\infty} \frac{\pi}{2}\left(\frac{8m_e^*}{h^2}\right)^{\frac{3}{2}} (E-E_C)^{\frac{1}{2}} dE.\frac{1}{1+\exp\left[\frac{E-E_F}{KT}\right]} \text{--------5}$$

The required energy to jump the electron from valence band to conduction band is 4 times KT. But in intrinsic semiconductor we have only KT. So,

$E-E_F >> KT$

Or $\left[\frac{E-E_F}{KT}\right] >> 1$

Or $\exp\left[\frac{E-E_F}{KT}\right] >> 1$

Or $1+\exp\left[\frac{E-E_F}{KT}\right] \approx \exp\left[\frac{E-E_F}{KT}\right]$ --6

Subs. Eqn. 6 in eqn. 5, we get

$$N_e = \int_{E_C}^{\infty} \frac{\pi}{2}\left(\frac{8m_e^*}{h^2}\right)^{\frac{3}{2}} (E-E_C)^{\frac{1}{2}} dE.\frac{1}{\exp\left[\frac{E-E_F}{KT}\right]}$$

Or $$N_e = \int_{E_C}^{\infty} \frac{\pi}{2}\left(\frac{8m_e^*}{h^2}\right)^{\frac{3}{2}} (E-E_C)^{\frac{1}{2}} dE.\exp\left[\frac{E_F-E}{KT}\right]$$ -----------------------7

Put, $x = E - E_C$	Put, $x = E - E_C$	
$E = E_C + x$	$E = E_C + x$	
Differentiating we get	Differentiating we get	------------8
$dE = dx$	$dE = dx$	
Lower limit $E=E_C$	Upper limit $E=\infty$	
Subs. $x = E_C - E_C$	Subs. $x = \infty - E_C$	
$x = 0$	$x = \infty$	

subs. Eqn.8 in eqn. 7 we get,

$$N_e = \int_{E_C}^{\infty} \frac{\pi}{2}\left(\frac{8m_e^*}{h^2}\right)^{\frac{3}{2}} (x)^{\frac{1}{2}}.\exp\left[\frac{E_F-E_C+x}{KT}\right].dx$$

$$N_e = \int_{E_C}^{\infty} \frac{\pi}{2}\left(\frac{8m_e^*}{h^2}\right)^{\frac{3}{2}} (x)^{\frac{1}{2}}.\exp\left[\frac{E_F-E_C}{KT}\right].\exp\left[\frac{x}{KT}\right].dx$$

Or $$N_e = \frac{\pi}{2}\left(\frac{8m_e^*}{h^2}\right)^{\frac{3}{2}} \exp\left[\frac{E_F-E_C}{KT}\right]\int_{E_C}^{\infty} (x)^{\frac{1}{2}}..\exp\left[\frac{x}{KT}\right].dx$$ -------------------9

According to Gamma function,

$$\int_{E_C}^{\infty} (x)^{\frac{1}{2}}..\exp\left[\frac{x}{KT}\right].dx = \frac{(KT)^{\frac{3}{2}}.\pi^{\frac{1}{2}}}{2}$$

Equation 9 can be written as,

$$N_e = \frac{\pi}{2}\left(\frac{8m_e^*}{h^2}\right)^{\frac{3}{2}} \exp\left[\frac{E_F - E_C}{KT}\right] . \frac{(KT)^{\frac{3}{2}} \pi^{\frac{1}{2}}}{2}$$

Or

$$N_e = \frac{1}{2}\left(\frac{8m_e^*}{h^2}\right)^{\frac{3}{2}} \exp\left[\frac{E_F - E_C}{KT}\right] . \frac{(KT)^{\frac{3}{2}} \pi^{\frac{3}{2}}}{2}$$

$$N_e = \frac{1}{4}\left(\frac{8\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}} \exp\left[\frac{E_F - E_C}{KT}\right] . \text{-------------------------------}10$$

$$8^{\frac{3}{2}} = (8^3)^{\frac{1}{2}} = 8(8)^{\frac{1}{2}} = 8(2^3)^{\frac{1}{2}} = 8(2)^{\frac{3}{2}} \text{------------------------------}11$$

$$N_e = \frac{8}{4}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}} \exp\left[\frac{E_F - E_C}{KT}\right] .$$

$$N_e = 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}} \exp\left[\frac{E_F - E_C}{KT}\right] . \text{-----------------------------}12$$

Equation 12 represents density of electron in conduction band.

2.4.2 Density of holes in valence band

The density of holes represented by the symbol N_h.

The density of holes in valence band, N_h=Density of states X Fermi distribution function

N_h= N(E) dE X 1-F(E)---13

F (E) represents occupation of electron in conduction band. 1- F (E) represents the occupation of holes in valence band. The maximum value of F(E) is 1 or 100%.

We know, $$N(E)dE = \frac{\pi}{2}\left(\frac{8m}{h^2}\right)^{\frac{3}{2}} E^{\frac{1}{2}} dE \text{ and---}14$$

$$1 - F(E) = 1 - \frac{1}{1 + \exp\left[\frac{E - E_F}{KT}\right]} \text{--}15$$

$$N_h = \frac{\pi}{2}\left(\frac{8m}{h^2}\right)^{\frac{3}{2}} E^{\frac{1}{2}} dE \left(1 - \frac{1}{1 + \exp\left(\frac{E - E_F}{KT}\right)}\right) \text{------------------------}16$$

Total holes in valence band can be calculated by integrating eqn. 16 within the limit -∞ to E_V

$$N_h = \int_{-\infty}^{E_V} \frac{\pi}{2}\left(\frac{8m}{h^2}\right)^{\frac{3}{2}} E^{\frac{1}{2}} dE \left(1 - \frac{1}{1 + \exp\left(\frac{E - E_F}{KT}\right)}\right)$$

Here mass of the electron (m) is replaced by effective mass of an electron (m_h^*) and energy of conduction band can be calculated as $E=E_V -E$.

$$N_h = \int_{-\infty}^{E_V} \frac{\pi}{2}\left(\frac{8m_h^*}{h^2}\right)^{\frac{3}{2}} (E_V - E)^{\frac{1}{2}} dE \left(1 - \frac{1}{1+\exp\left(\frac{E-E_F}{KT}\right)}\right)$$

$$N_h = \int_{-\infty}^{E_V} \frac{\pi}{2}\left(\frac{8m_h^*}{h^2}\right)^{\frac{3}{2}} (E_V - E)^{\frac{1}{2}} dE \left(\frac{1+\exp\left(\frac{E-E_F}{KT}\right)-1}{1+\exp\left(\frac{E-E_F}{KT}\right)}\right)$$

$$N_h = \int_{-\infty}^{E_V} \frac{\pi}{2}\left(\frac{8m_h^*}{h^2}\right)^{\frac{3}{2}} (E_V - E)^{\frac{1}{2}} dE \left(\frac{\exp\left(\frac{E-E_F}{KT}\right)}{1+\exp\left(\frac{E-E_F}{KT}\right)}\right) \text{------------------------17}$$

For holes, $E-E_F<<KT$

Or $\left[\frac{E-E_F}{KT}\right]<<1$

Or $\exp\left[\frac{E-E_F}{KT}\right]<<1$

Or $1+\exp\left[\frac{E-E_F}{KT}\right]\approx 1$ --18

Equation 17 becomes,

$$N_h = \int_{-\infty}^{E_V} \frac{\pi}{2}\left(\frac{8m_h^*}{h^2}\right)^{\frac{3}{2}} (E_V - E)^{\frac{1}{2}} dE.\exp\left(\frac{E-E_F}{KT}\right) \text{------------------------19}$$

Put, $x = E_V - E$

$E = E_V - x$

Differentiating we get

$dE = -dx$

Lower limit $E=-\infty$

Subs. $x = E_V - (-\infty)$

$x = \infty$

Put, $x = E_V - E$

$E = E_V - x$

Differentiating we get

$dE = -dx$

upper limit $E=E_V$

Subs. $x = E_V - E_V$

$x = 0$

--------------------20

Subs. eqn. 20 in eqn. 19, we get,

$$N_h = \int_{\infty}^{0} \frac{\pi}{2}\left(\frac{8m_h^*}{h^2}\right)^{\frac{3}{2}} (x)^{\frac{1}{2}}.\exp\left(\frac{E_V - x - E_F}{KT}\right)(-dx)$$

$$N_h = \int_0^\infty \frac{\pi}{2}\left(\frac{8m_h^*}{h^2}\right)^{\frac{3}{2}} (x)^{\frac{1}{2}}.\exp\left(\frac{E_V - x - E_F}{KT}\right)dx$$

$$N_h = \int_0^\infty \frac{\pi}{2}\left(\frac{8m_h^*}{h^2}\right)^{\frac{3}{2}} (x)^{\frac{1}{2}}.\exp\left(\frac{E_V - E_F}{KT}\right)\exp\left(\frac{-x}{KT}\right)dx$$

$$N_h = \frac{\pi}{2}\left(\frac{8m_h^*}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_V - E_F}{KT}\right)\int_0^\infty (x)^{\frac{1}{2}}.\exp\left(\frac{-x}{KT}\right)dx \text{ ------------------21}$$

According to Gamma function,

$$\int_{E_C}^\infty (x)^{\frac{1}{2}}..\exp\left[\frac{x}{KT}\right].dx = \frac{(KT)^{\frac{3}{2}}.\pi^{\frac{1}{2}}}{2}$$

$$N_h = \frac{\pi}{2}\left(\frac{8m_h^*}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_V - E_F}{KT}\right).\frac{(KT)^{\frac{3}{2}}\pi^{\frac{1}{2}}}{2}$$

$$N_h = \frac{1}{2}\left(\frac{8m_h^*}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_V - E_F}{KT}\right).\frac{(KT)^{\frac{3}{2}}\pi^{\frac{3}{2}}}{2}$$

$$N_h = \frac{1}{4}\left(\frac{8\pi m_h^* KT}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_V - E_F}{KT}\right). \text{ --------------------------------22}$$

$$8^{\frac{3}{2}} = (8^3)^{\frac{1}{2}} = 8(8)^{\frac{1}{2}} = 8(2^3)^{\frac{1}{2}} = 8(2)^{\frac{3}{2}} \text{ ------------------------------23}$$

$$N_h = \frac{8}{4}\left(\frac{2\pi m_h^* KT}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_V - E_F}{KT}\right).$$

$$N_h = 2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_V - E_F}{KT}\right). \text{ ------------------------------24}$$

Equation 24 represents density of holes in valence band.

2.4.3 Total carrier concentration in an intrinsic semi-conductor

According to law of mass action, the intrinsic carrier concentration $N_i=N_e=N_h$. So,

$$N_i^2 = N_e.N_h \text{ ---25}$$

Subs. Equation 12 & 24 in equation 25, we get

$$N_i^2 = 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_F - E_C}{KT}\right)..2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_V - E_F}{KT}\right).$$

$$N_i^2 = 4\left(\frac{2\pi KT}{h^2}\right)^{\frac{3}{2}} (m_e^*.m_h^*)^{\frac{3}{2}} \exp\left(\frac{E_F - E_C + E_V - E_F}{KT}\right).$$

$$N_i^2 = 4\left(\frac{2\pi KT}{h^2}\right)^{\frac{3}{2}}(m_e^*.m_h^*)^{\frac{3}{2}}\exp\left(\frac{E_V - E_C}{KT}\right).$$

$$N_i = 2\left(\frac{2\pi KT}{h^2}\right)^{\frac{3}{4}}(m_e^*.m_h^*)^{\frac{3}{4}}\exp\left(\frac{E_V - E_C}{KT}\right)^{\frac{1}{2}}. = 2\left(\frac{2\pi KT}{h^2}\right)^{\frac{3}{4}}(m_e^*.m_h^*)^{\frac{3}{4}}\exp\left(\frac{E_V - E_C}{2KT}\right)$$

$$N_i = 2\left(\frac{2\pi KT}{h^2}\right)^{\frac{3}{4}}(m_e^*.m_h^*)^{\frac{3}{4}}\exp\left(\frac{-E_g}{2KT}\right) \text{-----------------------------}25$$

Where, $E_g = E_C - E_V$

Equation 25 represents total carrier concentration in an intrinsic semiconductor.

2.5 CARRIER DENSITY OF ELECTRON IN N TYPE SEMICONDUCTOR

Definition –N type semiconductor

It is formed by V group element doped with IV group element.

During combination of V-IV group element, one electron is excess. These electrons form a new energy level named as donor energy level which lies just below the conduction band.

In N type semiconductor, electrons are jump from donor energy level to conduction band. Now holes are created in donor energy level.

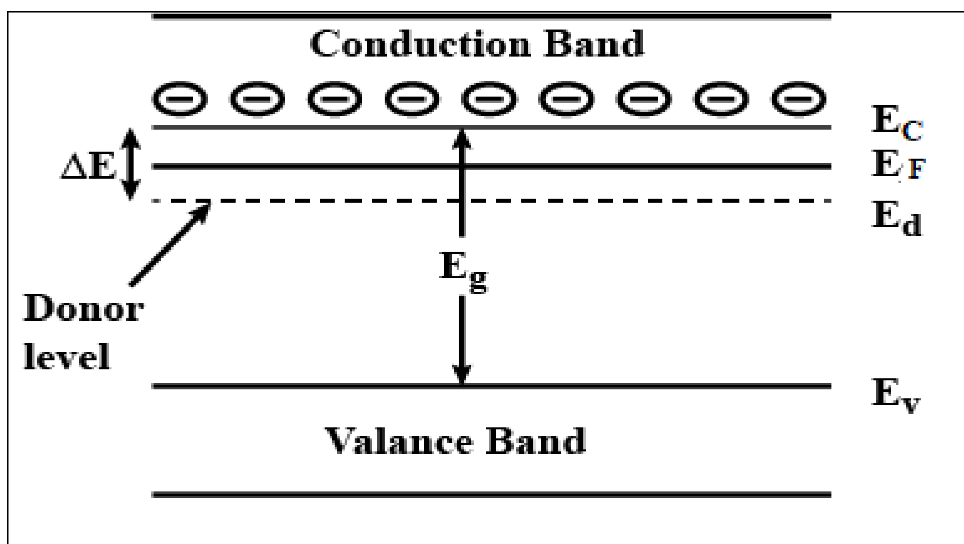


Fig 8. Energy level diagram of N type semiconductor

We know, density of electron in conduction band in an intrinsic semiconductor is given by,

$$N_e = 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}}\exp\left(\frac{E_F - E_C}{KT}\right)$$

Put

$$x = 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}}$$

$$N_e = x.\exp\left(\frac{E_F - E_C}{KT}\right) \text{---1}$$

The number of holes in donor energy level is given by,

$$N_h = N_d[1-[F(E)] \text{---2}$$

Where, N_d represents number of holes in donor energy level

We know,

$$F(E) = \frac{1}{1+\exp\left[\frac{E_d - E_F}{KT}\right]} \text{---------------------------------------3}$$

Equation 2 becomes,

$$N_h = N_d\left(1 - \frac{1}{1+\exp\left(\frac{E_d - E_F}{KT}\right)}\right)$$

$$N_h = N_d\left(\frac{1+\exp\left(\frac{E_d - E_F}{KT}\right) - 1}{1+\exp\left(\frac{E_d - E_F}{KT}\right)}\right)$$

$$N_h = N_d\left(\frac{\exp\left(\frac{E_d - E_F}{KT}\right)}{1+\exp\left(\frac{E_d - E_F}{KT}\right)}\right) \text{---------------------------------------4}$$

For holes, E_d-E_F<<KT

Or $\left[\frac{E_d - E_F}{KT}\right] << 1$

Or $\exp\left[\frac{E_d - E_F}{KT}\right] << 1$

Or $1+\exp\left[\frac{E_d - E_F}{KT}\right] \approx 1$ ---------------------------------------5

Equation 4 becomes

$$N_h = N_d \exp\left(\frac{E_d - E_F}{KT}\right) \text{---6}$$

At equilibrium condition, number of electrons in conduction band is equal to number holes in donor energy level.

i.e $N_e = N_h$

$$x.\exp\left(\frac{E_F - E_C}{KT}\right) = N_d.\exp\left(\frac{E_d - E_F}{KT}\right)$$

Rearranging,

$$\frac{N_d}{x} = \exp\left(\frac{E_F - E_C - E_d + E_F}{KT}\right)$$

Taking log on both sides

$$\log\left(\frac{N_d}{x}\right) = \log\left(\exp\left(\frac{E_F - E_C - E_d + E_F}{KT}\right)\right)$$

$$\log\left(\frac{N_d}{x}\right) = \left(\frac{E_F - E_C - E_d + E_F}{KT}\right)$$

$$\log\left(\frac{N_d}{x}\right) = \left(\frac{2E_F - (E_C + E_d)}{KT}\right)$$

$$2E_F = (E_C + E_d) + KT\log\left(\frac{N_d}{x}\right)$$

Or

$$E_F = \frac{(E_C + E_d)}{2} + \frac{KT}{2}\log\left(\frac{N_d}{x}\right) \text{------------------------------------7}$$

Or

If T=0K

$$E_F = \frac{(E_C + E_d)}{2} \text{--8}$$

In N type semiconductor, Fermi energy level lies exactly midway between conduction band donor energy level.

Now subs. Eqn.7 in eqn.1 we get

$$N_e = x.\exp\left(\frac{\left(\frac{E_C + E_d}{2}\right) - E_C + \left(\frac{KT}{2}\right)\log\left(\frac{N_d}{x}\right)}{KT}\right)$$

$$N_e = x.\exp\left(\frac{\left(\frac{E_C + E_d - 2E_C}{2}\right) + \left(\frac{KT}{2}\right)\log\left(\frac{N_d}{x}\right)}{KT}\right)$$

$$N_e = x.\exp\left(\frac{\left(\frac{-E_C + E_d}{2}\right) + KT\log\left(\frac{N_d}{x}\right)^{\frac{1}{2}}}{KT}\right)$$

$$N_e = x.\exp\left(\left(\frac{E_d - E_C}{2KT}\right) + \log\left(\frac{N_d}{x}\right)^{\frac{1}{2}}\right)$$

$$N_e = x.\exp\left(\frac{E_d - E_C}{2KT}\right).\left(\frac{N_d}{x}\right)^{\frac{1}{2}}$$

$$N_e = x.\exp\left(\frac{E_d - E_C}{2KT}\right).\left(\frac{(N_d)^{\frac{1}{2}}}{x^{\frac{1}{2}}}\right)$$

$$N_e = x.\exp\left(\frac{E_d - E_C}{2KT}\right).(N_d)^{\frac{1}{2}} x^{\frac{1}{2}}$$

$$N_e = x^{\frac{1}{2}}.\exp\left(\frac{E_d - E_C}{2KT}\right).(N_d)^{\frac{1}{2}} \quad \text{-------------------------------------9}$$

Subs. 'x' value in eqn.9 we get,

$$N_e = \left(2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}}\right)^{\frac{1}{2}}.\exp\left(\frac{E_d - E_C}{2KT}\right).(N_d)^{\frac{1}{2}}$$

$$N_e = 2^{\frac{1}{2}}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{4}}.\exp\left(\frac{E_d - E_C}{2KT}\right).(N_d)^{\frac{1}{2}}$$

$$N_e = (2N_d)^{\frac{1}{2}}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{4}}.\exp\left(\frac{E_d - E_C}{2KT}\right).$$

$$N_e = (2N_d)^{\frac{1}{2}}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{4}}.\exp\left(\frac{-\Delta E}{2KT}\right). \quad \text{-------------------------10}$$

Where, $\Delta E = E_C - E_d$. ΔE is called as ionization energy of donors i.e. the amount of energy required to jump the electron from donor energy level to conduction band.

Equation 10 represents density of electron in conduction band in terms of N_d.

