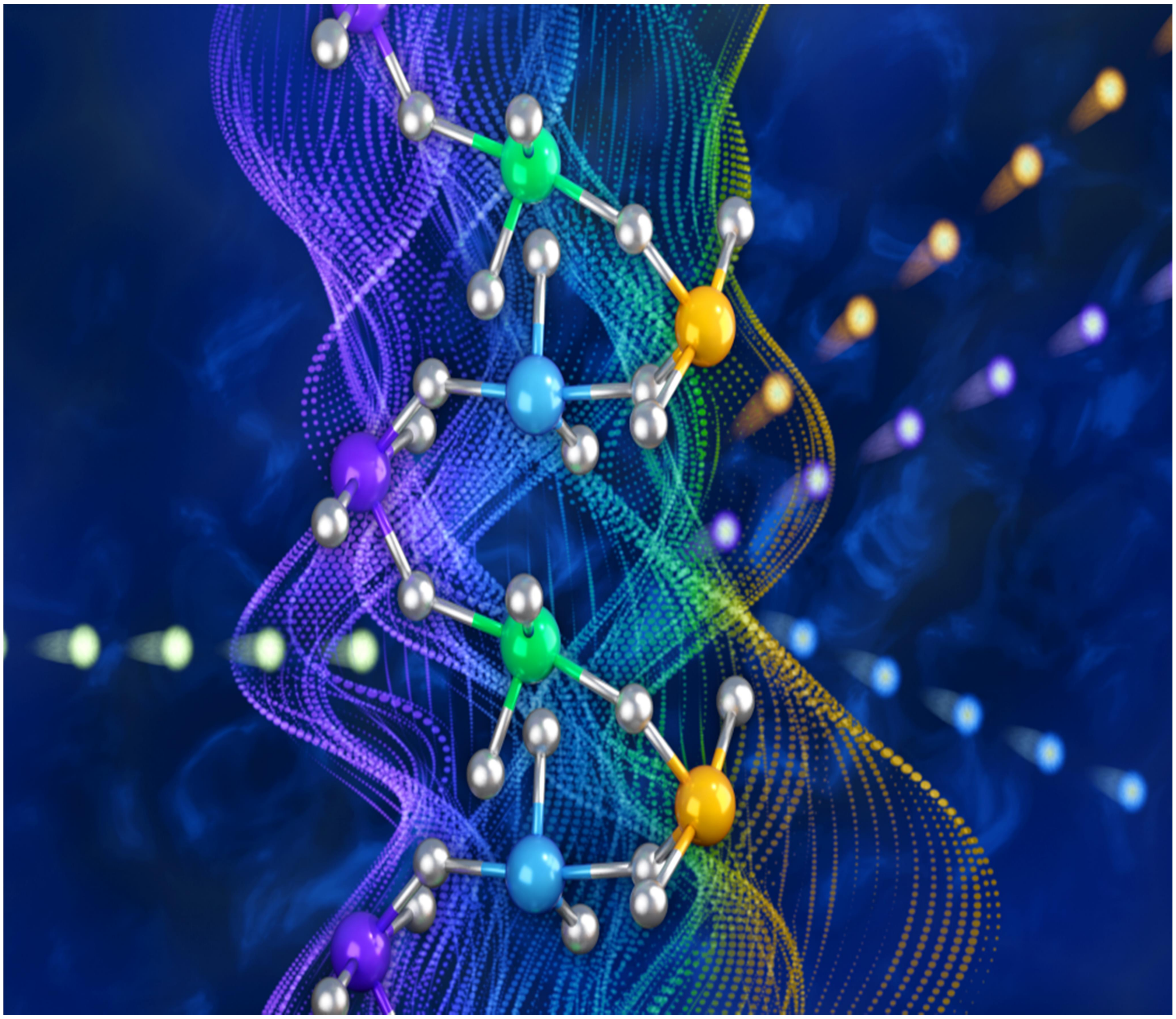

U23PHT23

APPLIED MATERIALS SCIENCE

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UNIT I	**CONDENSED MATTER PHYSICS**	**9**
Introduction - Lattice - Unit Cell - Seven Crystal Systems -Bravai's Lattices - Lattice Planes - Calculation of Number of Atoms per Unit Cell, Atomic Radius, Coordination Number and Packing Factor for SC, BCC, FCC and HCP Structures. Miller Indices – Derivation for Inter-Planar Spacing in terms of Miller Indices-Crystal Growth Techniques: Melt Growth Technique (Bridgman and Czochralski Techniques).		
UNIT II	**CONDUCTING AND INSULATING MATERIALS**	**9**
Conducting Materials: Classical Free Electron Theory: Postulates – Derivation of Electrical Conductivity and Thermal Conductivity- Derivation. Wiedemann-Franz Law and Its Verification-Merits and Demerits of Classical Free Electron Theory. Density of States – Carrier Concentration in Metals. Insulating Materials: Types of Polarization Mechanisms - Langevin- Debye Equation.		
UNIT III	**MAGNETIC AND SUPERCONDUCTING MATERIALS**	**9**
Magnetic Materials: Dia, Para and Ferromagnetic Materials and Its Properties – Ferromagnetic Domains – Wiess Theory of Ferromagnetism – Hysteresis - B-H Curve Studies – Soft and Hard Magnetic Materials-Applications. Superconducting Materials: Properties – Type I and Type II Superconductors – London equations– Applications: Magnetic Levitated Train.		
UNIT IV	**PHYSICS OF SEMICONDUCTOR**	**9**
Introduction – Properties - Intrinsic Semiconductors – Energy Band Diagram – Direct and Indirect Band Gap Semiconductors – Carrier Concentration in Intrinsic Semiconductors – Extrinsic Semiconductors - Carrier Concentration in N-Type & P-Type Semiconductors – Variation of Carrier Concentration with Temperature – Carrier Transport in Semiconductors: Drift, Mobility and Diffusion – Hall Effect And Devices.		
UNIT V	**MODERN ENGINEERING MATERIALS**	**9**