2.6 CARRIER DENSITY OF HOLES IN P TYPE SEMICONDUCTOR

Definition –P type semiconductor

It is formed by III group element doped with IV group element.

During combination of III-IV group element, one electron place is vacant. This vacant site is called as hole. These holes form a new energy level named as acceptor energy level which lies just above the valence band.

In P type semiconductor, electrons are jump from valence band to acceptor energy level. Now holes are created in valence band.

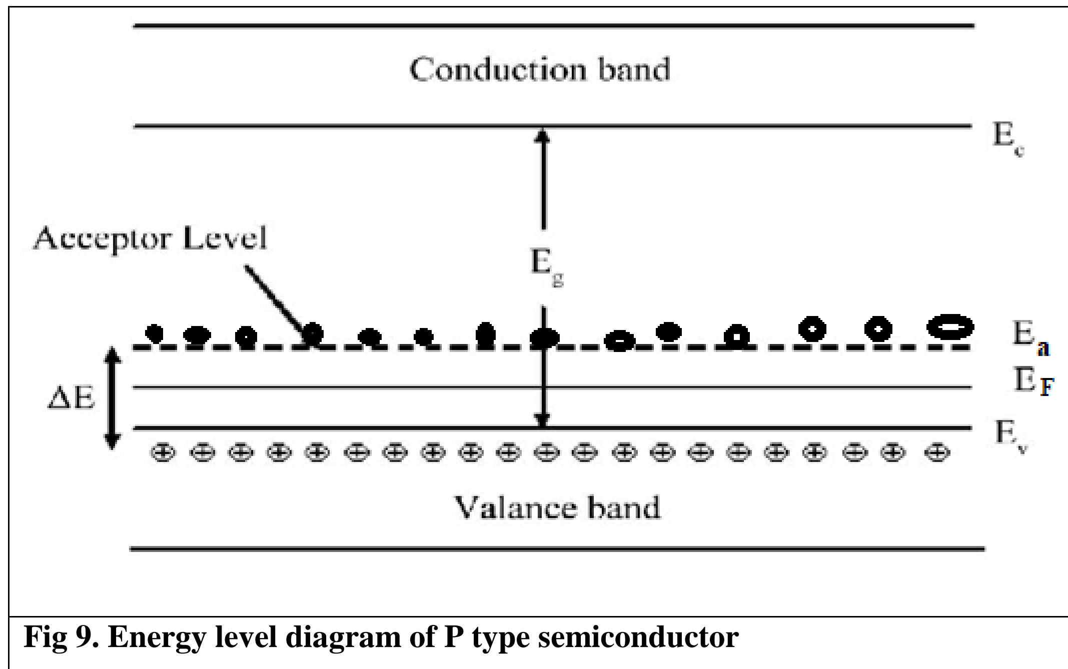


Fig 9. Energy level diagram of P type semiconductor

We know, density of hoes in valence band in an intrinsic semiconductor is given by,

$$N_h = 2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_V - E_F}{KT}\right)$$

Put

$$x = 2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{\frac{3}{2}}$$

$$N_h = x.\exp\left(\frac{E_V - E_F}{KT}\right) \quad \text{--}1$$

The number of electrons in acceptor energy level is given by,

$$N_e = N_a[F(E)] \quad \text{--}2$$

Where, N_a represents number of electrons in acceptor energy level

We know,

$$F(E) = \frac{1}{1 + \exp\left[\frac{E_a - E_F}{KT}\right]} \quad \text{---------------------------------------}3$$

Subs. Eqn.3 in 2 we get

$$N_e = N_a \left(\frac{1}{1+\exp\left(\frac{E_a - E_F}{KT}\right)} \right) \text{------------------------------------4}$$

For electron, E_a-E_F>>KT

Or $\left[\frac{E_a - E_F}{KT}\right] >> 1$

Or $\exp\left[\frac{E_a - E_F}{KT}\right] >> 1$

Or $1+\exp\left[\frac{E_a - E_F}{KT}\right] \approx \exp\left[\frac{E_a - E_F}{KT}\right]$ ------------------------5

Equation 4 becomes

$$N_e = N_a \exp\left(\frac{1}{\frac{E_a - E_F}{KT}} \right)$$

$$N_e = N_a \exp\left(\frac{E_F - E_a}{KT} \right) \text{--6}$$

At equilibrium condition, number of electrons in acceptor energy level is equal to number holes in valence band.

i.e $N_e = N_h$

$$x.\exp\left(\frac{E_V - E_F}{KT}\right) = N_a.\exp\left(\frac{E_F - E_a}{KT}\right)$$

Rearranging,

$$\frac{N_a}{x} = \exp\left(\frac{E_V - E_F - E_F + E_a}{KT}\right)$$

Taking log on both sides

$$\log\left(\frac{N_a}{x}\right) = \log\left(\exp\left(\frac{E_V - E_F - E_F + E_a}{KT}\right)\right)$$

$$\log\left(\frac{N_a}{x}\right) = \left(\frac{E_V - E_F - E_F + E_a}{KT}\right)$$

$$\log\left(\frac{N_a}{x}\right) = \left(\frac{-2E_F + (E_V + E_a)}{KT}\right)$$

$$2E_F = (E_V + E_a) + KT\log\left(\frac{N_a}{x}\right)$$

Or

$$E_F = \frac{(E_V + E_a)}{2} + \frac{KT}{2}\log\left(\frac{N_a}{x}\right) \quad \text{-------------------------------------7}$$

Or

If T=0K

$$E_F = \frac{(E_V + E_a)}{2} \quad \text{---8}$$

In P type semiconductor, Fermi energy level lies exactly midway between valence band and acceptor energy level.

Now subs. Eqn.7 in eqn.1 we get

$$N_h = x.\exp\left(\frac{E_V - \left(\frac{E_V + E_a}{2}\right) + \left(\frac{KT}{2}\right)\log\left(\frac{N_a}{x}\right)}{KT}\right)$$

$$N_h = x.\exp\left(\frac{\left(\frac{2E_V - E_V - E_a}{2}\right) + \left(\frac{KT}{2}\right)\log\left(\frac{N_a}{x}\right)}{KT}\right)$$

$$N_h = x.\exp\left(\frac{\left(\frac{E_V - E_a}{2}\right) + KT\log\left(\frac{N_a}{x}\right)^{\frac{1}{2}}}{KT}\right)$$

$$N_h = x.\exp\left(\left(\frac{E_V - E_a}{2KT}\right) + \log\left(\frac{N_a}{x}\right)^{\frac{1}{2}}\right)$$

$$N_h = x.\exp\left(\frac{E_V - E_a}{2KT}\right).\left(\frac{N_a}{x}\right)^{\frac{1}{2}}$$

$$N_h = x.\exp\left(\frac{E_V - E_a}{2KT}\right).\left(\frac{(N_a)^{\frac{1}{2}}}{x^{\frac{1}{2}}}\right)$$

$$N_h = x.\exp\left(\frac{E_V - E_a}{2KT}\right).(N_a)^{\frac{1}{2}}x^{\frac{1}{2}}$$

$$N_h = x^{\frac{1}{2}}.\exp\left(\frac{E_V - E_a}{2KT}\right).(N_a)^{\frac{1}{2}} \quad \text{-------------------------------------9}$$

Subs. 'x' value in eqn.9 we get,

$$N_h = \left(2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{\frac{3}{2}}\right)^{\frac{1}{2}} .\exp\left(\frac{E_V - E_a}{2KT}\right).(N_a)^{\frac{1}{2}}$$

$$N_h = 2^{\frac{1}{2}}\left(\frac{2\pi m_h^* KT}{h^2}\right)^{\frac{3}{4}} .\exp\left(\frac{E_V - E_a}{2KT}\right).(N_a)^{\frac{1}{2}}$$

$$N_h = (2N_a)^{\frac{1}{2}}\left(\frac{2\pi m_h^* KT}{h^2}\right)^{\frac{3}{4}} .\exp\left(\frac{E_V - E_a}{2KT}\right).$$

$$N_h = (2N_a)^{\frac{1}{2}}\left(\frac{2\pi m_h^* KT}{h^2}\right)^{\frac{3}{4}} .\exp\left(\frac{-\Delta E}{2KT}\right). \quad \text{-------------------------10}$$

Where, $\Delta E = E_a - E_V$. ΔE is called as ionization energy of acceptors i.e. the amount of energy required to jump the electron from valence band to acceptor energy level.

Equation 10 represents density of holes in valence band in terms of N_a.

2.7 HALL EFFECT

The development of a transverse electric field in a solid material when it carries an electric current and is placed in a magnetic field that is perpendicular to the current. This phenomenon was discovered in 1879 by the U.S. physicist Edwin Herbert Hall. The electric field, or Hall field, is a result of the force that the magnetic field exerts on the moving positive or negative particles that constitute the electric current. Whether the current is a movement of positive particles, negative particles in the opposite direction, or a mixture of the two, a perpendicular magnetic field displaces the moving electric charges in the same direction sideways at right angles to both the magnetic field and the direction of current flow. The accumulation of charge on one side of the conductor leaves the other side oppositely charged and produces a difference of potential. An appropriate meter may detect this difference as a positive or negative voltage. The sign of this Hall voltage determines whether positive or negative charges are carrying the current.

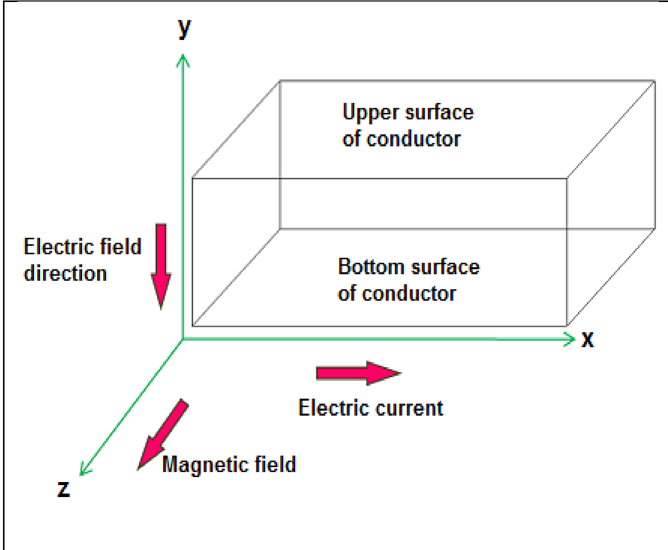


Fig 10. Hall Effect

Definition

When electric current is applied to as conductor or semiconductor along x axis perpendicular to magnetic field along z axis, then equal and opposite electric charges are produced along y direction which is perpendicular to both current and magnetic field. This phenomenon is called as Hall Effect.

The Voltage generated in Hall Effect is called as Hall Voltage.

2.7.1 HALL COEFFICIENT (R_H) FOR N TYPE AND P TYPE SEMICONDUCTOR

Hall Coefficient (R_H) For N Type Semiconductor:

If the magnetic field is applied to an n-type semiconductor, both free electrons and holes are pushed down towards the bottom surface of the n-type semiconductor. Since the holes are negligible in n-type semiconductor, so free electrons are mostly accumulated at the bottom surface of the n-type semiconductor.

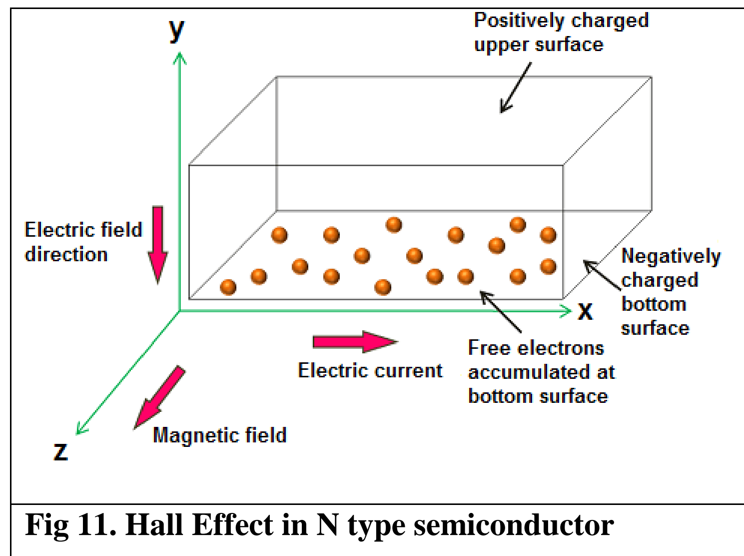


Fig 11. Hall Effect in N type semiconductor

This produces a negative charge on the bottom surface with an equal amount of positive charge on the upper surface. So in n-type semiconductor, the bottom surface is negatively charged and the upper surface is positively charged.

As a result, the potential difference is developed between the upper and bottom surface of the n-type semiconductor. In the n-type semiconductor, the electric field is primarily produced due to the negatively charged free electrons. So the hall voltage produced in the n-type semiconductor is negative.

The force experienced by the free electron due to electric field is given by

$$F = -eE_H \text{ --- } 1$$

Where, e be the charge of an electron

E be the applied electric field

The force experienced by the free electron due to magnetic field is given by

$$F = B(-e)v \text{ --- } 2$$

Where, B be the applied magnetic field

V be the velocity of the electron

At equilibrium condition, the due to electric field is equal to magnetic field.

Equating eqns. 1&2 we get,

$$-eE_H = B(-e)v$$

$$E_H = Bv \text{ --3}$$

We know, current density in terms of velocity is given by

$$J = n_e(-e)v$$

$$v = -\frac{J}{n_e e} \text{ --4}$$

Subs. Eqn. 4 in 3we get,

$$E_H = B\left(-\frac{J}{n_e e}\right)$$

Or $$E_H = B.J..R_H \text{ ---5}$$

Where, $R_H = \left(-\frac{1}{n_e e}\right)$ is called as Hall coefficient for N type semiconductor. Its' value changes with number of free electrons available in N type semiconductor.

Hall Coefficient (R_H) For P Type Semiconductor:

If the magnetic field is applied to a p-type semiconductor, the majority carriers (holes) and the minority carriers (free electrons) are pushed down towards the bottom surface of the p-type semiconductor. In the p-type semiconductor, free electrons are negligible. So holes are mostly accumulated at the bottom surface of the p-type semiconductor.

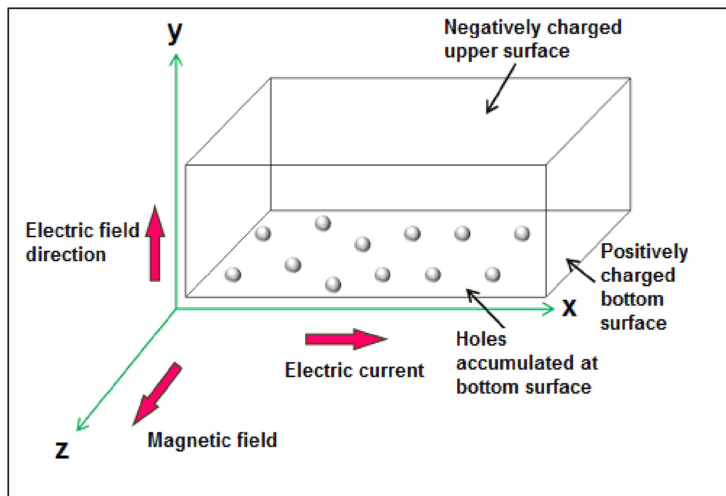


Fig 12. Hall Effect in P type semiconductor

So in the p-type semiconductor, the bottom surface is positively charged and the upper surface is negatively charged.

As a result, the potential difference is developed between the upper and bottom surface of the p-type semiconductor. In the p-type semiconductor, the electric field is primarily produced due to the positively charged holes. So the hall voltage produced in the p-type semiconductor is positive. This leads to the fact that the produced electric field is having a direction in the positive y-direction.

The force experienced by the free electron due to electric field is given by

$$F = eE_H \text{ --6}$$

Where, e be the charge of an electron

E be the applied electric field

The force experienced by the free electron due to magnetic field is given by

$$F = Bev \text{ ---7}$$

Where, B be the applied magnetic field

V be the velocity of the electron

At equilibrium condition, the due to electric field is equal to magnetic field.

Equating eqns. 6&7 we get,

$$eE_H = Bev$$

$$E = Bv \text{ --8}$$

We know, current density in terms of velocity is given by

$$J = n_h ev$$

$$v = \frac{J}{n_h e} \text{ --9}$$

Subs. Eqn. 9 in 8we get,

$$E_H = B\left(\frac{J}{n_h e}\right)$$

Or $$E_H = B.J..R_H \text{ ---10}$$

Where, $R_H = \left(\frac{1}{n_h e}\right)$ is called as Hall coefficient for P type semiconductor. Its' value changes with number of holes available in P type semiconductor.

Hall coefficient in terms of Hall voltage

We know,

Electric field=$\frac{\text{Voltage applied}}{\text{thickness}}$

$$E_H = \frac{V_H}{t} \text{ --11}$$

Where, V_H be the Hall Voltage and t be the thickness of the semiconductor piece taken.

Rearranging we get,

$$V_H = E_H.t \text{ -----------------------------------12}$$

Subs. Eqn. 10 in 12 we get,

$$V_H = B.J.R_H..t \text{ ----------------------------------13}$$

We know, current density, $J = \frac{I}{A}$ -----------------------------------14

But area $A = b.t$ (b- breadth)

Equation 14 can be written as

$$J = \frac{I}{b.t} \text{ --------------------------------------15}$$

Subs. Eqn. 15 in eqn.13

$$V_H = B..R_H..t\left(\frac{I}{b.t}\right)$$

$$V_H = B..R_H\left(\frac{I}{b.}\right)$$

Rearranging $R_H = \frac{V_H b}{IB}$ ---16

Eqn. 16 represents Hall coefficient in terms of Hall voltage.

2.7.2 EXPERIMENTAL DETERMINATION OF HALL COEFFICIENT

A semiconductor slab of thickness 't' and breadth 'b' is taken and current is passed using the battery as shown in Figure.13.

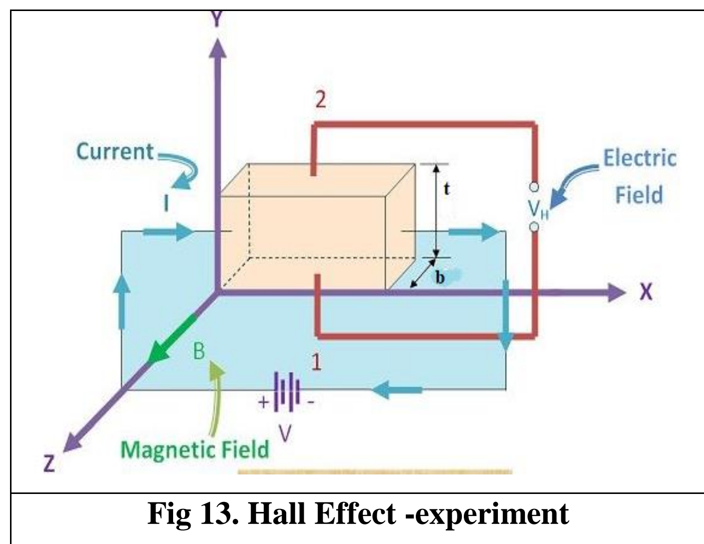


Fig 13. Hall Effect -experiment

The slab is placed between the pole of an electromagnet so that current direction coincides with x-axis and magnetic field coincides with z-axis. The hall voltage (VH) is measured by placing two probes at the center of the top and bottom faces of the slab (y-axis).

If B is magnetic field applied and the VH is the Hall voltage produced, then the Hall coefficient can be calculated from the formula,

$$R_H = \frac{V_H b}{IB} \text{ ---------------------------1}$$

By subsuming the known values of $V_{H,}$ b, I and B, the Hall coefficient of semiconductor can be determined.

2.7. 3 APPLICATIONS OF HALL EFFECT

- Hall Effect is used to find whether a semiconductor is N-type or P-type.
- Hall Effect is used to find carrier concentration.
- Hall Effect is used to calculate the mobility of charge carriers (free electrons and holes).
- Hall Effect is used to measure conductivity.
- Hall Effect is used to measure a.c. power and the strength of magnetic field.
- Hall Effect is used in an instrument called Hall Effect multiplier which gives the output proportional to the product of two input signals

UNIT III MODERN ENGINEERING MATERIALS

3.1 INTRODUCTION

Share memory alloys (SMA's) are metals, which exhibit two very unique properties, pseudo-elasticity and the shape memory effect. Arne Olander first observed these unusual properties in 1938 (Oksuta and Wayman 1998), but not until the 1960's were any serious research advances made in the field of shape memory alloys. The most effective and widely used alloys include Ni-Ti (Nickel – Titanium), CuZnA1 and CuA1Ni.

3.2 DEFINITION

The ability of the metallic alloys to retain to their original shape when heating or cooling is called as Shape Memory Alloys (SMA).

These metallic alloys exhibit plastic nature when they are cooled to very low temperature and they return to their original nature when they are heated. This effect is known as Shape Memory Effect.

It is also called as smart materials or intelligent materials or Active materials. There are two types of shape memory alloys,

- One-way shape memory – It returns to its memory only when heating
- Two-way shape memory – It returns to its memory on both heating and Cooling.

Classification

- Piezo electric SMA materials.
- Electrostrictive SMA materials.
- Magnetostrictive SMA materials.
- Thermo elastic SMA materials.

Examples: Ni-Ti (Nickel – Titanium), Cu Zn A1, Cu A1 Ni, Au – Cd, Ni-Mn-Ga and Fe based alloys.

3.3 Working Principle of SMA

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

The shape memory effect occurs between two temperature states known as Martensite and Austenite. The Martensite structure is a low temperature phase and is relatively soft, it has platelet structure the Austenite is a high temperature phase and is hard it has needle like structure.

Martensite is the relatively soft and easily deformed phase of shape memory alloys which exists at lower temperatures. It has two molecular structures namely, twinned Martensite and

deformed Martensite. Austenite is the stronger phase of shape memory alloys which occurs at higher temperatures, the shape of the Austenite structure is cubic.

When we apply a constant load on a shape memory alloy and cool it, its shape changes due to produced strain. During the deformation, the resistivity, thermal conductivity, Young's modulus and yield strength are decreased by more than 40%.

Twinned Martensite state alloy becomes deformed Martensite when it is loaded. The deformed Martensite becomes Austenite when it is heated, the Austenite transformed to original twinned Martensite state when it is cooled.

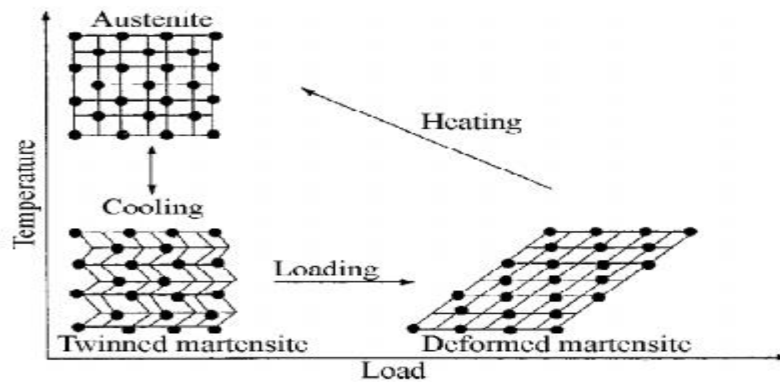


Fig. Material crystalline arrangement during shape memory effect

3.4 Characteristics of SMA

1. Hysteresis

Hysteresis of a SMA is defined as the difference between the temperatures at which the material is 50% transformed to austenite when heating and 50% transformed to martensite when cooling.

When the temperature is decreased in a metallic material, the phase transformation takes place from austenite to martensite. This transformation takes place not only at a single temperature, but over a range of temperatures.

The hysteresis curve for a shape memory alloy is shown below.

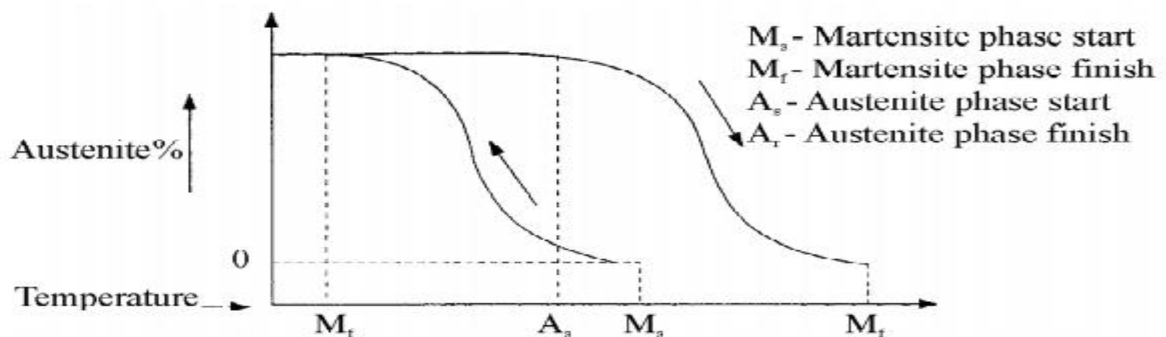


Fig. Hysteresis curve for SMA's

2. Pseudo elasticity

When a metallic material is cooled from a temperature T to a lower temperature T_C it deforms and changes its shape. On reheating the material to Temperature (T) the shape change is received so that the material returns to its original state. This effect is known as pseudo elasticity or thermo elastic property.

3. Super elasticity

Super elasticity is a property of SMA. When a material is deformed at a temperature slightly greater than its transformation temperature super elasticity property appears (Rubber like property).

3.5 Properties of Ni – Ti alloy

Ni – Ti is a compound of Nickel and Titanium and it finds many applications in the field of engineering due to the following properties.

- It has greater shape memory strain.
- It has more thermal stability and excellent corrosion resistance.
- It has higher ductility and more stable transformation temperatures.
- It has better bio-compatibility and it can be electrically heated.

3.5 Advantages of SMA's

- They have good bio-Compatibility.
- They have simplicity, Compactness and high safety mechanism.
- They have good mechanical properties and strong corrosion-resistance.
- They have high power and weigh ratio.

3.6 Disadvantages of SMA's

- They have poor fatigue properties.
- They are expensive and difficult to preparing in a machine.
- They have low energy efficiency.
- They have limited band with due to heating (or) cooling.

3.7 Applications of SMA

Eye glass frames: We know that the recently manufactured eye glass frames can be bent back and forth and can retain its original shape within fraction of time.

Toys: We might have seen toys such as butterflies, snakes etc., which are movable and flexible.

Helicopter blades: The life time of helicopter blades depends on vibrations and their return to its original shape. Hence shape memory alloys are used in helicopter blades.

Coffee Valves: Used to release the hot milk and the ingredients at a certain temperature

Medical Applications of SMA's

- It is used as Micro – Surgical instruments.
- It is used as dental arch wires.
- It is used as flow control devices.
- It is used as ortho – dentil implants.
- It is used for repairing of bones.
- They are used to correct the irregularities in teeth.

Engineering Applications of SMA's

- It is used as a thermostat valve in cooling system.
- It is used as a sealing plug for high pressure.
- It is used as a fire safety valve.
- It is used for cryofit hydraulic pipe couplings.
- It is used for eye glass frame, toys, liquid safety valve.
- It is used to make microsurgical instruments, orthopedic implants.
- It is used as blood clot filter and for fracture pulling.
- It is used to make antenna wires in cell phones.
- It can be used as circuit edge connector.

METALLIC GLASSES

The Metallic glasses are materials which have the properties of both metals and glasses.

Metallic glass = Amorphous metal

In general, metallic glasses are strong, ductile, malleable, opaque and brittle. They also have good magnetic properties and high corrosion resistance.

3.8 Methods of Preparation

Principle

The principle used in making metallic glasses is extremely rapid cooling of the molten alloy. The technique is called as rapid quenching.

The cooled molten alloys are fed into highly conducting massive rollers at high speeds to give ribbons of metallic glasses.

Melt spinning system

A melt spinner consists of a copper roller over which a refractory tube with fine nozzle is placed. The refractory tube is provided with induction heater as shown in fig.

The metal alloy is melted by induction heating under inert gas atmosphere (helium or argon). The properly super-heated molten alloy is ejected through the fine nozzle at the bottom of the refractory tube.

The molten alloy falls on the copper roller which is rotated at high speed. Thus, the alloy is suddenly cooled to form metallic glass. In this method a continuous ribbon of metallic glass can be obtained.

Fig. Melt spinning unit

3.9 Types of Metallic Glasses.

Metallic glasses are classified into two types:

They are combination of metals

(i) Metal –Metal metallic glasses

	Metals		Metals
Examples:	Nickel (Ni)	-	Niobium (Nb)
	Magnesium (Mg)	-	Zinc (Zn)
	Copper (Cu)	-	Zirconium (Zr)

(ii) Metal –Metalloid metallic glasses

These are combinations of metals and metalloids.

These are combinations of metals and metalloids.

Examples:	Metals		Metalloids
	Fe, Co, Ni	-	B, Si, C, **P**

3.10 Properties of Metallic Glasses

Structural properties

1. They do not have any crystal defects such as grain boundaries, dislocation etc.
2. Metallic glasses have tetrahedral close packing (TCP).

Mechanical properties

1. Metallic glasses have extremely high strength, due to the absence of point defects and dislocation.
2. They have high elasticity.

3. They are highly ductile.
4. Metallic glasses are not work-hardening but they are work –soften. (work harnening is a process of hardening a material by compressing it).

Electrical properties

1. Electrical resistivity of metallic glasses is high and it does not vary much with temperature.
2. Due to high resistivity, the eddy current loss is very small.
3. The temperature coefficient is zero or negative.

Magnetic properties

1. Metallic glasses have both soft and hard magnetic properties.
2. They are magnetically soft due to their maximum permeabilities and thus they can be magnetised and demagnetized very easily.
3. They exhibit high saturation magnetisation.
4. They have less core losses.
5. Most magnetically soft metallic glasses have very narrow hysteresis loop with same crystal composition. This is shown in fig.

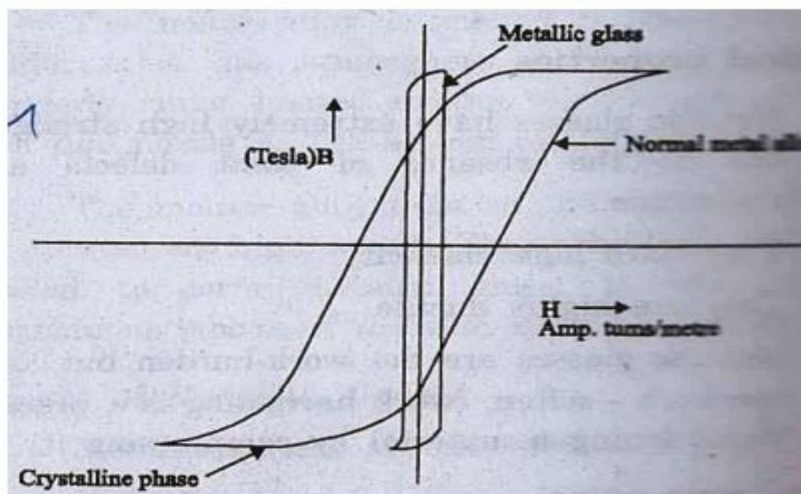


Fig. Hysteresis loop of iron-based alloy in crystalline and metallic glassy phase.

Chemical properties

1. They are highly resistant to corrosion due to random ordering.
2. They are highly reactive and stable.
3. They can act as a catalyst. The amorphous state is more active than the crystalline state from the catalytic point of view.

3.11 Applications of Metallic Glasses

Metallic glasses also called as met glasses have found wide applications in different fields.

Structural application

1. They possess high physical and tensile strength. They are superior to common steels and thus they are very useful as reinforcing elements in concrete, plastic and rubber.
2. Strong ribbons of metallic glasses are used for simple filament winding to reinforce pressure vessels and to construct large fly wheels for energy storage.
3. Due to their good strength, high ductility, rollability and good corrosion resistance, they are used to make razor blades and different kinds of springs.

Electrical and Electronics

1. Since metallic glasses have soft magnetic properties, they are used in tape recorder heads, cores of high-power transformers and magnetic shields.
2. They use of metallic glasses in motors can reduce core loss very much when compared with conventional crystalline magnets.
3. Superconducting metallic glasses are used to produce high magnetic fields and magnetic levitation effect.
4. Since metallic glasses have high electrical resistance, they are used to make accurate standard resistance, computer memories and magneto resistance sensors.

Metallic glasses as transformer core materials

Metallic glasses have excellent magnetic properties. When they are used as transformer core, they give maximum magnetic flux linkage between primary and secondary coils and thus reduce flux leakage losses.

In view of their features like small thickness, smaller area, light weight, high resistivity, soft magnetic property and negligible hysteresis and eddy current loss, metallic glasses are considered as suitable core materials in different frequency transformers.

Nuclear reactor engineering

The magnetic properties of metallic glasses are not affected by irradiation and so they are useful in preparing containers for nuclear waste disposal and magnets for fusion reactors.

Chromium and phosphorous based (iron chromium, phosphorous-carbon alloys) metallic glasses have high corrosion resistances and so they are used in iner surfaces of reactor vessels, etc.

Bio-medical Industries

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.

CERAMICS

Ceramics (ceramic materials) are non-metallic inorganic compounds formed from metallic (Al, Mg, Na, Ti, W) or semi-metallic (Si, B) and non- metallic (O, N, C) elements.

Atoms of the elements are held together in a ceramic structure by one of the following bonding mechanism: Ionic Bonding, Covalent Bonding, Mixed Bonding (Ionic-Covalent).

Most of ceramic materials have a mixed bonding structure with various ratios between Ionic and Covalent components. This ratio is dependent on the difference in the electronegativities of the elements and determines which of the bonding mechanisms is dominating ionic or covalent.

3.12 Types of ceramics

They are mainly of two types of ceramics based on their atomic structure.

1. Crystalline ceramics
2. Non-crystalline ceramics

They can also be classified into three different material categories.

1. Oxides
2. Non-oxides
3. Composites

3.13 Examples of ceramics

- Barium titanate
- Boron oxide
- Boron nitride
- Ferrite
- Lead zirconate titanate
- Porcelain
- Silicon carbide
- Silicon nitride
- Titanium carbide
- Zinc oxide
- Zirconium dioxide

3.14 Properties of ceramics

1. They have high hardness
2. Its melting point is high
3. They have good thermal insulating property
4. Its electricity resistance is high
5. They have low mass density
6. Generally, chemically inert
7. They are brittle in nature
8. They have Zero ductility
9. Its tensile strength is low

3.15 Applications of ceramics

- They are used in space industry because of their low weight
- They are used as cutting tools
- They are used as refractory materials
- They are used as thermal insulator
- They are used as electrical insulator

NANOMATERIALS

A nano metre (nm) is one billionth ($1/10^9$) of a metre. For comparison, thickness of a single human hair is about 80,000 nm (80 μm), a red blood cell is approximately 7,000 nm (7 μm) wide and a water molecule is almost 0.3 nm across. Scientists and engineers are nowadays interested in nano scale which is from 1 nm to 100 nm. At nano scale, the properties of materials are very different from those at larger scale. Therefore, the nano-world is in between quantum world and macro world.

Nano science is concerned with the study of phenomena and manipulation of materials at nano metere scales. Nanotechnology is the design, characterization, production and application of structures, devices and systems by controlling shape and size at the nano meter scale**.**

Nanotechnology means putting to use the unique physical properties of atoms, molecules and other things measuring roughly 1 to 100 nanometers. The word "nano" comes from nanos, a Greek word meaning dwarf. Presently, we are using many devices made of nano electronic devices. The microelectronics industry was born out of the invention of the bi-polar transistor in 1947 and by the invention of the integrated circuit (IC) in 1958.

Gordon Moore (co-founder of INTEL Corporation) observed that the number of transistors per square inch on IC chip roughly doubled by every 18 to 24 months. This general rule of thumb is now called as "Moore's law".

3.16 Definition of Nano System

Nano phase materials are newly developed materials with grain size at the nano metre range (10^{-9}m), i.e., in the order of 1 - 100 nm. The particle size in a nanomaterial is 1 nm. They are simply called nano materials.

3.17 Different Forms of Nanomaterials

5. 17.1 Nano-structured material

The structures, whose characteristic variations in design length are at the nano scale (nm).

5. 17.2 Nano particles

The particle size is in the order of 10^{-9} m.

5. 17.3 Nano dots

Nanoparticles which consist of homogeneous material, especially those that are almost spherical or cubical in shape.

5. 17.4 Nanorods

Nanorods which are shaped like long sticks or rods with diameter in nanoscale and a length very much longer.

5. 17.5 Nanotubes

The carbon nanotubes are the wires of pure carbon like rolled sheets of graphite or like soda straws.

5. 17.6 Nanowires

Nanowires are nanorods which especially conduct electricity.

5. 17.7 Fullerenes

A form of carbon having a large molecule consisting of an empty cage of 60 or more carbon atoms.

5. 17.8 Nanocomposites

Composite structures whose characteristic dimensions are found at nanoscale.

5. 17.9 Cluster

A collection of units (atoms or reactive molecules) uptoabout 50 units.

5. 17.10 Colloids

A stable liquid phase containing particles in the 1-1000 nm range.

5.18 Preparation of Nano Phase Materials

The Nano materials can be synthesized by two processes, they are

- Top – down approach
- Bottom – up approach

5.18.1. Top – down approach

The removal or division of bulk material or the miniaturization of bulk fabrication processes to produce the desired nanostructure is known as top-down approach. It is the process of breaking down bulk material to Nano size.

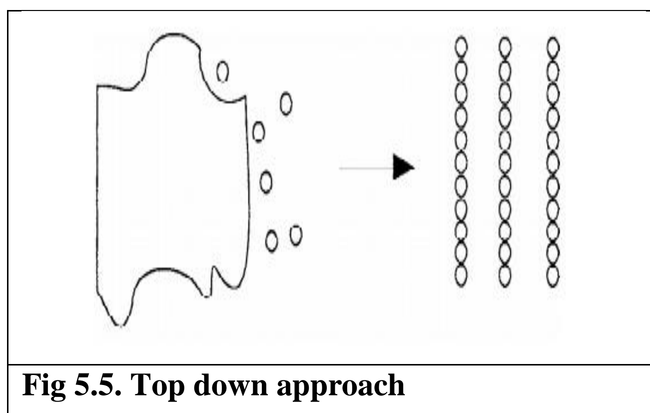


Fig 5.5. Top down approach

Types of Top – down Methods

- Ball Milling
- Lithographic
- Machining

5.18.2 Bottom – up approach

Molecules and even nano particles can be used as the building block for producing complex nanostructures. This is known as Bottom – up approach. The Nano particles are made by building atom by atom.