Shape Memory Alloys – Structures – Properties – Applications. Metallic Glasses – Preparation and Applications. Nanomaterials – Types – Properties and Applications – Preparation Techniques: Electrodeposition – Pulsed Laser Deposition. CNT – Structure – Types – Properties – Applications		
		TOTAL: 45 PERIODS

TEXT BOOKS:	
T1.	Charles Kittel, Introduction to Solid State Physics, Wiley India Edition, 2019.
T2.	Jasprit Singh, Semiconductor Devices: Basic Principles, Wiley (India), 2007.
T3.	G.W.Hanson. Fundamentals of Nanoelectronics. Pearson Education (Indian Edition), 2009.
T4.	Dr. P. Mani, "Physics for Electronics Engineering" Dhanam Publications, 2017.
T5.	Dr. G. Senthilkumar, "Engineering Physics II" VRB Publishers, 2013.
REFERENCE BOOKS:	
R1.	R.Balasubramaniam,Callister's Materials Science and Engineering.Wiley (Indian Edition), 2014.
R2.	Wendelin Wright and Donald Askeland, Essentials of Materials Science and Engineering, CL Engineering, 2013.
R3.	Robert F.Pierret, Semiconductor Device Fundamentals, Pearson, 2006.
R4.	Ben Rogers, Jesse Adams and Sumita Pennathur, Nanotechnology: Understanding Small Systems, CRC Press, 2017.
SUPPLEMENTARY BOOKS:	
S1	Dr. G. Senthilkumar, Dr.S.Murugavel, "Physics for Electrical Engineering", VRB Publishers, 2023.
S2	Dr. G. Senthilkumar,"Physics for Civil Engineering", VRB Publishers, 2022.
S3	Dr. G. Senthilkumar, "Engineering Physics II" VRB Publishers, 2013.

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.

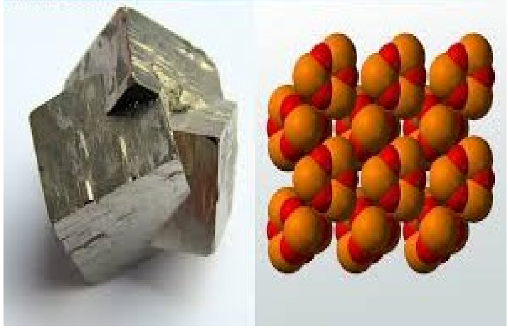


Fig 1. Solids

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.

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.

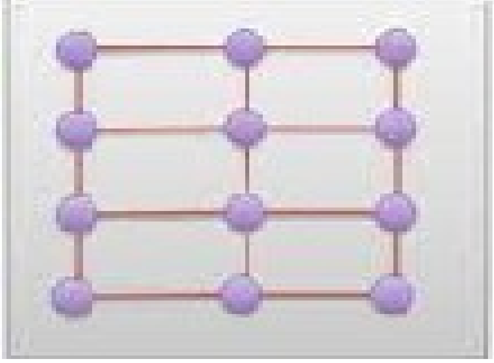


Fig 2. Crystalline Solids

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.

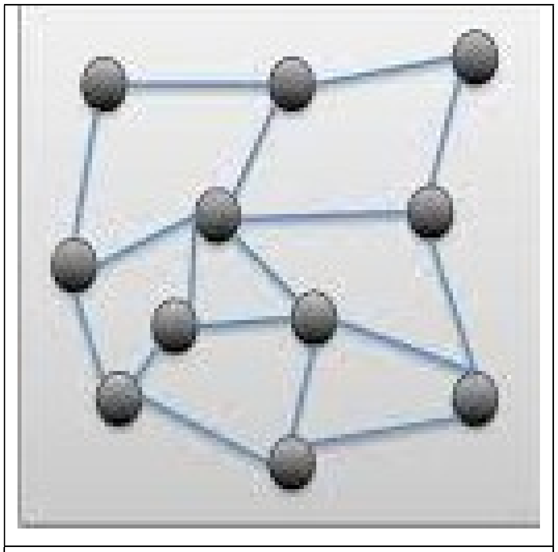


Fig 3. Amorphous Solids

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.

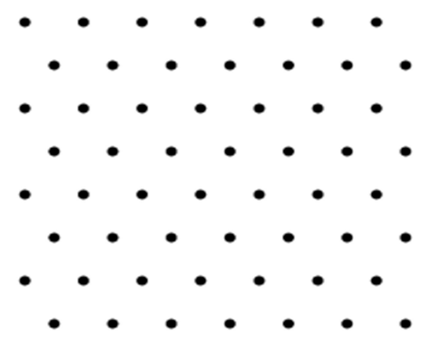


Fig 4. Lattice and Lattice Point

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.

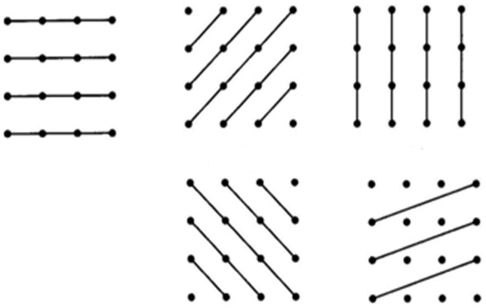


Fig 5. Lattice lines and Lattice plane

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.

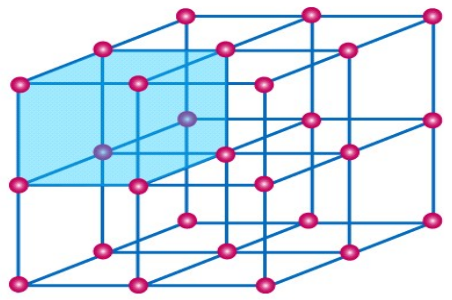


Fig 6. Space Lattice and Unit cell

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.

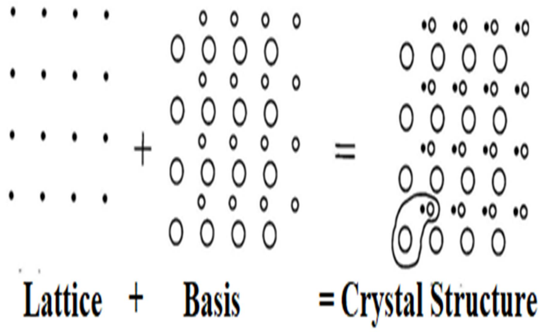


Fig 7. Basis and Crystal structure

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:

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.

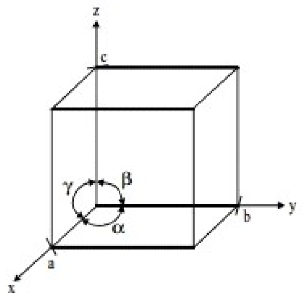


Fig 8. Lattice Parameters

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. $a \neq b \neq c$

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

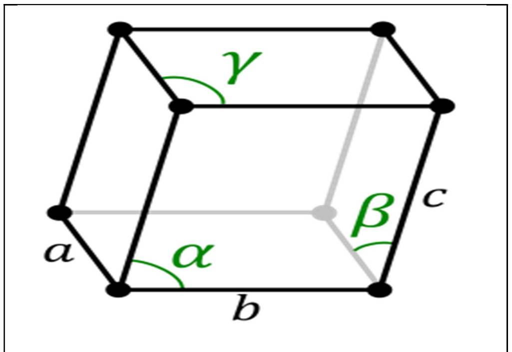


Fig9. Triclinic System

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. $a \neq b \neq c$

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

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

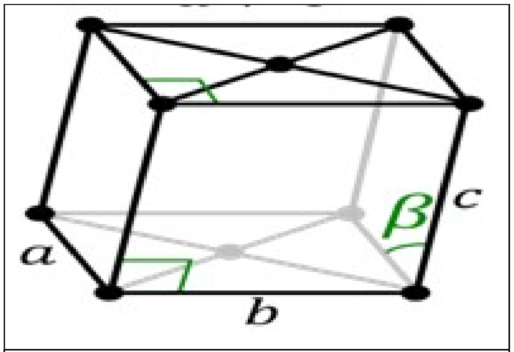


Fig10Monoclinic System

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.