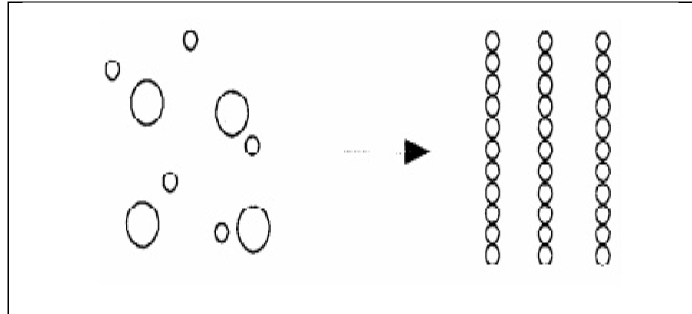


Fig 5.5. Bottom up approach

Types of Bottom up Methods

- Vapour phase deposition Method
- Molecular beam epitaxy Method
- Plasma assisted deposition Method
- Metal Organic Vapour Phase Epitaxy [MOVPE]
- Liquid phase process [Colloidal method and Sol – Gel method]

5.19 Synthesis Methods

5.19.1 Pulsed Laser Deposition Method

Principle

PLD is an extremely simple technique, which uses pulses of laser energy to remove material from the surface of a target. These atoms are deposited over substrate.

Construction

- It consists of laser beam which is used to produce beam of laser.
- A Convex lens is used to see the process directly
- A Pressure transducer is used to check the pressure inside the vacuum chamber.
- Target holder used to hold the target material
- Gas inlet is used to maintain the temperature inside the vacuum chamber and it is used to carry atoms for deposition.

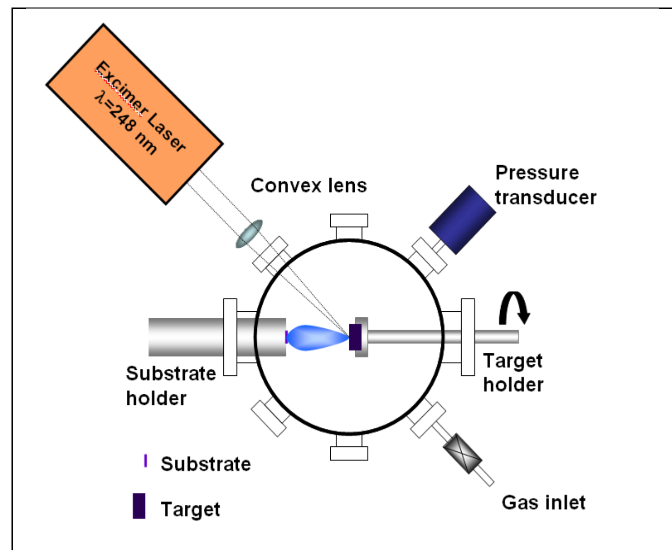


Fig 5.6. Schematics of PLD

- The substance holder is used to hold the substance.
- The target material is nothing but the material to be converted as nano materials
- The substrate is used to deposit the nanomaterial

Working

- A laser device is switched on, and is produced mass of Photons. These photons are allowed to fall on the surface of substance.
- Now the photons of energy are transferred to atom which is present over metal surface. Due to high energy, the atoms are ejected from the surface of metal.
- The air flow inside the chamber carries these atoms and is deposited over the substrate.
- The thickness of the nano material can be controlled by pressure and adjusting the distance between substance and substrate.

Advantages

- More than 99% of graphite is converted into carbon nano tubes.
- A selective growth of nano tube is achieved due to presence of catalysts.
- The diameter of the nano tube is controlled by the reaction temperature.

5.19.2 ELECTRO DEPOSITION METHOD

Principle

This technique is generally used in electroplating and in the production of nano films.

Construction

- This set up consists of a container.
- The electrolyte (aqueous solution of salts, acids etc.) is taken in the container.
- Two electrodes (cathode & anode) are used.
- E_1 is called cathode & E_2 is called anode.
- A battery is connected with these electrodes.

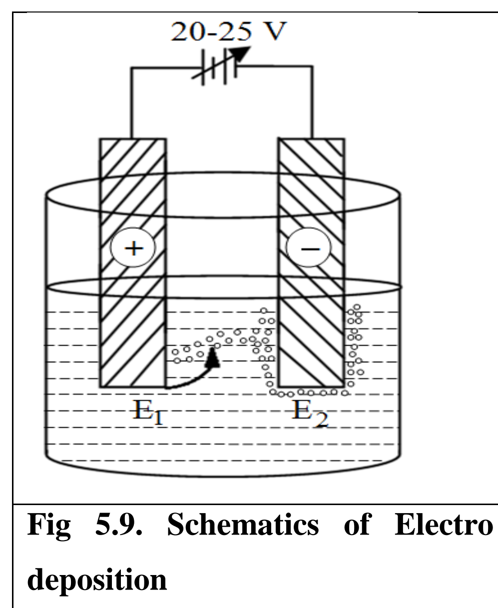


Fig 5.9. Schematics of Electro deposition

Working

- Two electrodes are immersed in the electrolyte.
- The battery is switched ON.
- The current is passed through the electrodes.
- Now certain mass of substance is liberated from E_1.
- The liberated substance is deposited on the surface of E_2 and forms nano film.
- If the deposition is made in the cathode, it is called cathodic deposition.
- If the deposition is made in the anode, it is called anodic deposition.
- If the current through the circuit is made constant, it is called galvanostatic method.

Advantages

- Simplest and inexpensive method.
- The thickness of the film can be controlled by adjusting the deposition rate.

5.20 CARBON NANOTUBES (CNT)

A group of nanostructures with large potential applications are carbon nanotubes. The hexagonal lattice of carbon is simply graphite. A single layer of graphite is called graphene. (fig. 5.10) The carbon nanotube (CNT) consists of a graphene layer which is rolled up into a cylindrical shape as shown in fig.5.10.

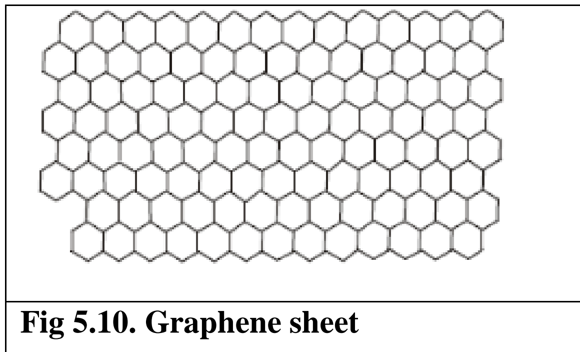


Fig 5.10. Graphene sheet

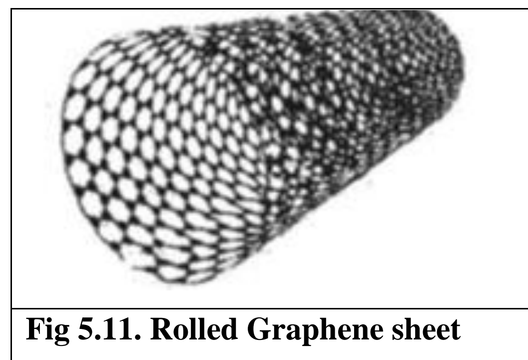


Fig 5.11. Rolled Graphene sheet

When the graphene layer is rolled, the structure is tube like and it is a single molecule. Each single molecule nanotube is made up of a hexagonal network of covalently bonded carbon atoms. In some cases, the hexagons are arranged in a spiral form. The layer appears like a rolled-up chicken wire (net having a large hexagonal mesh) with carbon atoms at the apexes of the hexagon as shown in fig.5.11.

The carbon nanotubes are hollow cylinders of extremely thin diameter, 10,000 times smaller than a human hair.

Structures of CNT

The CNTs have many structures on the basis of their length, type of spiral and number of layers. Their electrical properties depend on their structure and they act as both metal and semiconductor.

There are a variety of structures of carbon nanotubes with different properties.

5.21 TYPES CNT STRUCTURES

Based on no. of walls, the CNTs are classified in to two types. They are

1. Single walled CNT
2. Multi walled CNT

Single walled CNT

SWCNTs have a diameter range of 0.5 to 12 nm but the smallest diameter of SWCNTs is 0.4 nm with different tube lengths starting from few micrometers depending on manufacturing and treatment techniques.

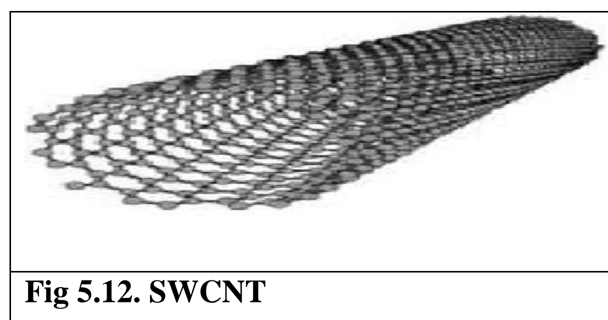


Fig 5.12. SWCNT

Multi walled CNT

MWCNTs consist of multi rolled layers of graphene inserted one into the other and the number of graphene walls may reach more than 25 walls with spacing of 0.34 nm. The outside diameter of MWCNTs ranges from 1 nm to 50 nm while the inside diameter is several nanometers. As a material modification, MWCNTs is better than SWCNTs as it is stiffer, easier, and cheaper to produce on a large scale.

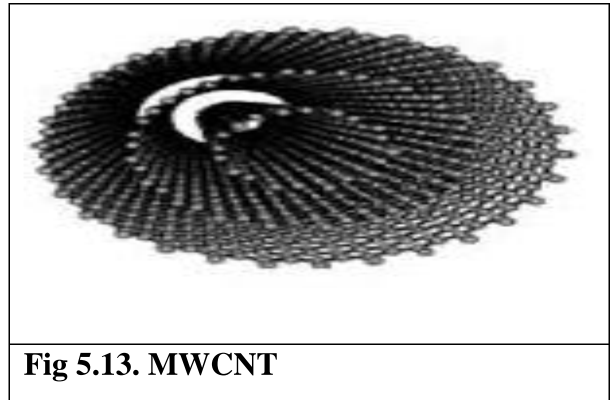


Fig 5.13. MWCNT

Three types of nanotube structures are considered by rolling a graphite sheet with different orientations about the axis.They are

1. Armchair structure
2. Zig-zag structure
3. Chiral structure

Armchair structure

When the axis of the tube parallel to C=C bonds of thecarbon hexagons, the structure shown in fig. 5.14(a) is obtained. It is referred as “armchair” structure.

Zig-zag and Chiral structure

The tubes sketched in figs. 5.14(b) and 5.14(c), referred as zig-zag and chiral structure. They are formed by rolling graphene sheet such that the axis of the tube is not parallel to C-C bonds. Zig-zag structure consists of tube axis perpendicular to C-C bonds. In chiral structure, C-C bond is inclined towards the axis of the tube. Generally, nanotubes are closed at both ends with half of fullerene structure.

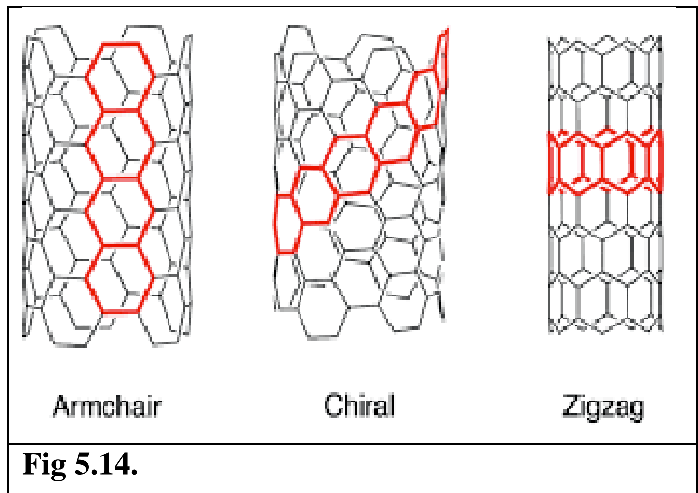


Fig 5.14.

3.22 Properties of CNT

1. Carbon nanotubes are stiff. They are as stiff as a diamond (the hardest natural material in nature).
2. The gravitational weight of the nanotube is very low.
3. The density of the carbon nanotubes is one-fourth of that of steel.
4. Carbon nanotubes are stronger than steel. They exhibit extraordinary mechanical properties. Carbon nanotubes are ten times stronger than steel.

5. Carbon nanotubes have a high thermal capacity. Generally, it is twenty times stronger than steel. Therefore, it does not expand on heating like that of steel. Therefore, carbon nanotubes use in making bridges and aircrafts material
6. In carbon nanotubes, each carbon atom is surrounded by three other carbon atoms through covalent bonds. These carbon-carbon covalent bonds form lattices in the shape of hexagons.
7. The crystalline structure of carbon nanotubes exists in the form of regular hexagons.
8. Carbon nanotubes are elastic.
9. Carbon nanotubes are good conductors of heat.
10. Carbon nanotubes have good electrical conductivity.
11. The young's modulus is high. The young modulus of carbon nanotubes is around 1 terra pascal which makes carbon nanotubes ten times stronger than steel.
12. Carbon nanotubes are chemically neutral. So, they are chemically stable. Therefore, carbon nanotubes resist corrosion.

3.23 Applications of Carbon Nanotubes

1. **Breast cancer tumour destruction:**

   nanotubes are used to destroy breast cancer tumours. They play with an antibody. The antibody along with nanotubes is attracted to the proteins by cancer cells in the body and nanotubes absorb the laser beam killing the bacteria of the tumour.

2. **Windmill blades:**

   They are also used in the windmill blades because of their low weight. It increases the efficiency of the windmill and helps to produce more electricity at a faster rate.

3. **Filtration:**

   carbon nanotubes can be used to separate particles of size greater than the diameter of carbon nanotubes during filtration through them. They can also be used to trap smaller sized ions from a solution.

4. **Carbon nanotubes as Nano cylinders:**

   gas like H2, for energy, battery for vehicles can be safely stored inside the carbon nanotubes and the problem of H2 storage hazards can be solved.

   Carbon nanotubes have also been shown to absorb infrared light and may have applications in the IR optics industry.

5. **Aircraft stress reduction:**

   nanotubes are also used in space and aircraft to reduce the weight and stress of the various components working together.

Other uses of carbon nanotubes – they are used as catalysts in some reactions. They are also used in drug delivery systems and in applications related to conductivity in electronics

UNIT IV OPTOELECTRONICS AND DEVICES

4.1 Classification of optical materials

The optical characteristics of materials are determined by the type of interaction between the electromagnetic radiation and the electrons of the atoms in the material.

We see many of the common optical characteristics of materials such as their colour, brightness, transparency, reflectivity etc.

Besides, these common properties, there are many more special optical properties of materials which make them useful in a wide range of optical devices.

Some of the commonly used optical materials and devices are window glasses, lenses, mirrors, antireflection coatings etc.

Some of the most recently developed high-technology optical devices are lasers, optical fibers, photodiodes, optical memories (CD-ROM), electro-optic modulators.

Definition

The materials which are sensitive to light are known as Optical materials. These optical materials exhibit a variety of optical properties.

4.2 Classification of Optical Materials

Generally, optical materials are classified into three types based on the nature of propagation of light namely,

(i) Transparent
(ii) Translucent
(iii) Opaque

(i) Transparent

Transparent materials are the materials which transmit the light with little absorption and reflection. These materials are transparent in nature and hence, one can clearly view the object through the material.

Electrical insulated materials are transparent. Similarly, few semiconducting materials are also transparent.

(ii) Translucent

The incident light gets scattered within the materials and hence, the diffused light is transmitted with the other side of the materials.

One cannot clearly view the object while viewing through the materials. These materials are known as translucent material.

(iii) Opaque

The material which absorbs the visible light is termed as opaque. When an electromagnetic radiation in the entire visible spectrum is incident on this material, either it gets reflected or absorbed.

Thus, the materials are opaque. Few semiconducting materials also exhibit this opaque nature.

4.3 Optical Processes in Semiconductors

When light incident on a semiconductor, an electron in the valence band goes to the conduction band. This process generates electron-hole pairs. It is also possible for an electron and a hole to recombine and emit light.

The interaction between light (photons) and electrons in a variety of phenomena. These are used in the field of opto electronics.

The important optoelectronic interaction in semiconductors is the band-to-band transition (Fig.4.1). In the photon absorption process, a photon scatters an electron in the valence band.

Thus, electron jumps to the conduction band and leaving a hole in VB. In the reverse process the electron in the conduction band recombines with a hole in the valence band to generate a photon.

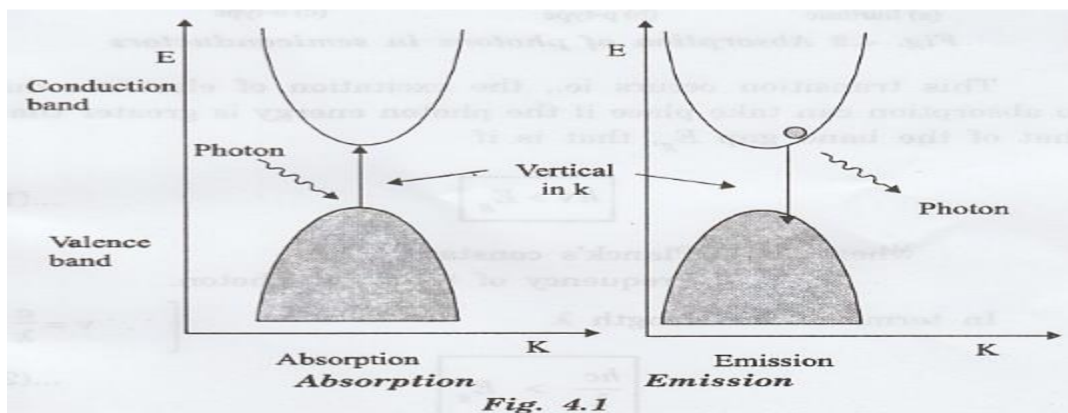


Fig. 4.1

These two processes are importance for light-detection and light-emission devices. The rate of the light-emission and absorption processes are determined by quantum mechanics.

4.4 Light detectors

For processing the light signal at the receiver end of the fibre link we require a device to convert the light signals to electrical wave forms. This task is done by the photo-detectors.

Definition

It is a device which converts light signal into electrical wave forms.

Types of photo-detectors

Photo-detectors are of three types:

- **Photo emissive detectors:** The emission of electrons from a photo cathode by the incident photon is called photo-emission.

- **Photo conductive detectors:** These types of devices have variation of resistance due to incident light on the photo-conductive materials.
- **Photo voltaic detectors:** Semiconductor junction photo diodes are called as photo-voltaic devices

4.4.1 Photo detector

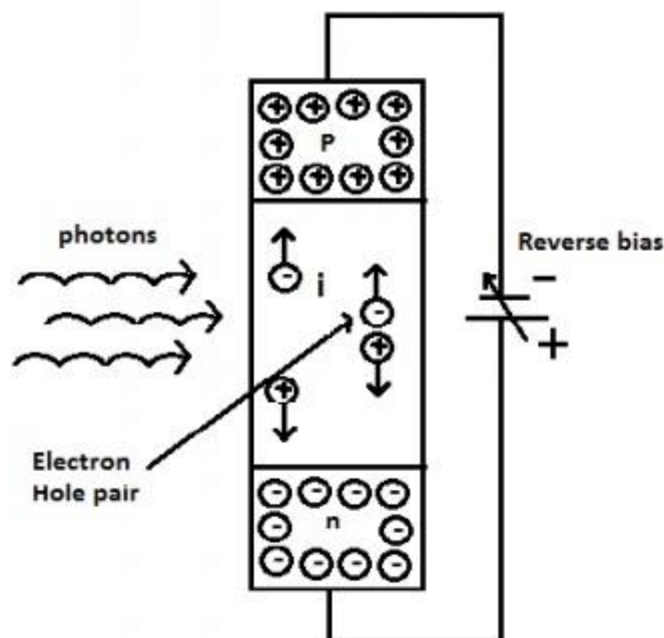
Principle:

This is a device used to convert the light energy into electrical energy. Under the reverse bias condition, if the light ray is incident over the intrinsic region, then it will produce the electron hole pair.

The accelerated electron-hole pair charges carrier produces the photo-current.