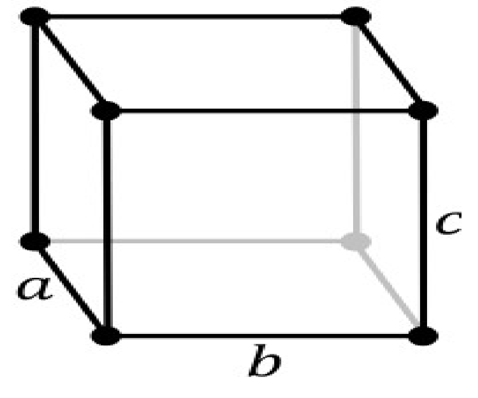


Fig 11. Orthorhombic System

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

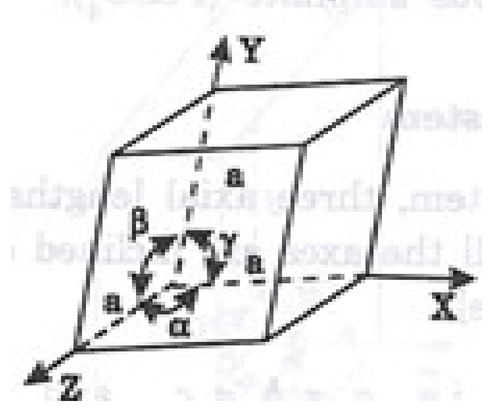


Fig 12.Trigonal

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 ≠ c

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

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

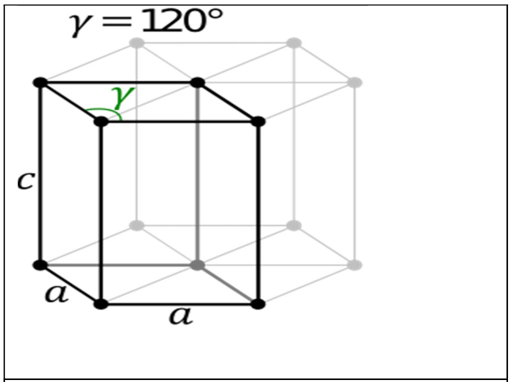


Fig. 13.Hexagonal System

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 ≠ 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.

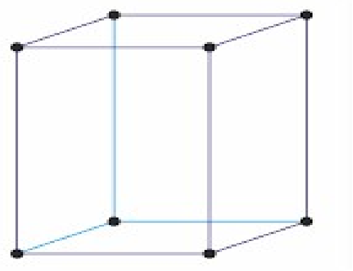


Fig. 14.Tetragonal System

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.

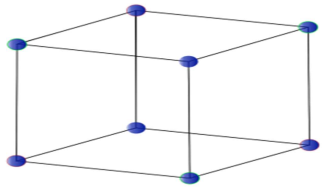


Fig. 15.Cubic System

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

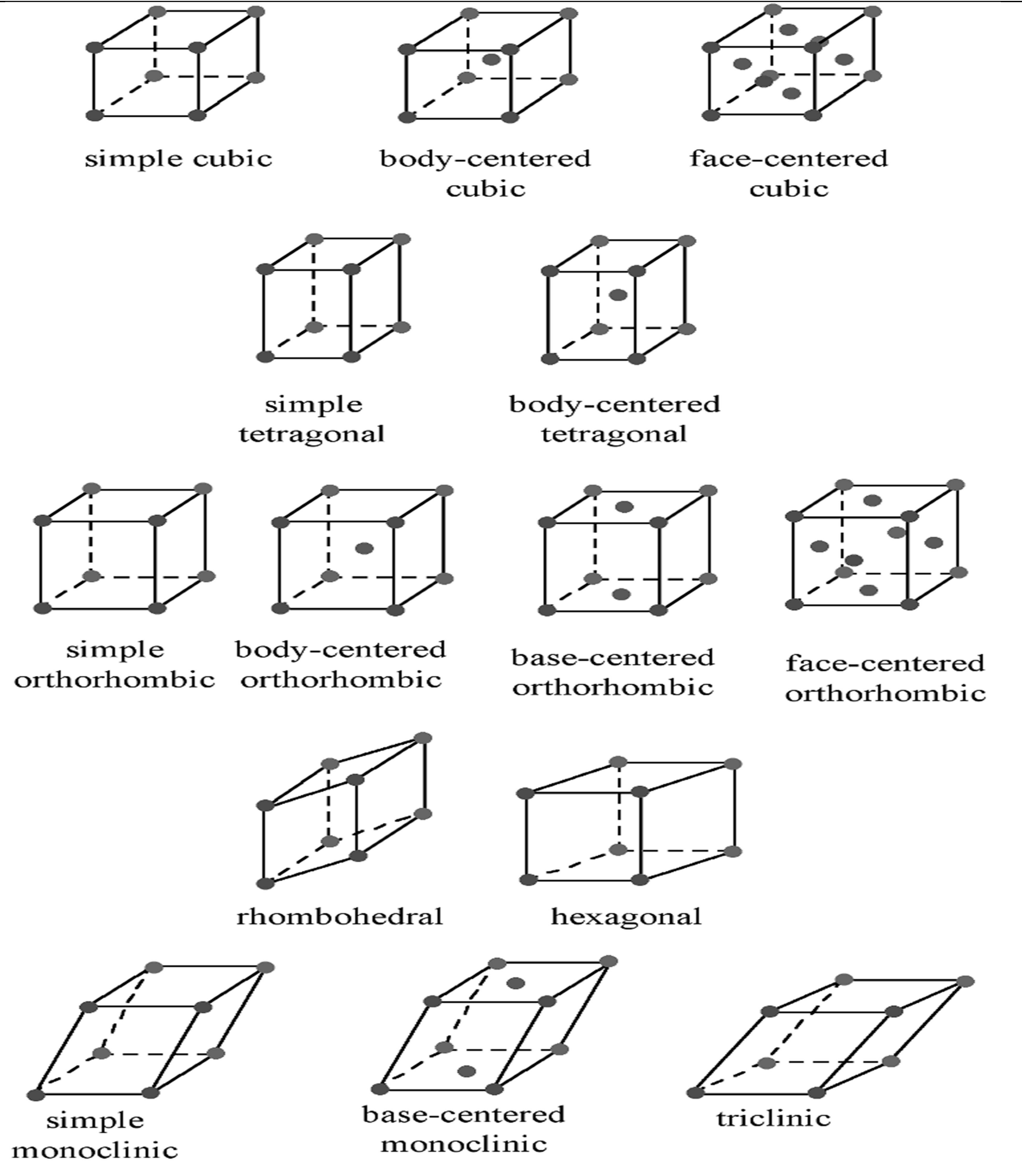


Fig 16. Bravai's Lattices

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.

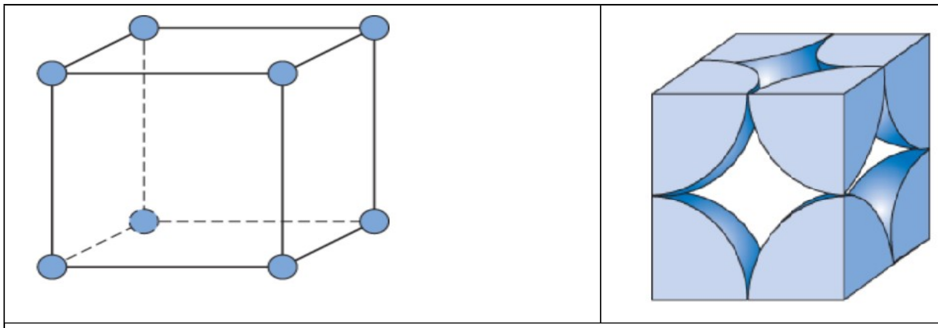


Fig 17. Simple cubic system

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

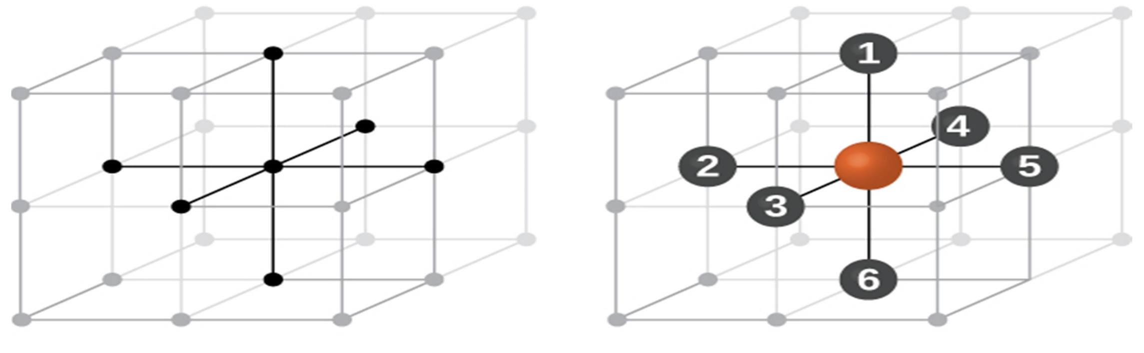


Fig 18. Coordination number

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

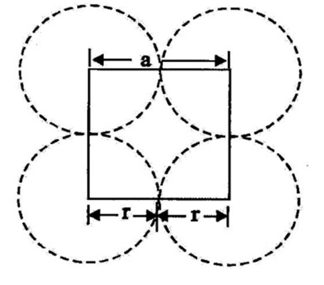


Fig 19. Atomic radius

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.

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

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

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

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

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

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.

1.9.2BODY 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.

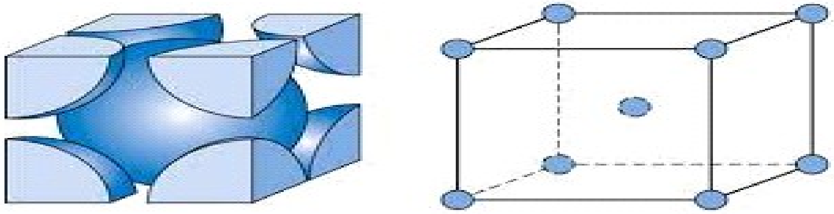


Fig 20. Body centered cubic system

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

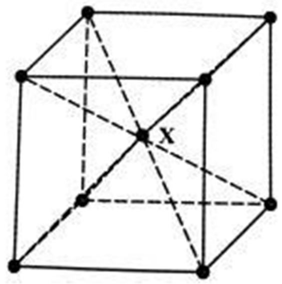


Fig 21. Coordination number of BCC

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.

Atomic radius:

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

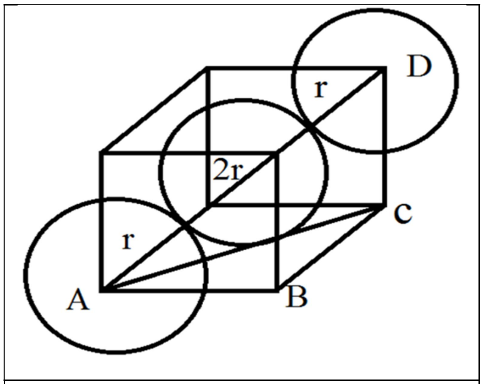


Fig 22. Atomic radius

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

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.