Construction:

It consists of three layers such as p, n and intrinsic region with proper biasing. The P and N region are heavily doped. The intrinsic layer is slightly larger than both the p-type and n-type for receive the light photons.



Working:

The PIN diode is heavily reverse biased. When a photon of higher energy is incident over the larger width intrinsic semiconductor layer, then the electron hole pairs are created. The mobile charges are accelerated by the applied voltage, which gives rise to photo current in the external circuit. It is a linear device because the photo-current is directly proportional to the incident optical power on the PIN photo-diode.

Advantages of Photodiodes

1. The reverse current is low in the tens of microamperes.
2. The rise and fall times in case of photodiodes is very small making it suitable for high-speed counting and switching applications.

Disadvantages of Photodiodes

Photodiodes have lower light sensitivity than cadmium sulphide LDRs (Light dependent resistors), thus they CdS LDRs are considered more suitable for some applications.

Applications of Photodiodes

1. It is used for detection of both visible as well as invisible light rays.
2. Photodiodes are used for the communication system for encoding & demodulation purpose.
3. It is also used for digital and logic circuits which require fast switching and high-speed operation.
4. These diodes also find application in character recognition techniques and IR remote control circuits.

4.4.2 Solar cell

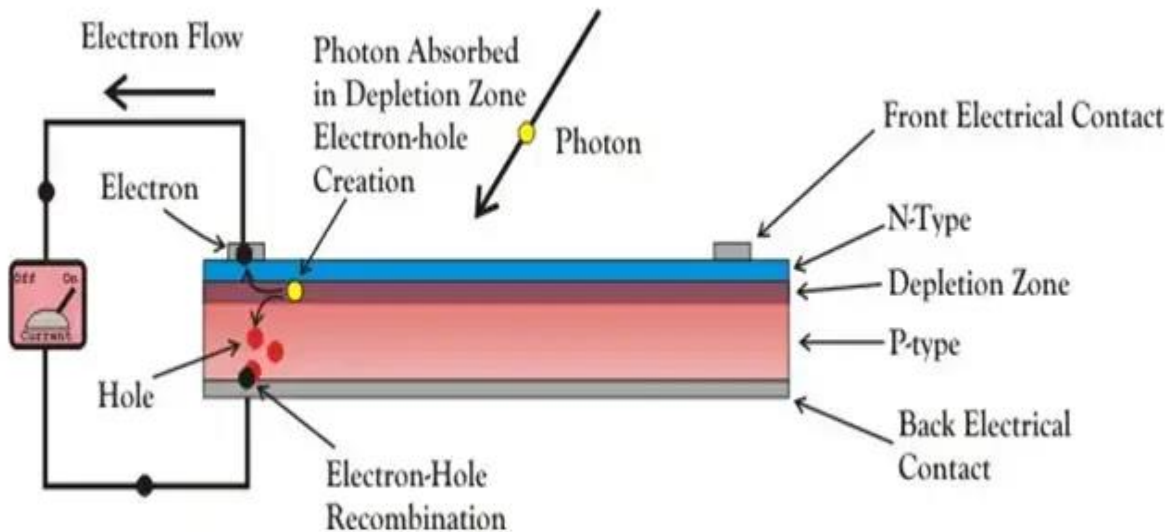
A **solar cell** (also known as a photovoltaic cell or PV cell) is defined as an electrical device that converts light energy into electrical energy through the photovoltaic effect. A solar cell is basically a p-n junction diode. Solar cells are a form of photoelectric cell, defined as a device whose electrical characteristics – such as current, voltage, or resistance – vary when exposed to light.

Individual solar cells can be combined to form modules commonly known as solar panels. The common single junction silicon solar cell can produce a maximum open-circuit voltage of approximately 0.5 to 0.6 volts. By itself this isn't much – but remember these solar cells are tiny. When combined into a large solar panel, considerable amounts of renewable energy can be generated.

Construction of Solar Cell

A solar cell is basically a junction diode, although its construction it is little bit different from conventional p-n junction diodes. A very thin layer of p-type semiconductor is grown on a relatively thicker n-type semiconductor. We then apply a few finer electrodes on the top of the p-type semiconductor layer

These electrodes do not obstruct light to reach the thin p-type layer. Just below the p-type layer there is a p-n junction. We also provide a current collecting electrode at the bottom of the n-type layer. We encapsulate the entire assembly by thin glass to protect the **solar cell** from any mechanical shock.



Working Principle of Solar Cell

When light reaches the p-n junction, the light photons can easily enter in the junction, through very thin p-type layer. The light energy, in the form of photons, supplies sufficient energy to the junction to create a number of electron-hole pairs. The incident light breaks the thermal equilibrium condition of the junction. The free electrons in the depletion region can quickly come to the n-type side of the junction.

Similarly, the holes in the depletion can quickly come to the p-type side of the junction. Once, the newly created free electrons come to the n-type side, cannot further cross the junction because of barrier potential of the junction.

Similarly, the newly created holes once come to the p-type side cannot further cross the junction became of same barrier potential of the junction. As the concentration of electrons becomes higher in one side, i.e. n-type side of the junction and concentration of holes becomes more in another side, i.e. the p-type side of the junction, the p-n junction will behave like a small battery cell. A voltage is set up which is known as photo voltage. If we connect a small load across the junction, there will be a tiny current flowing through it.

Advantages of Solar Cell

1. No pollution associated with it.
2. It must last for a long time.
3. No maintenance cost.

Disadvantages of Solar Cell

1. It has high cost of installation.
2. It has low efficiency.

3. During cloudy day, the energy cannot be produced and also at night we will not get solar energy.

Uses of Solar Generation Systems

1. It may be used to charge batteries.
2. Used in light meters.
3. It is used to power calculators and wrist watches.
4. It can be used in spacecraft to provide electrical energy.

4.4.3 Light Emitting Diode (LED)

It is a semiconductor p-n junction diode which emits light when it is forward biased.

Principle:

The electrons injected into the p- region make a direct downward transition from the conduction band into valence band and they recombine with holes and emit photons of energy Eg. We know that the forbidden gap energy is given by

$$E_g = h\nu \longrightarrow (1)$$

Where h = Planck's constant

ν = frequency of the emitted radiation

But we know $\nu = \frac{c}{\lambda} \longrightarrow (2)$

Substituting (2) in (1)

$$E_g = \frac{hc}{\lambda}$$

Hence, the wavelength of the emitted photon is given by relation

$$\lambda = \frac{hc}{E_g}$$

Therefore, the wavelength of the light emitted purely depends on the band gap energy.

Construction:

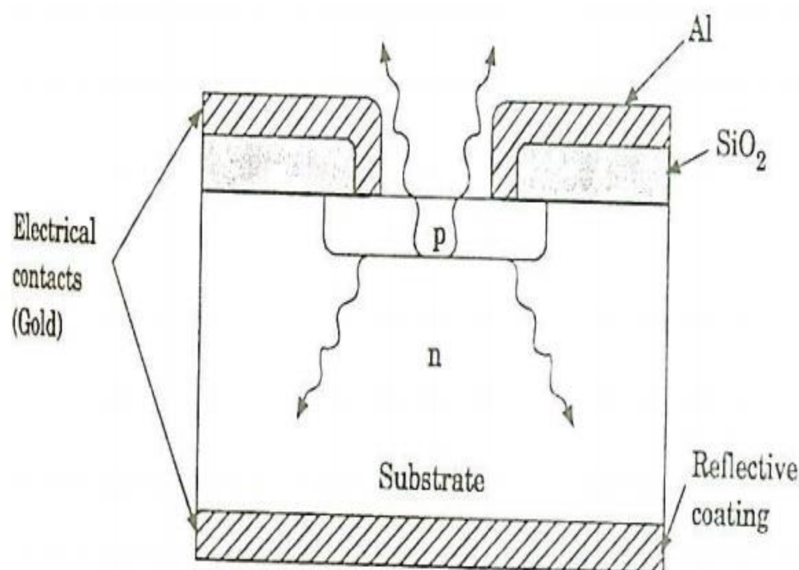


Figure shows cross sectional view of a LED.

A n- type layer is grown on a substrate and a p- type layer is deposited on it by diffusion. Since carrier recombination takes place in the p-layer, it is deposited upper most.

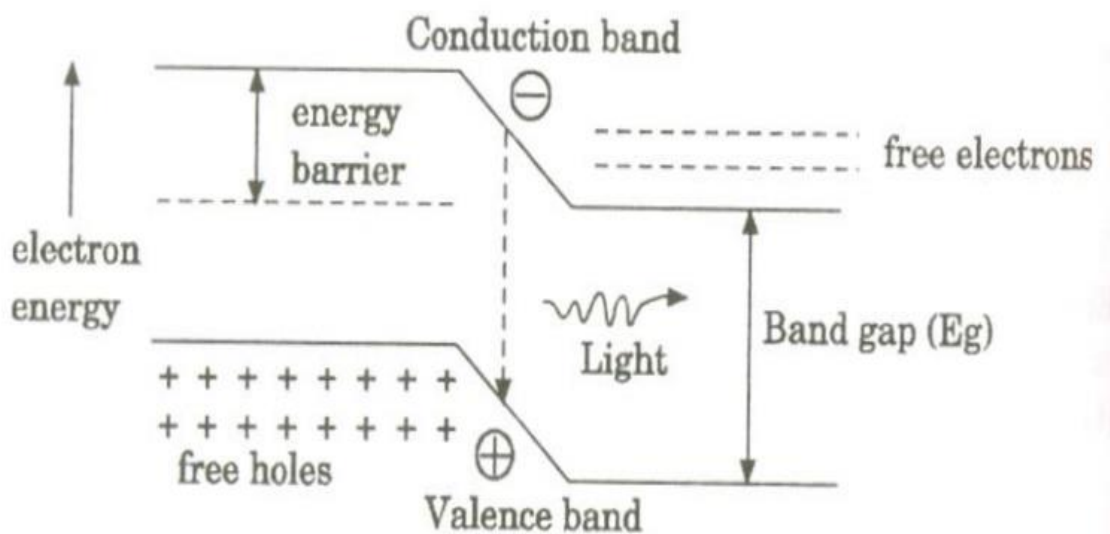
For maximum light emission, a metal film anode is deposited at the outer edges of the p-layer. The bottom of the substrate is coated with metal (gold) film for reflecting most of the light surface of the device and also to provide connection with n- type layer.

Working:

When the p –n junction diode is forward biased, the barrier width is reduced, raising the potential energy on the n-side and lowering that on the p-side.

The free electrons and holes have sufficient energy to move into the junction region. If a free electron meets a hole, it recombines with each other resulting in the release of a photon

Thus, light radiation of the LED is caused by the recombination of holes and electrons that are injected into the junction by forward bias voltage.



Advantages of LED:

- Light output is proportional to the current. Hence, the light intensity of LEDs can be controlled easily by varying the current flow.
- LEDs are rugged and therefore withstand shocks and vibrations.
- Varieties of LEDs are available which emit in different colours like red, green, yellow etc.
- It has long life time and high degree of reliability.
- It has low drive voltage and low noise.
- It is easily interfaced to digital logic circuits
- It can be operated over a wide range of temperatures.

Disadvantages of LED:

- 1. It requires high power.
- 2. Its preparation cost is high.

- 3. LED is not suitable for large area display because of its high cost.
- 4. It cannot be used for illumination purposes.

4.4.4 Semiconductor Laser diodes

Definition:

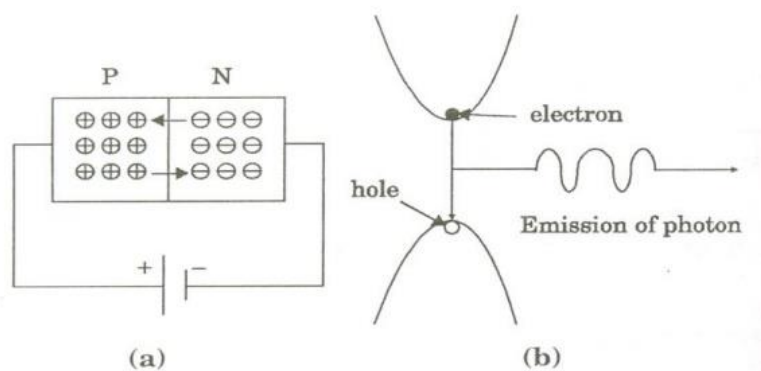
It is specifically fabricated p-n junction diode. This diode emits laser light when it is forward biased.

Principle:

When a p-n junction diode is forward biased, the electrons from n – region and the holes from the p- region cross the junction and recombine with each other.

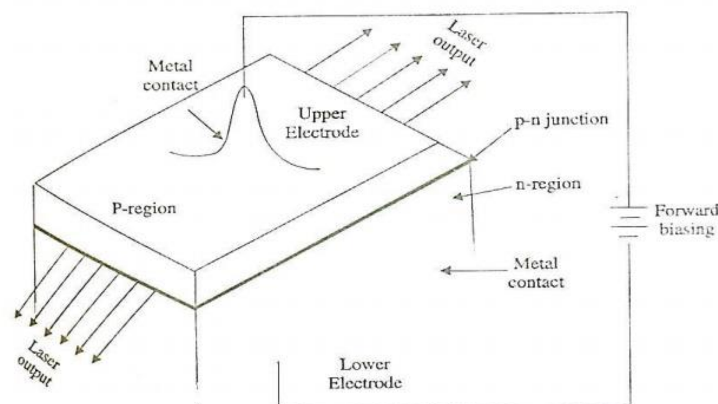
During the recombination process, the light radiation (photons) is released from a certain specified direct band gap semiconductor like Ga-As. This light radiation is known as recombination radiation.

The photon emitted during recombination stimulates other electrons and holes to recombine. As a result, stimulated emission takes place which produces laser.



Construction:

Figure shows the basic construction of semiconductor laser. The active medium is a p-n junction diode made from the single crystal of gallium arsenide. This crystal is cut in the form of a platter having thickness of 0.5μmm.



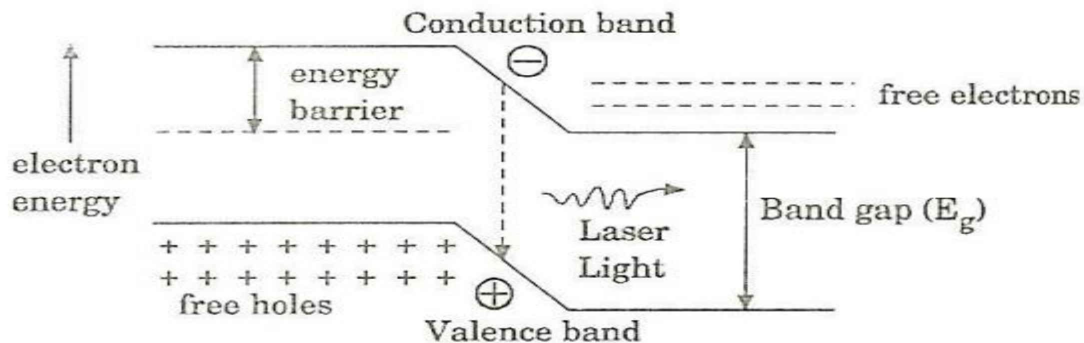
The platelet consists of two parts having an electron conductivity (n-type) and hole conductivity (p-type).

The photon emission is stimulated in a very thin layer of PN junction (in order of few microns). The electrical voltage is applied to the crystal through the electrode fixed on the upper surface.

The end faces of the junction diode are well polished and parallel to each other. They act as an optical resonator through which the emitted light comes out.

Working:

Figure shows the energy level diagram of semiconductor laser.



When the PN junction is forward biased with large applied voltage, the electrons and holes are injected into junction region in considerable concentration

The region around the junction contains a large number of electrons in the conduction band and a large number of holes in the valence band.

If the population density is high, a condition of population inversion is achieved. The electrons and holes recombine with each other and this recombination's produce radiation in the form of light.

When the forward – biased voltage is increased, more and more light photons are emitted and the light production instantly becomes stronger. These photons will trigger a chain of stimulated recombination resulting in the release of photons in phase.

The photons moving at the plane of the junction travels back and forth by reflection between two sides placed parallel and opposite to each other and grow in strength.

After gaining enough strength, it gives out the laser beam of wavelength 8400o A . The wavelength of laser light is given by

$$E_g = h\nu = h\frac{c}{\lambda}$$

$$\lambda = \frac{hc}{E_g}$$

Where E_g is the band gap energy in joule.

Advantages:

1. It is very small in dimension. The arrangement is simple and compact.
2. It exhibits high efficiency.
3. The laser output can be easily increased by controlling the junction current
4. It is operated with lesser power than ruby and CO2 laser.
5. It requires very little auxiliary equipment
6. It can have a continuous wave output or pulsed output.

Disadvantages:

1. It is difficult to control the mode pattern and mode structure of laser.
2. The output is usually from 5 degree to 15 degree i.e., laser beam has large divergence.
3. The purity and monochromacity are power than other types of laser
4. Threshold current density is very large (400A/mm2).
5. It has poor coherence and poor stability.

Application:

1. It is widely used in fiber optic communication
2. It is used to heal the wounds by infrared radiation
3. It is also used as a pain killer
4. It is used in laser printers and CD writing and reading.

4.4.5 Optical Process in Organic Semiconductor Device or Organic Light Emitting Diode (OLED)

Organic Light Emitting Diode, shortly called as OLED is new type of electronic device which emits light, consuming very less energy. It overcome the drawback of LCD, in which we suffer from poor viewing angle.

Organic LEDs are generally made up of many layers with organic molecules of different conductivity levels, ranging from insulators to conductors.

Principle

An electron moves from the cathode to the emissive layer and the hole moves from the anode to the conductive layer and they recombine to produce photons. This is the principle used to emit light in OLED.

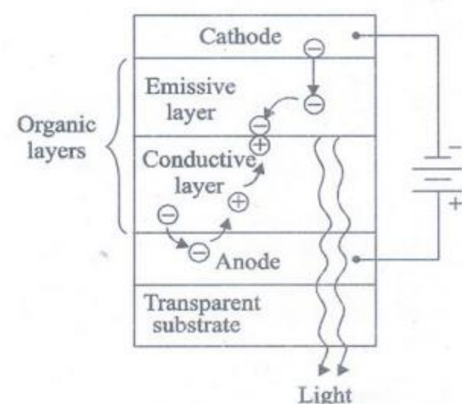


Fig. 4.24

Fabrication

The 2-layer OLED consists of a cathode and an anode, in between which we have two organic layers viz.

1. Emissive layer

2. Conductive layer, made up of different conductivities.

All the layers are grown over a transparent substrate, through which the light has to be emitted.

Necessary biasing is given for the OLED, in such a way that the anode is given positive and the cathode is given negative as shown in Fig. 4. 24.

Working

1. Voltage is applied across the OLED.
2. Due to the applied voltage, the cathode gives electrons to the emissive layer.
3. The anode withdraws an electron from the conductive layer and creates a hole in the conductive layer as shown in Fig. 4.24.
4. In other words, we can say that the anode gives electron-hole i.e., polarons [A quasiparticle - A positive (or) negative ion slightly attracted to a negatively (or) positively charged carriers respectively].
5. Soon, the emissive layer becomes rich in negatively charged particles [Electrons] and the conductive layer becomes rich is positively charged particles [holes].
6. Now, due to the electrostatic forces between these electrons and holes, They come closer and recombine with each other.
7. In OLED, the recombination occurs closer to the emissive layer, because in organic semiconductors, holes move faster than electrons.
8. Thus, the recombination of electrons and holes produces light and is emitted through the transparent substrate as shown in Fig. 4.24.

Advantages

1. OLED is very thin, and more flexible.
2. They are light in weight.
3. Light emission is brighter than normal LED's.
4. The conductive and emissive layers can be increased to increase the efficiency of OLED.
5. OLED's do not require backlighting like LCD's.
6. They have large field of view [About 170°]

Disadvantages

1. Cost of manufacturing is very high.
2. OLED's can be easily damaged when water falls on it.
3. Blue OLED have less life time, when compared to Red OLED.
4. Maintenance cost also increases due to different life time.

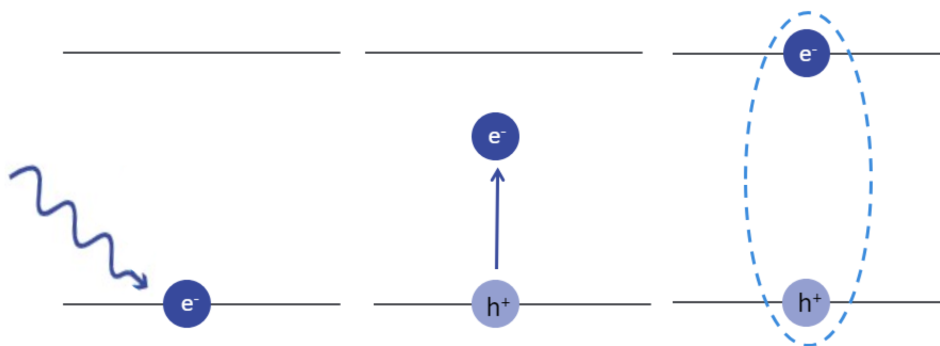
Applications

1. OLED's are widely used in cell phones, digital cameras etc.
2. They are also used in TV screens, computer monitors.

3. They are nowadays used in Automotive dash boards & backlight in cars.
4. OLEDs are used in flexible display boards, for displaying video's in real time.
5. In future, newspapers also may have OLED displays to refresh us with the latest or breaking news.

4.5 Excitonic state

Excitons are quasi-particles made up of bound electron and hole pairs. Having a clear understanding of exciton theory is essential to comprehend the behaviour of semiconductor materials. Excitonic properties will often determine the potential application of a material in optoelectronic devices, for example as photovoltaics, light-emitting diodes or even as lasers.



When an electron is excited into a higher energy state, either through absorption of a photon or another excitation method (such as in electroluminescence), this creates a positively charged space in the lower energy level known as a "hole." This results in the formation of an electron-hole pair. In some cases, these two particles exist in a bound state, forming a single quasi-particle known as an exciton. Within an exciton, the electron and hole are bound together by Coulombic interactions, and the strength of this bond is quantified by its exciton binding energy.

4.6 Electro-Optics and Non-Linear Optics

Usually light waves or photons transmitted through a fiber have little interaction with each other, and are not changed by their passage through the fiber (except for absorption and scattering). There are exceptions, however, arising from the interactions between light waves and the material transmitting them, which can affect optical signals. These processes are normally referred to as nonlinear effects or phenomena because their strength typically depends on the square (or some higher power) of the optical intensity. Hence nonlinear effects are weak at low powers but they can become much stronger at high optical intensities. This situation can result either when the power is increased, or when it is concentrated in a small area such as the core of a single-mode optical fiber.

Although the nonlinear effects in optical fibers are small, they accumulate as light passes through many kilometres of single-mode fiber. The small core diameters, together with the long transmission distances that may be obtained with these fibers, have enabled the occurrence of nonlinear phenomena at power levels of a few milliwatts which are well within the capability of semiconductor lasers. Furthermore, the optical power levels become much larger when wavelength division multiplexing packs many signal channels into one single-mode fiber such that the overall power level is the summation of the individual channel optical powers.

4.7 Optical modulator

Optical modulator, used to control the intensity of light, classification of electro-optic, thermo optic, acousto-optic, all optical, basic theory of electro-optic effect. Optical modulator is one of the most important integrated optical devices in high-speed and short-range optical communication. Light modulator according to its modulation principle, can be divided into electro-optic, thermo optic, acousto-optic, all optical, etc., they are based on the basic theory is a variety of different forms of electro-optic effect, acousto-optic effect, magneto optic effect, Franz-Keldysh effect, quantum well Stark effect, carrier dispersion effect.

The electro-optical modulator is a device that regulates the refractive index, absorptivity, amplitude or phase of the output light through the change of voltage or electric field. It is superior to other types of modulators in terms of loss, power consumption, speed and integration, and is also the most widely used modulator at present. In the process of optical transmission, transmission and reception, the optical modulator is used to control the intensity of light, and its role is very important.

The purpose of light modulation is to transform the desired signal or the transmitted information, including "eliminating background signal, eliminating noise, and anti-interference", so as to make it easy to process, transmit and detect.

Modulation types can be divided into two broad categories depending on where the information is loaded onto the light wave:

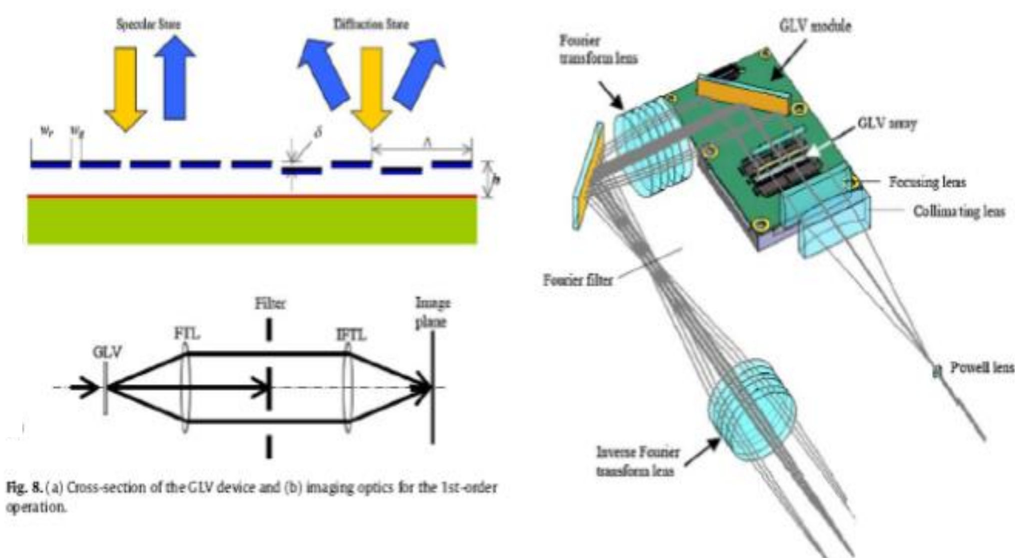


Fig. 8. (a) Cross-section of the GLV device and (b) imaging optics for the 1st-order operation.

One is the driving power of the light source modulated by the electric signal; The other is to modulate the broadcast directly.

The former is mainly used for optical communication, and the latter is mainly used for optical sensing. For short: internal modulation and external modulation.

According to the modulation method, the modulation type is:

1) Intensity modulation;
2) Phase modulation;
3) Polarization modulation;
4) Frequency and wavelength modulation.

Intensity modulation

Light intensity modulation is the intensity of light as the modulation object, the use of external factors to measure the DC or slow change of the light signal into a faster frequency change of the light signal, so that the AC frequency selection amplifier can be used to amplify, and then the amount to be measured out continuously.

Phase modulation

The principle of using external factors to change the phase of light waves and measuring physical quantities by detecting phase changes is called optical phase modulation.

The phase of the light wave is determined by the physical length of the light propagation, the refractive index of the propagation medium and its distribution, that is to say, the change of the phase of the light wave can be generated by changing the above parameters to achieve phase modulation.

Polarization modulation

The simplest way to achieve light modulation is to rotate two polarizers relative to each other. According to Malus' theorem, the output light intensity is $I=I_0\cos 2\alpha$

Where: I_0 represents the light intensity passed by the two polarizers when the principal plane is consistent; Alpha represents the Angle between the two polarizers' principal planes.

Frequency and wavelength modulation

The principle of using external factors to change the frequency or wavelength of light and measuring external physical quantities by detecting changes in the frequency or wavelength of light is called frequency and wavelength modulation of light.

4.8 Opto Electric switch

Optical switches, a key component in modern network infrastructure, are devices used in optical fiber networks for signal management. Unlike traditional electrical switches, which transmit data as electrical signals, optical switches handle data transmission in the form of light.

They essentially work by converting the incoming light signals into electrical signals, processing them, and then converting them back into light signals. This conversion process is known as O-E-O (Optical-Electrical-Optical).

Working

At their core, optical switches work on the principle of controlling light signals. They employ various techniques to manipulate these signals. One such method involves using tiny mirrors or prisms that can be mechanically controlled to direct the light signals. In other methods, changes in the properties of the optical medium itself are used to control the light path.

The advantages of optical switches are manifold:

1. **High Speed:** Optical switches provide a high-speed data transmission capacity that surpasses that of traditional electrical switches.
2. **Interference Resistance:** They are immune to electromagnetic interference, ensuring a reliable data transfer.
3. **Low Power Consumption:** With no need for O-E-O conversion, all-optical switches consume significantly less power.

4.9 Plasmonics

Plasmonics (or nanoplasmonics) is a young topic of research, which is part of nanophotonics and nano-optics. Plasmonics concerns to the investigation of electron oscillations in metallic nanostructures and nanoparticles (NPs). Surface plasmons have optical properties, which are very interesting. For instance, surface plasmons have the unique capacity to confine light at the nanoscale. Moreover, surface plasmons are very sensitive to the surrounding medium and the properties of the materials on which they propagate. In addition to the above, the surface plasmon resonances can be controlled by adjusting the size, shape, periodicity, and materials nature. Indeed, the technological progress allows researchers to produce new plasmonic systems by controlling all the parameters described previously. Moreover, theoretical, computational, and numerical simulation tools have been developed in this last decade, allowing for a better understanding of the optical properties of plasmonic systems. Thus, all these optical properties of plasmonic systems can enable a great number of applications, such as biosensors, optical devices, and photovoltaic devices

4.10 Applications of opto-electronic devices

1. LEDs could become the next generation of lighting and used anywhere like in indication lights, computer components, medical devices, watches, instrument panels, switches, fiber-optic communication, consumer electronics, household appliances, traffic signals, automobile brake lights, 7 segment displays and inactive displays, and also used in different electronic and electrical engineering projects.

2. The solar cells are applicable in rural electrification, telecommunication systems, ocean navigation aids, and electric power generation in space and remote monitoring and control systems and also used in different solar energy based projects.
3. Photodiodes are used in many types of circuits and different applications such as cameras, medical instruments, safety equipments, industries, communication devices and industrial equipments.
4. Optical fibers are used in telecommunications, sensors, fiber lasers, bio-medicals and in many other industries.
5. The laser diodes are used in fiber optic communication, optical memories, military applications, CD players, surgical procedures, Local Area Networks, long distance communications, optical memories, fiber optic communications and in electrical projects such as RF Controlled Robotic Vehicle with Laser Beam Arrangement and so on.

UNIT V DIELECTRIC MATERIALS

5.1 INTRODUCTION

The word 'Dielectric' comes from the Greek prefix 'di' or 'die' meaning 'across'. Dielectrics are the insulating materials having electric dipole moment permanently or temporarily by applying the electric field. These are mainly used to store electrical energy and used as electrical insulators. All dielectrics are electrical insulators, but all electrical insulators need not to be dielectrics.

Vacuum, Solids, Liquids and Gases can be a dielectric material. Some of the examples of solid dielectric materials are ceramics, paper, mica, glass etc. Liquid dielectric materials are distilled water, transformer oil etc. Gas dielectrics are nitrogen, dry air, helium, oxides of various metals etc. Perfect vacuum is also a dielectric.

Dielectric materials can be used in capacitors for energy storage. It is used in photosensitive materials for charge storage in laser printers and copying machines. It is used for mechanical actuation, sound generation, piezoelectricity, cap sense etc.

Dielectrics are non - metallic materials of high specific resistance and have negative temperature coefficient of resistance.

5.2 PROPERTIES OF DIELECTRICS

- Its energy band gap value lies between 3 eV to 6eV
- They have negative temperature coefficient of resistance
- They are all amorphous solid
- The bounding of the electrons with the nucleus is very high.
- It could not conduct electricity
- Dielectric material is act as a good conductor when breakdown is occurs
- It shows Piezo, pyro and Ferro electric properties
- All the dielectrics are insulators, but all the insulators are not a dielectrics

5.3 BASIC DEFINITIONS

Electric dipole

A system consists of two equal and opposite charges which are separated by smallest distance d is called electric dipole.

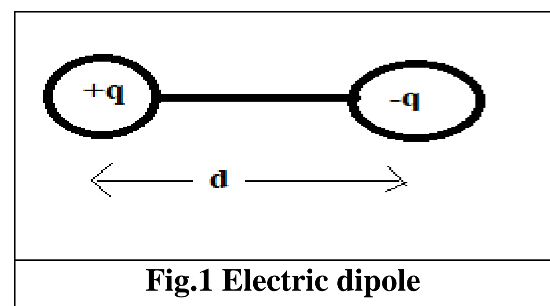


Fig.1 Electric dipole

Dipole moment (μ)

The product of magnitude of any charge and distance between two charges is called as dipole moment.

It is represented by the symbol μ.

μ=q.d

Unit: coloumb meter

Displacement vector ($\vec{D}$)

In electrostatics, we have two vectors namely displacement vector and electric field intensity vector. The electric field intensity vector depends upon the medium, but displacement vector independent to the medium. So,

$$\vec{E} = \frac{q}{4\pi\varepsilon r^2} \text{ --1}$$

$$\vec{D} = \frac{q}{4\pi r^2} \text{ --2}$$

Rearranging eqn.1

$$\varepsilon\vec{E} = \frac{q}{4\pi r^2} \text{ --3}$$

Comparing eqn. 2 and 3, we get

$$\vec{D} = \varepsilon\vec{E} \text{ ---4}$$

Polarization

Let us assume that a dielectric medium placed in between two metal plates also called as capacitor plate. When electrical energy is applied to the dielectric material, dipoles are created inside the dielectric material due to movement of charges. So, the process of producing dipoles inside the dielectric material in the presence of electric field is called as polarization.

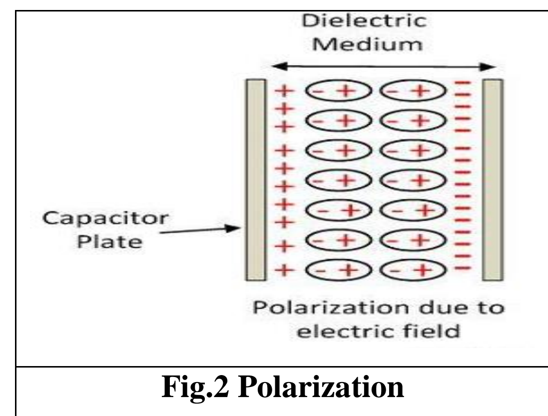


Fig.2 Polarization

Polarisability

We know, the dipole moment is directly proportional to applied electric field.

$$\mu \propto E$$

$$\mu = \alpha E$$

Where, α is a constant. It is called as polarisability.

The term polarizability is defined as dipole moment per unit electric field is applied.

$$\alpha = \frac{\mu}{E}$$

Polarization vector

It is defined as the product of number of atoms per unit volume and average dipole moment.

$$P = \frac{N}{V}\mu$$

Or $P = N\mu$ (V=1)

We know, $\mu = \alpha E$

$$P = N\alpha E$$

Permittivity (Ɛ)

It is defined as the product of permittivity of free space and relative permittivity.

$$\varepsilon = \varepsilon_0 \varepsilon_r$$

Relative Permittivity (ε_r)

It defined as the ratio between permittivity of any medium to the permittivity of free space.

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$

Electric susceptibility (χ_e)

We know the polarization is directly proportional to applied field E.

$$P \propto E$$

$$P = \varepsilon_0 \chi_e E$$

Or $$\chi_e = \frac{P}{\varepsilon_0 E}$$

Where, χ_e is called as electric susceptibility.

Relation between $\vec{P}$ and $\vec{D}$

We know, $\vec{D} = \varepsilon\vec{E}$ ---1

We know, $P = \varepsilon_0 \chi_e E$ ---2

We know $\varepsilon_r = 1 + \chi_e$ or $\chi_e = \varepsilon_r - 1$ ----------------------------3

Subs. Eqn. 3 in 2 we get

$$P = \varepsilon_0(\varepsilon_r - 1)E$$

Or $$P = \varepsilon_0 \varepsilon_r E - \varepsilon_0 E$$

$$P = \varepsilon E - \varepsilon_0 E$$

$$\varepsilon E = P + \varepsilon_0 E \quad \text{-------------------------------------4}$$

Subs, eqn. 4 in 1 we get

$$D = P + \varepsilon_0 E \quad \text{---5}$$

Equation 5 gives the relation between P and D.

Relation between $\vec{P}$ and χ_e

We know, $P \propto E$

$$P = \varepsilon_0 \chi_e E$$

Or $$\chi_e = \frac{P}{\varepsilon_0 E} \text{ ---------------------------------1}$$

But, $\varepsilon_r = 1 + \chi_e$ or $\chi_e = \varepsilon_r - 1$ ----------------------------------2

Comparing eqn. 1 and 2

$$\varepsilon_r - 1 = \frac{P}{\varepsilon_0 E}$$

Or $$\varepsilon_0 E(\varepsilon_r - 1) = P \text{ -----------------------3}$$

Equation 3 gives the relation between $\vec{P}$ and χ_e.

Polar molecules

Polar Molecules which are having permanent dipole moment even in the absence of an applied field are called polar molecules.

Example: H_2O, HCl, CO_2

Non Polar molecules

Molecules which do not have permanent dipole moment, but they have induced dipole moment in the presence of applied electric field are called non - polar molecules.

Example: O_2, H_2, N_2

COMPARISION BETWEEN POLAR AND NON-POLAR MOLECULES

BASIS OF COMPARISON	POLAR MOLECULES	NON-POLAR MOLECULES
Shape	Polar molecules are asymmetrical in shape.	The Nonpolar molecules are symmetrical in shape.
Electric poles	The polar molecules have electrical poles.	The Nonpolar molecules do not have electrical poles.
Poles	In polar molecules, one end of the molecule is positive while there is a negative charge on the other end.	There is no profusion of charges on opposite ends of non-polar molecules.
Bonds	Hydrogen bonds occur in polar molecules.	The Van Waal interactions amongst the Nonpolar bonds.
Nonpolar Covalent	Minimum one polar covalent in polar bonds is present in all polar molecules.	There is no Nonpolar covalent in all Nonpolar molecules.
Charge Separation	The polar bond has charge separation.	There is no charge separation in the non-polar molecules.

Dipole moment	Has dipole moment.	Has no dipole moment.
Surface Tension, Boiling and Melting Point	It has high surface tension, melting point & boiling point.	It has low surface tension, melting and boiling point.
Interaction with Other Molecules	It interacts with other polar molecules.	It does not interact with other Nonpolar molecules.
Examples	Water, ammonia and ethanol	Oil, benzene, methane.

5.4 TYPES OF POLARIZATION

There are four different types of polarization.

- Electronic (or) induced polarization
- Ionic (or) atomic polarization
- Orientation (or) dipolar polarization
- Space - Charge (or) interfacial polarization

5.4.1 Electronic (or) induced polarization

Definition

Electronic Polarization occurs due to the displacement of positively charged nucleus and negatively charged electron in opposite directions by an external electric field. It creates a dipole moment in the dielectric.

This type of polarization occurs in all materials.

Induced dipole moment $\mu = \alpha_e E$ -------------------------------1

Derivation

a. Without field

An atom consists of positively charged nucleus with charge (+Ze) surrounded by negatively charged by electron with charge (-Ze). Let R be the radius of the atom.