1.9.3FACE 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.

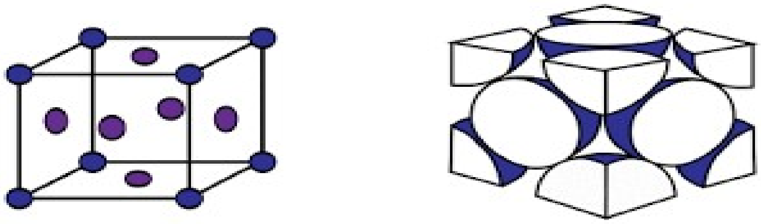


Fig 23. Face centered cubic system

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).

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

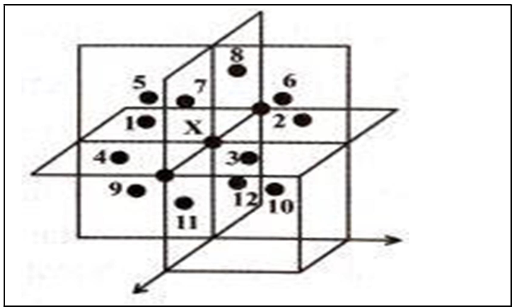


Fig 24. Coordination number of FCC

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, $r = \frac{a}{2\sqrt{2}}$

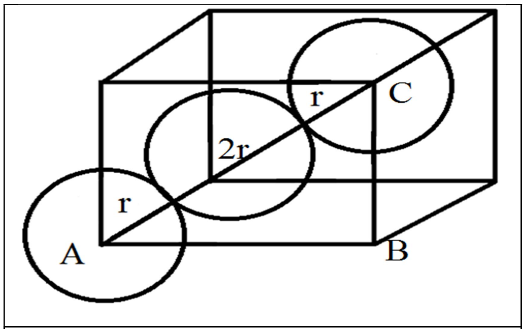


Fig 25. Atomic radius

Atomic Packing factor:x

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

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

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.

1.9.4HEXAHONAL 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.

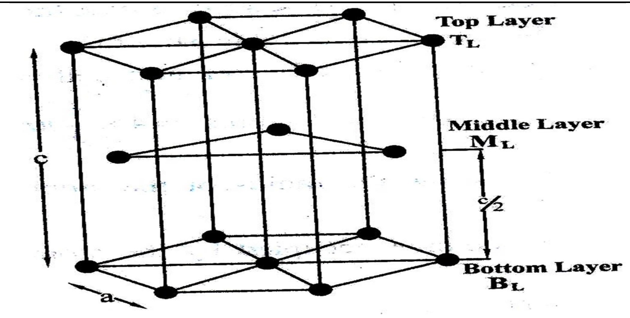


Fig 26. Hexagonal closely packed structure

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.

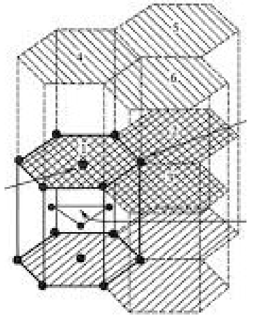


Fig 27. 6 unit cell structure

a) No. of corner atom/ unit cell:

No. of corner atom per unit cell,

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

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

$N_f = \frac{1}{2} \times 2 = 1$ 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.

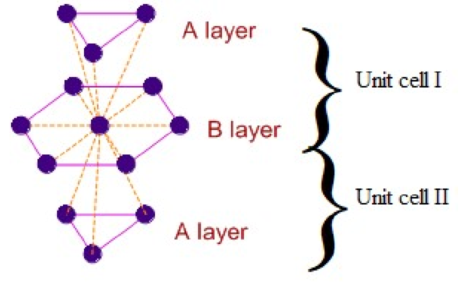


Fig 28. Coordination number

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

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

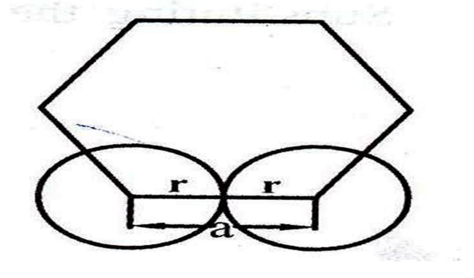


Fig 29. Atomic radius

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.

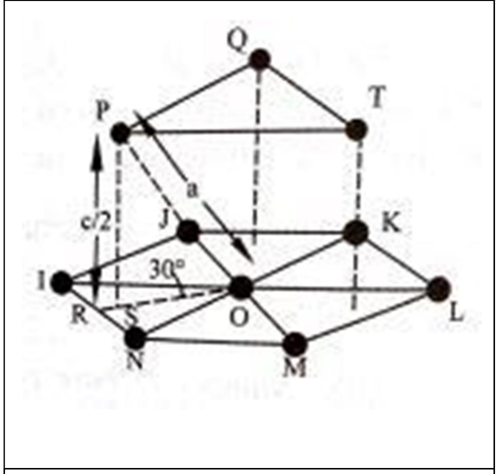


Fig 30. c/a ratio

In the triangle IRO,

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

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

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

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

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

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

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

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

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

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 (142) 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.