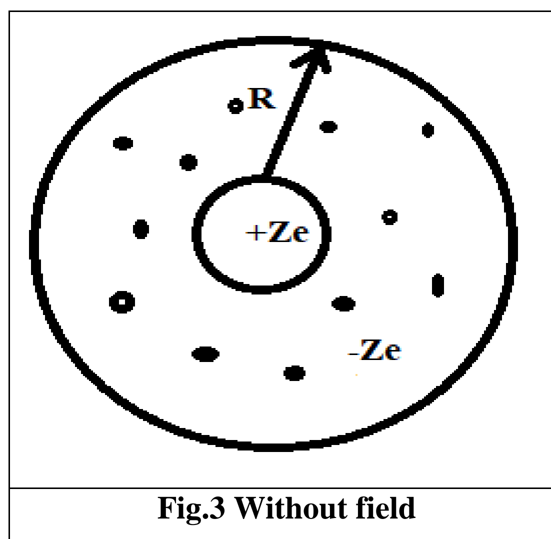


Fig.3 Without field

Density of electron with in the sphere of radius R, $= \frac{\text{Total negative charge}}{\text{Volume}}$

$$= \frac{-Ze}{\frac{4}{3}\pi R^3}$$

$$= \frac{-3Ze}{4\pi R^3} \text{ ---2}$$

b. With field

When electric field is applied to the dielectric material with the help of battery, positive and negative charges are displaced from their original position with radius "r" as shown in the figure.

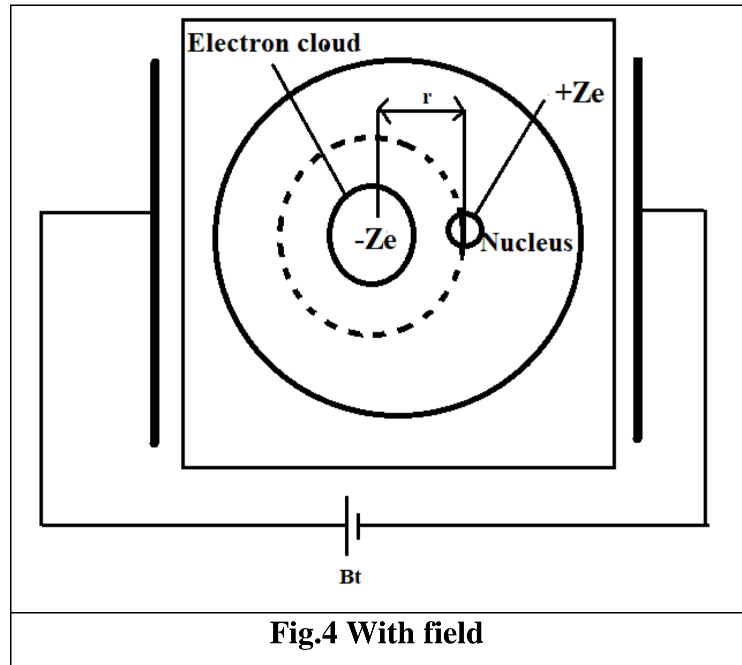


Fig.4 With field

When the atom of the dielectric is placed in an electric field (E), two types of forces are arises.

Lorentz force: Force which separates electrons and positive nucleus due to applied field.

Coulomb force: An attractive force which is produced after separation.

Lorentz repulsive force is given by,

$F_L = -Ze.E$ --3

Coulomb attraction force

$$F_C = \frac{\text{Total positive charge X Total negative charge within the sphere of radius 'r'}}{4\pi\varepsilon_0 r^2} \text{-----4}$$

Total negative charge within the sphere of radius

= density of electron X Volume of sphere of radius 'r

$$= \frac{-3Ze}{4\pi R^3} \text{ X } \frac{4}{3}\pi r^3$$

$$= \frac{-Zer^3}{R^3} \text{ -----------------------------5}$$

Subs. Eqn.5 in 4 we get,

$$F_C = \frac{+ZeX\frac{-Ze}{R^3}r^3}{4\pi\varepsilon_0 r^2}$$

$$F_C = \frac{-Z^2 e^2 r}{4\pi\varepsilon_0 R^3} \text{------------------------6}$$

At equilibrium condition, Lorentz force = Coulomb force

$$-Ze.E = \frac{-Z^2 e^2 r}{4\pi\varepsilon_0 R^3}$$

$$.E = \frac{Zer}{4\pi\varepsilon_0 R^3}$$

Rearranging, we get,

$$r = \frac{4\pi\varepsilon_0 R^3 E}{Ze} \text{----------------------7}$$

Eqn. 7 gives the distance between positive and negative charges. It is depends on radius of the atom.

We know, induced dipole moment = charge X displacement

$$\mu_e = Ze \text{ X } r \text{----------------------------8}$$

Subs. Eqn. 7 in 8

$$\mu_e = Ze.\frac{4\pi\varepsilon_0 R^3 E}{Ze}$$

Or

$$\mu_e = 4\pi\varepsilon_0 R^3 E \text{----------------------9}$$

Comparing eqn.1 & 9, we get

$$\alpha_e = 4\pi\varepsilon_0 R^3 \text{------------------------10}$$

Eqn. 10 represents electronic polarizability.

Conclusion:

- It is depending on radius of the atom
- It is temperature independent

5.4.2 Ionic (or) atomic polarization

Definition

It occurs due to the displacement of positive ions (cations) and negative ions (anions) in the opposite direction in the presence of electric field. It creates dipole moment in dielectric.

It occurs only in ionic crystals such as NaCl, KCl…. etc.

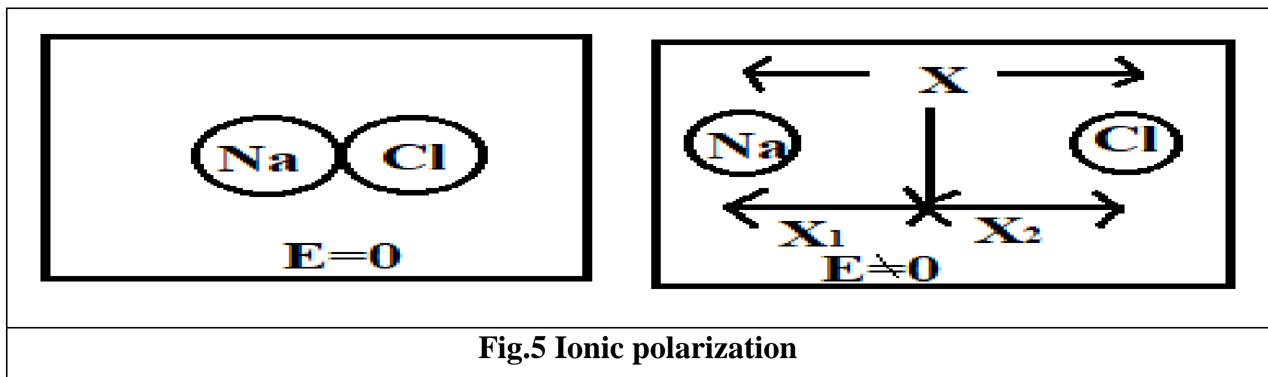


Fig.5 Ionic polarization

Induced dipole moment, $\mu = \alpha_i E$ --------------------------------1

Derivation:

Let us consider an ionic crystal say NaCl. It contains Na^+ and Cl^- ions.

When electric field E is applied to the ionic crystal, ions are displaced from their equilibrium position.

Let X_1 and X_2 be the displacement of positive and negative ions respectively. The total displacement,

$$X=X_1+X_2 \text{--}2$$

The force experienced by the ion is directly proportional to its displacement.

For + ion, $F \infty X_1$

$$F = K_1 X_1 \text{---}3$$

For - ion, $F \infty X_2$

$$F = K_2 X_2 \text{--}4$$

Where, K_1 and K_2 are the elastic restoring constants. It is depending upon mass of the ion and angular frequency.

$$K_1 = M_1 \omega_0^2 \text{---}5$$

$$K_2 = M_2 \omega_0^2 \text{--}6$$

Where, M_1 & M_2 are the masses of positive and negative ion respectively.

Eqns. 3 & 4 can be written as,

$$F = M_1 \omega_0^2 X_1 \text{--------------------------------------}7$$

$$F = M_2 \omega_0^2 X_2 \text{-------------------------------------}8$$

When field is applied, the force experienced by the ion is given by

$$F = eE \text{---}9$$

Equating eqn. 7 & 9, we get,

$$eE = M_1 \omega_0^2 X_1$$

$$X_1 = \frac{eE}{M_1\omega_0^2} \text{ ------------------------------------10}$$

Equating eqn. 8 & 9, we get,

$$eE = M_2\omega_0^2 X_2$$

$$X_2 = \frac{eE}{M_2\omega_0^2} \text{ ------------------------------------11}$$

Subs. 10 & 11 in eqn, 2

Displacement, $X = X_1 + X_2$

$$X = \frac{eE}{M_1\omega_0^2} + \frac{eE}{M_2\omega_0^2}$$

$$X = \frac{eE}{\omega_0^2}\left(\frac{1}{M_1} + \frac{1}{M_2}\right) \text{-----------------------12}$$

We know, dipole moment = charge X displacement

$$\mu = e.X \text{ --13}$$

Subs eqn. 12 in 13

$$\mu = e.\frac{eE}{\omega_0^2}\left(\frac{1}{M_1} + \frac{1}{M_2}\right)$$

$$\mu = \frac{e^2E}{\omega_0^2}\left(\frac{1}{M_1} + \frac{1}{M_2}\right) \text{---------------------14}$$

Comparing, eqn. 1 & 14, we get,

$$\alpha_i = \frac{e^2}{\omega_0^2}\left(\frac{1}{M_1} + \frac{1}{M_2}\right) \text{---------------------15}$$

Equation 15 represents ionic polarizability.

Conclusion:

- Ionic polarisability is depends on square of angular frequency and mass of the ion.
- It is temperature independent.

5.4.3 Orientation (or) dipolar polarization

Definition:

When an electric field is applied on the dielectric medium with polar molecules, the electric field tries to align these dipoles along its field direction as shown in figure. Due to this there is a resultant dipole moment in that material and this process is called orientation polarization.

The orientation polarization is due to the existence of a permanent dipole moment (polar molecule) in the dielectric medium. Polar molecules have permanent dipole even in the absence of an electric field.

It occurs only in polar molecules.

Induced dipole moment, $\mu = \alpha_o E$ ---1

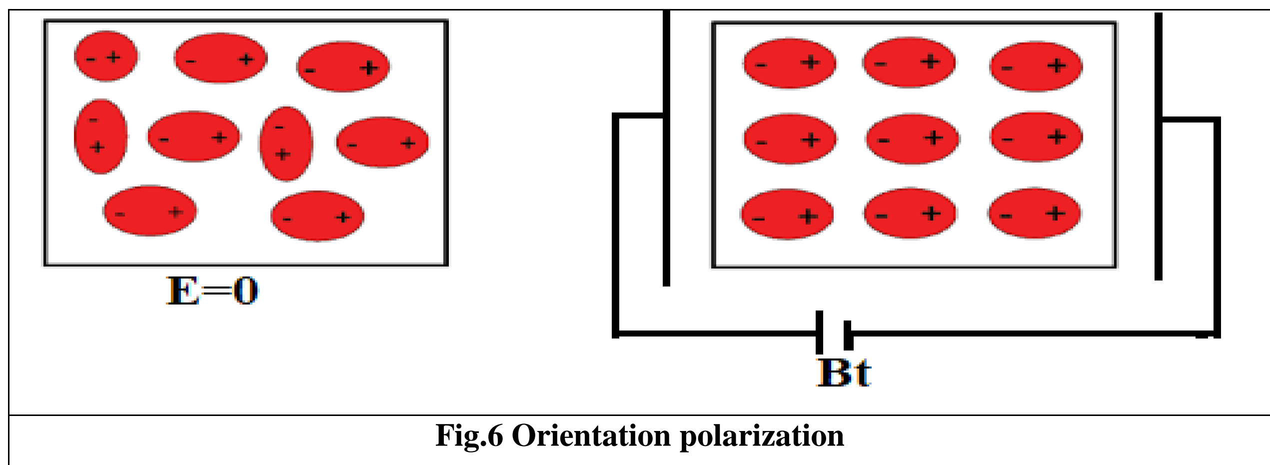


Fig.6 Orientation polarization

Derivation:

According to Langevin theory of paramagnetism, the intensity of magnetization is given by,

$$I = \frac{N\mu^2 B}{3KT}$$

Where, N be the number of molecules,

B be the applied magnetic field

K be the Boltzmann constant

T be the temperature

The polarization can be written as,

$$P = \frac{N\mu^2 E}{3KT} \text{--}2$$

We know, $P=N\alpha_i E$---3

Comparing eqn.2&3

$$\alpha_o = \frac{\mu^2}{3KT} \text{--4}$$

Equation 4 represents orientation polarization.

Conclusion:

- Orientation polarization change with temperature
- It is temperature dependent

5.4.4 Space-charge polarization or interfacial polarization

Definition

Interfacial or space charge polarization occurs when there is an accumulation of charge at an interface between two materials or between two regions within a material because of an external field.

This can occur when there is a compound dielectric, or when there are two electrodes connected to a dielectric material. This type of electric polarization is different from orientational and ionic polarization because instead of affecting bound positive and negative charges i.e. ionic and covalent bonded structures, interfacial polarization also affects free charges as well. As a result, interfacial polarization is usually observed in amorphous or polycrystalline solids. Figure 7 shows an example of how free charges can accumulate in a field, causing interfacial polarization. The electric field will cause a charge imbalance because of the dielectric material's insulating properties. However, the mobile charges in the dielectric will migrate over maintain charge neutrality. This then causes interfacial polarization.

It occurs in some semiconducting materials and ferrites.

The space charge polarization is very small. So, it is negligible (α_s=0)

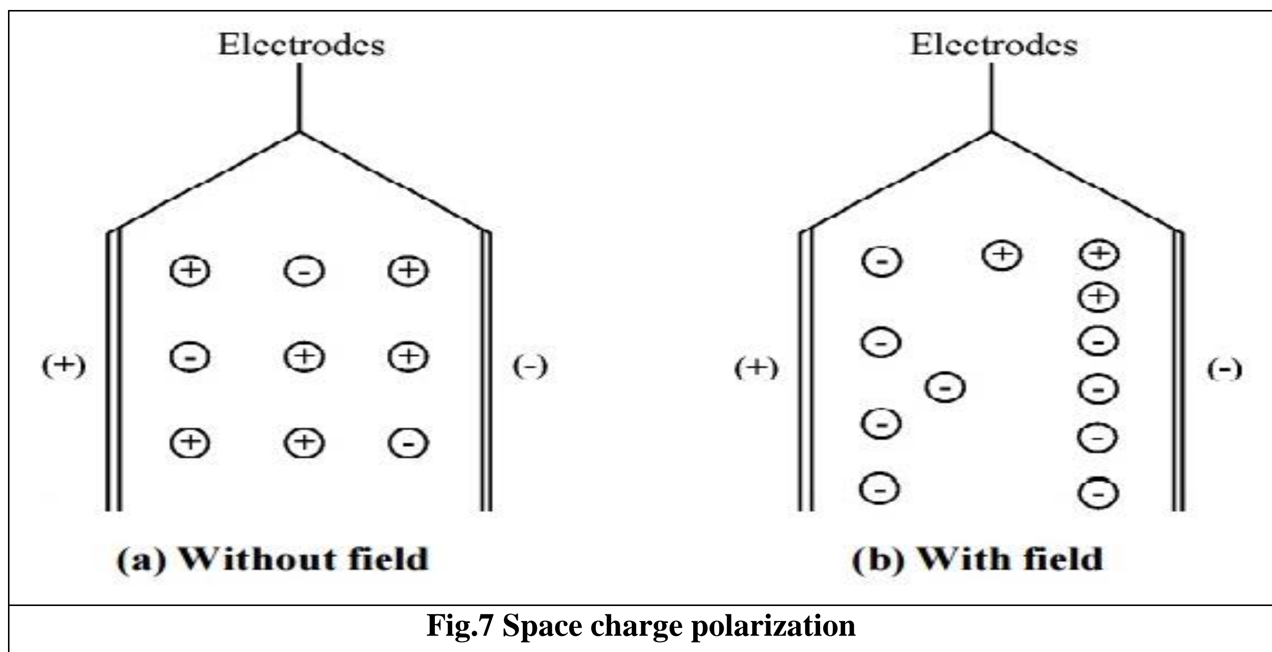


Fig.7 Space charge polarization

2.4.5 Total polarization

It can be calculated by summing the all four types of polarization.

$$P=P_e+P_i+P_o+P_s \text{ --1}$$

Polarizabilities are $\alpha = \alpha_e + \alpha_i + \alpha_o + \alpha_s$ ---------------------------------2

$\alpha_s = 0$

$$\alpha = \alpha_e + \alpha_i + \alpha_o \text{ ---------------------------------------3}$$

$$\alpha = 4\pi\varepsilon_o R^3 + \frac{e^2}{\omega_0^{\ 2}}\left(\frac{1}{M_1}+\frac{1}{M_2}\right)+\frac{\mu^2}{3KT} \text{ --------------4}$$

Polarization, P=NEα

$$P = NE\left[4\pi\varepsilon_0 R^3 + \frac{e^2}{\omega_0^2}\left(\frac{1}{M_1}+\frac{1}{M_2}\right)+\frac{\mu^2}{3KT}\right] \text{------5}$$

Equation 5 is called as 'Langevin-Debye equation.

3.5 FREQUENCY AND TEMPERATURE DEPENDENCE OF POLARIZATION

Frequency dependence

On application of an alternating field across the material, the polarization occurs as function of time

$$P(t) = P_m(1-\exp\left(\frac{-t}{t_r}\right))$$

Where, P_m is the maximum polarization attained due to applied field and t is the relaxation time. Which is the time taken for a polarization process to reach 0.63 of the maximum value. The relaxation times are different for different kinds of polarization mechanisms.

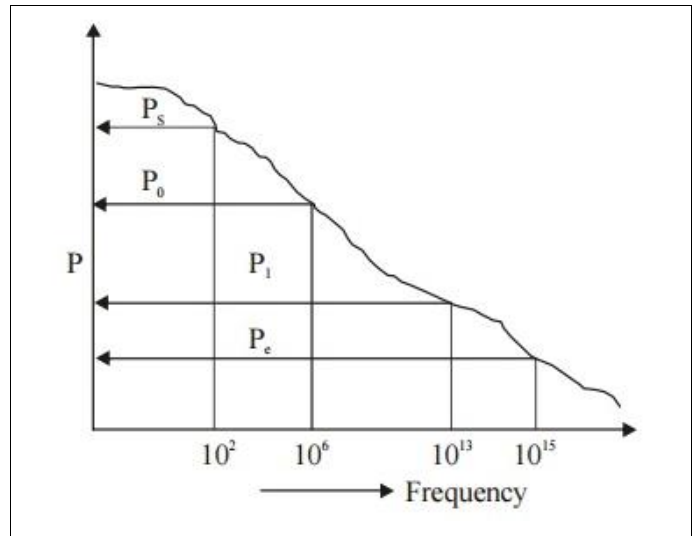


Fig.7 Frequency dependence of polarization

1. **Electronic polarization** is very fast and is completed at any instant of time even when the frequency of the voltage is very high in the optical range (10^{15} Hz). Thus, it occurs at all frequencies.
2. **Ionic Polarization** is slower and the ions do not respond when the voltage corresponds to visible optical frequencies, i.e., the electric field changes in polarity at very fast, so that the ions are not able to reorient themselves due up to the field. So the ionic polarization does not occur at visible optical frequencies. It occurs only at frequencies less than 10^{13} Hz.

3. **Orientation Polarization** is even slower than ionic polarization and occurs only at electrical frequencies (audio and radio frequencies 10^6 Hz).
4. **Space-charge polarization** is the slowest process because the ions have to diffuse (jump) over several inter atomic distances. This occurs at very low frequencies of 50 - 60 Hz (power frequencies).