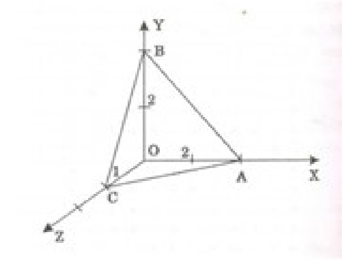


Fig 31. Example

- 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 (112).

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

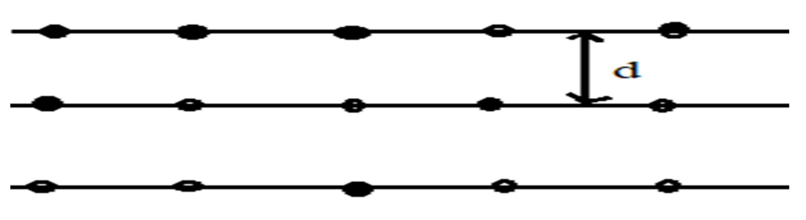


Fig 32. Interplanar spacing

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:

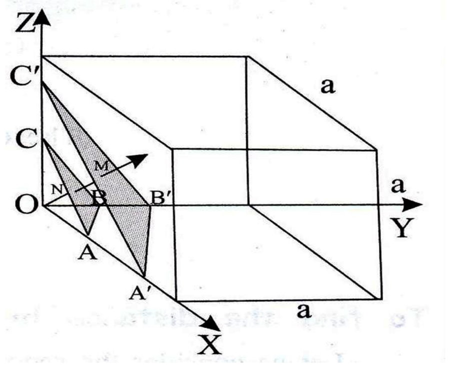


Fig 33. Interplanar spacing

- 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 d_1:

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

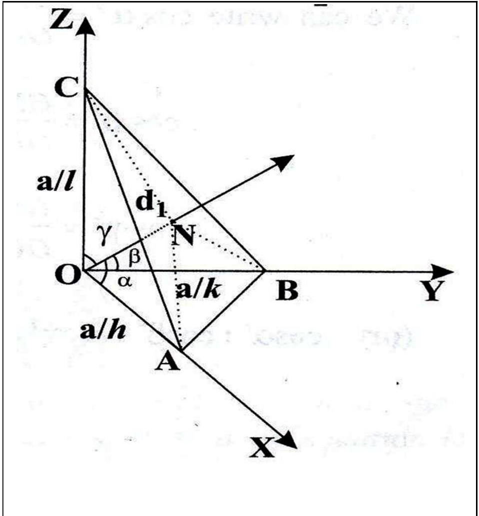


Fig 34. To find d_1

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

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

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

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

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 d_2:

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

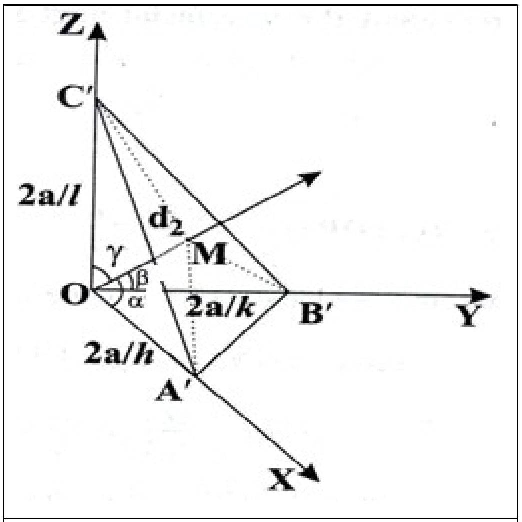


Fig 35. To find d_2

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

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

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

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

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 = $\mathbf{d_2 - d_1}$

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

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

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 amelt 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^{o} C) and Furnace 2 is kept at cold zone (620o C).

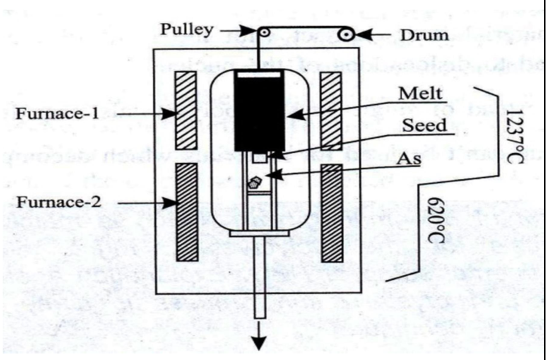


Fig 36. Bridgmann method

- 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

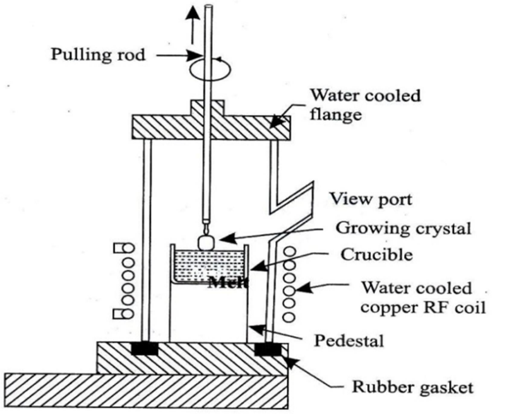


Fig 37. Czochralski method

- 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 CONDUCTING AND INSULATING MATERIALS

2.1 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 am.
- **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 am.
- **Electrons**: Electrons have a mass of approximately 0 am, orbit the nucleus, and have a charge of -1.