Thus, at low frequencies all the four polarizations will occur and the total polarization is very high, but at high frequencies, the value of the total polarization is very small. The following graphs show the frequency dependence of polarization mechanism and the corresponding power losses at those frequencies.

Temperature dependence

Electronic and ionic polarizations are independent of temperature and the orientation and space charge polarizations are dependent of temperature. Orientation polarization is inversely proportional to the temperature.

Orientation polarization decreases when temperature increases. Because, the random nature decreases the tendency of permanent dipoles to align along the field direction. Thus the dielectric constant increases.

Space charge polarization is directly proportional to the temperature. The space charge polarization increases with increase the temperature. It is because of the fact that the thermal energy helps to overcome the activation barrier and the ions diffuse easily, this results in decrease of dielectric constant.

5.5 INTERNAL FIELD OR LORENTZ LOCAL FIELD

Definition

In dielectric solids, the atoms or molecules experience not only the external applied electric field but also the electric field produced by the dipoles. The resultant electric field acting on the atoms or molecules of dielectric substance is called the local field or an internal field.

To find an expression for local electric field on a dielectric molecule or an atom, we consider a dielectric material in the electric field of intensity *E*, between the capacitor plates so that the material is uniformly polarized, as a result opposite type of charges are induced on the surface of the dielectric near the capacitor plates. The local field is calculated by using the method suggested by Lorentz. It is represented by E_i.

$$E_i = E + \frac{P}{3\varepsilon_o}$$

Where, E be the applied field

P be the polarization

ε_o be the permittivity of free space

Derivation

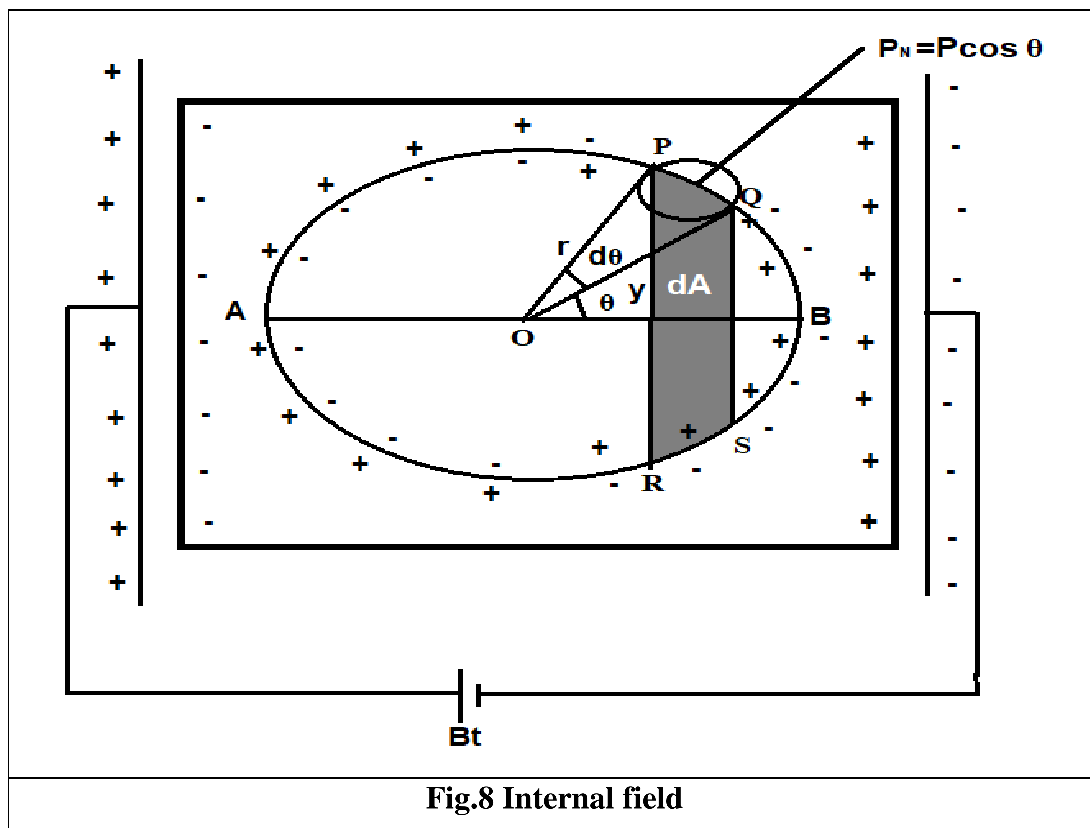


Fig.8 Internal field

The dielectric material which is placed in between two plates of a parallel plate capacitor is uniformly polarized as shown in Figure.8.

Let r be the radius of the spherical sphere considered. Y be the radius of small element taken. Let dA be the small area considered.

Let θ and dθ be the angle subtended.

Assume an imaginary small spherical cavity around an atom for which the internal field must be calculated at its centre.

The internal field E_i at the atom site (0) can be considered to consist of components namely E_1, E_2, E_3 and E_4.

$$E_i = E_1 + E_2 + E_3 + E_4 \text{--}1$$

Where, E_1 is the field due to charges over the metal plates

E_2 is the field due to charges inside the dielectric

E_3 is the field due to charges over spherical cavity considered

E_4 is the field due to charges inside the spherical cavity considered

Macroscopically, we can take $E = E_1 + E_2$ i.e., the field externally applied (E_1) and the field induced on the plane surface of the dielectric (E_2) can be considered as a single field (E).

If we consider the dielectric which is highly symmetric, then the field due to the dipoles present inside the imaginary cavity will cancel each other. Therefore, the electric field due to permanent dipoles E_4=0.

Eqn.1 becomes $E_i = E + E_3$ ---2

To find E_3

The normal component of polarization is given by,

$P_N = \frac{Charge}{Area} = P\cos\theta$

$P_N = P\cos\theta = \frac{q}{dA}$

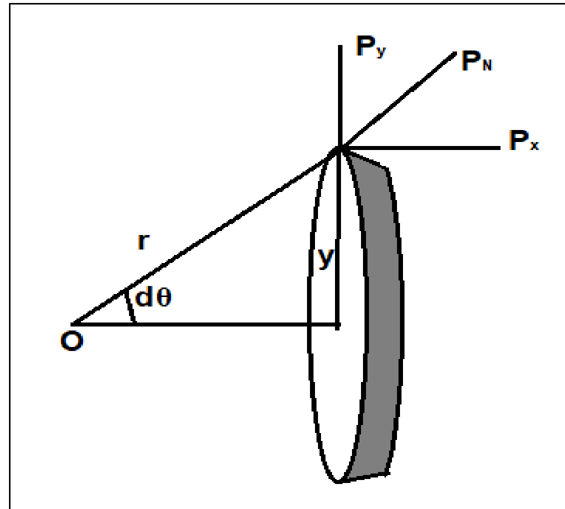


Fig.9 Internal field

Rearranging,

$$q = P\cos\theta dA \text{ -----------------------------3}$$

The electric field intensity can be written as,

$$E = \frac{q}{4\pi\varepsilon_O r^2}$$

Subs. Eqn. 3 in 4

$$E = \frac{P\cos\theta dA}{4\pi\varepsilon_O r^2} \text{ ----------------------------4}$$

The electric field intensity along x axis can be written as,

$$E_x = E\cos\theta \text{ ----------------------------5}$$

Subs. Eqn. 4 in 5

$$E_x = \frac{P\cos\theta dA}{4\pi\varepsilon_O r^2}.\cos\theta$$

$$E_x = \frac{P\cos\theta^2 dA}{4\pi\varepsilon_O r^2} \text{ ----------------------6}$$

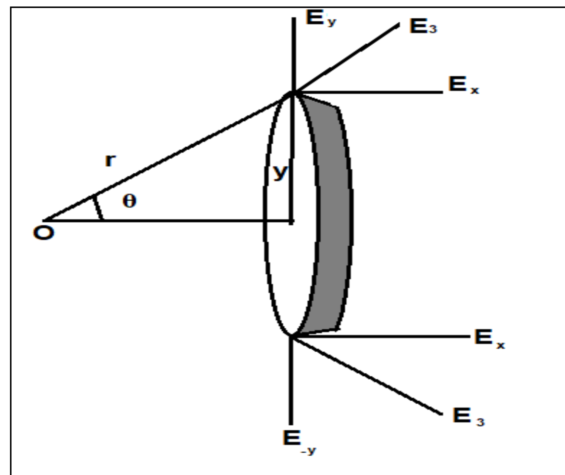


Fig.10 Internal field

The electric field intensity is in opposite direction along y axis. They are cancelled out each other. So the parallel components alone are taken into consideration.

Smallest area, dA=circumference X thickness--------------------7

Circumference of the circle with radius y is, 2πy-------------------------8

Thickness of smallest area can be calculated as, y = r.dθ-----------------9 (Fig.9)

Subs. Eqns. 8&9 in eqn. 7, we get

dA=2πy. r.dθ---10

From fig.10.

$$\sin\theta = \frac{y}{r} \quad \text{or} \quad y = r.\sin\theta \text{ --11}$$

Subs. Eqn.11 in 10

dA=2πr.sinθ. r.dθ

$$dA = 2\pi r^2 .\sin\theta.d\theta \text{ --12}$$

Subs. Eqn. 12 in 6 we get

$$E_x = \frac{P\cos^2\theta}{4\pi\varepsilon_O r^2} .2\pi r^2 \sin\theta d\theta$$

$$E_x = \frac{P\cos^2\theta \sin\theta d\theta}{2\varepsilon_O} \text{ ---------------------------------------13}$$

Equation 13 represents the electric field over the spherical cavity at a point. Total electric field can be calculated by integrating equation 13 within the limit 0 to π.

$$E_3 = \int_0^\pi \frac{P\cos^2\theta \sin\theta d\theta}{2\varepsilon_O}$$

$$E_3 = \frac{P}{2\varepsilon_0}\int_0^\pi \cos^2\theta \sin\theta d\theta \text{ --------------------------------14}$$

Put, $x = \cos\theta$

Differentiating, $dx = -\sin\theta.d\theta$

Limits: if x=0, cos 0=1,

x=π, cos 0=-1

Eqn. 14 can be written as

$$E_3 = \frac{P}{2\varepsilon_0}\int_1^{-1} x^2(-dx)$$

$$E_3 = -\frac{P}{2\varepsilon_0}\left[\frac{x^3}{3}\right]_1^{-1} = -\frac{P}{2\varepsilon_0}\left[-\frac{1}{3}-\frac{1}{3}\right] = -\frac{P}{2\varepsilon_0}\left[-\frac{2}{3}\right] = \frac{P}{2\varepsilon_0}\left[\frac{2}{3}\right]$$

$$E_3 = \frac{P}{3\varepsilon_0} \text{ --15}$$

Subs. eqn. 15 in 2,

$$E_i = E + \frac{P}{3\varepsilon_0} \text{ ---16}$$

This equation (16) shows that E_i is different from E. The local intensity E_i is larger than the macroscopic intensity E. So the molecules are more effectively polarised.

DEDUCTION: CLAUSIUS MOSOTTI RELATION

If N be the number of molecules, α be the polarizability and E_i be the internal field, then,

Polarization vector, $P = N\alpha E_i$

Or $$E_i = \frac{P}{N\alpha} \text{------------------------}17$$

We know, $$D = P + \varepsilon_0 E$$

$$D = \varepsilon E$$

From above 2 equation, $$\varepsilon E = P + \varepsilon_0 E$$

Rearranging, $$P = \varepsilon E - \varepsilon_0 E$$

$$P = (\varepsilon - \varepsilon_0)E$$

$$E = \frac{P}{(\varepsilon - \varepsilon_0)} \text{---------------------}18$$

Subs. eqn.18 in 16 we get,

$$E_i = \frac{P}{(\varepsilon - \varepsilon_0)} + \frac{P}{3\varepsilon_0}$$

$$E_i = P\left(\frac{1}{\varepsilon - \varepsilon_0} + \frac{1}{3\varepsilon_0}\right)$$

$$E_i = P\left(\frac{3\varepsilon_0 + (\varepsilon - \varepsilon_0)}{3\varepsilon_0(\varepsilon - \varepsilon_0)}\right)$$

$$E_i = \frac{P}{3\varepsilon_0}\left(\frac{\varepsilon + 2\varepsilon_0}{(\varepsilon - \varepsilon_0)}\right) \text{--------}19$$

We know $\varepsilon = \varepsilon_0 \varepsilon_r$

Eqn. 19 becomes

$$E_i = \frac{P}{3\varepsilon_0}\left(\frac{\varepsilon_o \varepsilon_r + 2\varepsilon_0}{\varepsilon_o \varepsilon_r - \varepsilon_o}\right)$$

$$E_i = \frac{P}{3\varepsilon_0}\left(\frac{\varepsilon_o(\varepsilon_r + 2)}{\varepsilon_o(\varepsilon_r - 1)}\right)$$

$$E_i = \frac{P}{3\varepsilon_0}\left(\frac{(\varepsilon_r + 2)}{(\varepsilon_r - 1)}\right) \text{-------------------------20}$$

Equating eqn. 17 and 20

$$\frac{P}{N\alpha} = \frac{P}{3\varepsilon_0}\left(\frac{(\varepsilon_r + 2)}{(\varepsilon_r - 1)}\right)$$

$$\frac{1}{N\alpha} = \frac{1}{3\varepsilon_0}\left(\frac{(\varepsilon_r + 2)}{(\varepsilon_r - 1)}\right)$$

Rearranging, $$\frac{N\alpha}{3\varepsilon_0} = \frac{\varepsilon_r - 1}{\varepsilon_r + 2} \text{--------------------------------21}$$

Eqn.21 represents Clausius Mosotti realtion. This equation relates dielectric constant and polarizability.

5.6 DIELECTRIC BREAKDOWN

Definition

When a dielectric material is subjected to large amount of electric field, at $E > E_C$, the material lose its dielectric property and becomes good conductor. This phenomenon is called as dielectric breakdown.

Dielectric strength

Dielectric strength is the voltage that an insulating material can withstand before breakdown occurs. It usually depends on the thickness of the material and on the method and conditions of the test.

Dielectric strength$=\frac{\text{Voltage}}{\text{Thickness}}=\frac{V}{d}$

Types of dielectric breakdown

- Intrinsic breakdown
- Thermal breakdown.
- Electrochemical breakdown.
- Defect breakdown.
- Discharge breakdown.

1. Intrinsic breakdown

When a dielectric material is subjected to large electric field, a large number of electrons are transferred from the valence band to the conduction band. Thus the dielectric material loses its insulating property and becomes a conductor. This is known as intrinsic breakdown.

Further the conducting electrons may collide with the atoms and release some of the valence electrons. These electrons may collide with some more atoms and may release more

electrons. This becomes a chain process resulting in a large current. It is known as avalanche breakdown.

Characteristics

- This type of breakdown occurs at room temperature and low temperatures.
- This requires relatively large electric fields
- This kind of breakdown occurs in all materials.

2. Thermal breakdown

Thermal breakdown occurs in dielectric when the rate of heat generation is greater than the rate of heat dissipation.

When a dielectric is subjected to an electric field, heat is generation. The generation heat is dissipated by the dielectric material. When the amount of heat generation is higher than the amount of heat dissipation, the temperature inside like dielectric increases and this causes the breakdown called thermal breakdown.

Characteristics:

- This can occur only at high temperatures.
- The Thermal breakdown time is of the order of few milliseconds.
- This requires moderate electric fields.
- It depends on size and shape of dielectric material.
- Since the dielectric loss its directly proportional to frequency, the electric field strength to create this dielectic breakdown will be smaller for a.c fields and higher d.c fields.

3. Electrochemical breakdown

When temperature increases, mobility of ions increases and hence leakage curent also increases. This decreases the insulation resistance and finally creates a dielectric breakdown. Hence this type of breakdown is called electrochemical breakdown.

Characteristics

- This is used to determine the leakage current, density of ions and dipoles inside the material.
- They are accelerated by high temperatures
- This occurs only at low temperature
- This type of breakdown occurs even in absence of elcetric field also.

4. Discharge breakdown

This type of breakdown occurs when the insulator contains occluded gas bubbles. When the dielectic is subjected to an electric field, the gas present in the material will be easily ionized than the solids. The ionized gas particles bombarded with the solid dielectric and produce large ionization current called discharge breakdown.

Characteristics

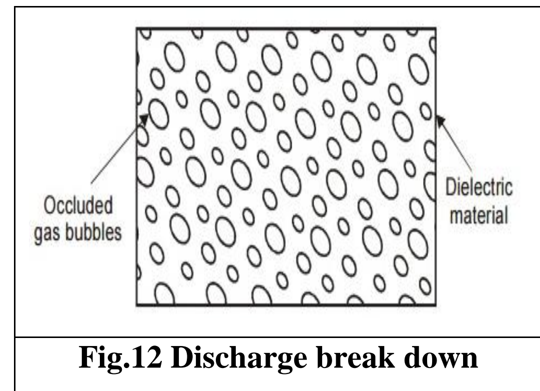


Fig.12 Discharge break down

- This is possible at low voltages where, there are large number of occluded gas bubbles is present in the material.
- The life time of the material depends upon the number of discharges taking place inside the material
- This occurs due to presence of gas bubbles.

5. Defect breakdown

If the surface of the dielectric material has defects such as cracks, pores, etc. Moisture and other impurities can fill at these places leading to breakdown, this type of breakdown called Defect breakdown.

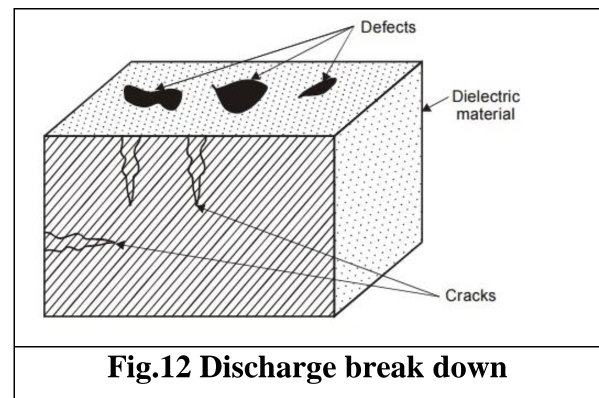


Fig.12 Discharge break down

Remedies to Avoid Breakdown Mechanisms

To avoid breakdown, the dielectric material should have the following properties

- It should have high resistivity.
- It must have low dielectric loss and less density.
- If should have sufficient mechanical strength.
- Thermal expansion should be small.
- It should be fire proof.
- It must in pure form and not have any defects.

3.8 APPLICATIONS OF DIELECTRIC MATERIALS

Some of the applications of dielectrics are as follows-

- These are used for energy storage in capacitors.
- To enhance the performance of a semiconductor device, high permittivity dielectric materials are used.
- Dielectrics are used in Liquid Crystal Displays.
- Ceramic dielectric is used in Dielectric Resonator Oscillator.
- Barium Strontium Titanate thin films are dielectric which are used in microwave tunable devices providing high tunability and low leakage current.
- Parylene is used in industrial coatings acts as a barrier between the substrate and the external environment.

- In electrical transformers, mineral oils are used as a liquid dielectric and they assist in the cooling process.
- Castor oil is used in high-voltage capacitors to increase its capacitance value.
- Electrets, a specially processed dielectric material acts as electrostatic equivalent to magnets.
- In the substation equipment where medium and high voltages flow this type of insulating material is used.
- Practically, for the high voltage is driven transformers bushes are coated with such insulating materials as well as on switch gears.
- The exposable components for example cables are firmly coated with dielectrics so that they are protected from hazardous effects.
- Even Resin and varnish are used in electrical pieces of equipment such that its working life will be increased.
- The liquid type of dielectrics is the cooling medium for the transformers, Rheostats, and Capacitors.