Each element exists as either a solid, or a liquid, or a gas at ambient temperature and pressure. Alloys or compounds can be formed by assembling a mixture of different elements on a common lattice. Typically this is done by melting followed by solidification. Any material is, therefore, composed of a combination of the elements listed in the periodic table. Among them, we are most interested in solids, which are often divided into metals, semiconductors and insulators. Roughly speaking, a metal represents a material which can conduct electricity well, whereas an insulator is a material which cannot convey a measurable electric current. At this stage, a semiconductor may be simply classified as a material possessing an intermediate character in electrical conduction. Most elements in the periodic table exist as metals and exhibit electrical and magnetic properties unique to each of them. Moreover, we are well aware that the properties of alloys differ from those of their constituent elemental metals. Similarly, semiconductors and insulators consisting of a combination of several elements can also be formed. Therefore, we may say that unique functional materials may well be synthesized in metals, semiconductors and insulators if different elements are ingeniously combined.

A molar quantity of a solid contains as many as 10 atoms. A solid is formed as a result of bonding among such a huge number of atoms. The entities responsible for the bonding are the electrons. The physical and chemical properties of a given solid are decided by how the constituent atoms are bonded through the interaction of their electrons among themselves and with the potentials of the ions.

2.2 CLASSIFICATION OF MATERIALS

Based on the electrical resistivity, materials are classified as follows:

- Zero resistive materials
- Low resistive materials
- High resistive materials

2.2.1 ZERO RESISTIVE MATERIALS

The materials of resistivity is zero when it is cooled to below transition temperature is called as zero resistive materials or super conducting materials.

Example: Hg, Al, Nb, Zn………………….etc.

2.2.2 LOW RESISTIVE MATERIALS

The materials of resistivity is low and electrical conductivity is high is called as low resistive materials or conducting materials.

Example: All metals such as Fe, Co, Ni, Cu, Zn, Mg, Mn …….etc.

2.2.3 HIGH RESISTIVE MATERIALS

The materials of resistivity is high and electrical conductivity is low is called as high resistive materials or insulating materials.

Example: All non-metals such as C, Zr, Ceramics, Porcelain………..etc

On the basis of width of forbidden gap between valence and conduction band, the solids are classified as

- Conductors
- Semiconductors
- Insulators

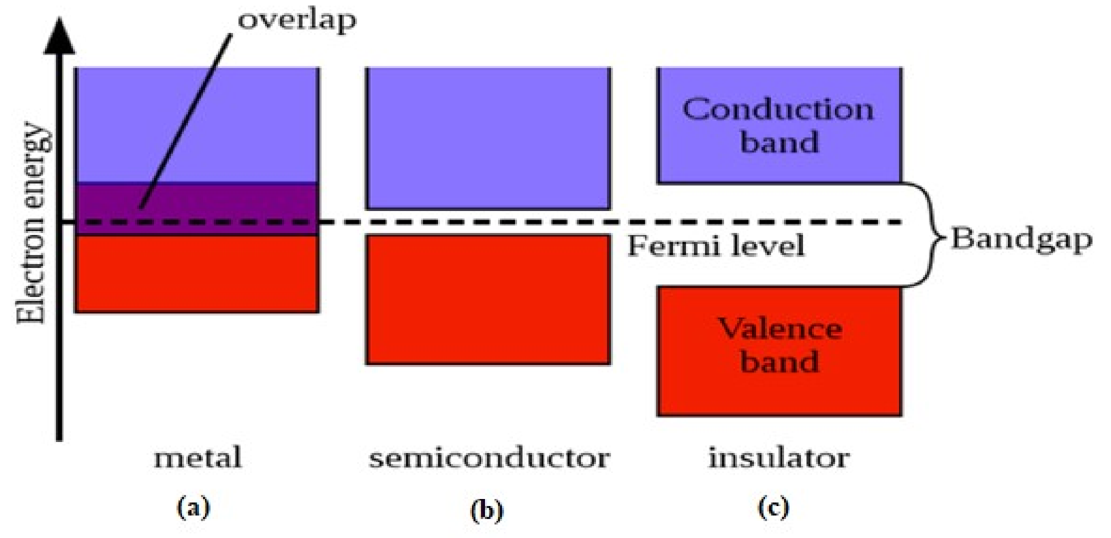


Fig 1. Band structure of conductors, semiconductors & insulators

2.2.4 CONDUCTORS

In case of conductors, there is no forbidden gap. Because, valence and conduction bands are overlap each other as shown in the fig. 1(a).

In conduction band, plenty of free electrons are available for the process of electric conduction. The electrons from valence band freely enter into the conduction band.

The most important fact in conductors is that due to the absence of forbidden gap, there is no structure to establish holes. The total current in conductors is simply the flow of electrons.

2.2.5 SEMICONDUCTORS

In semiconductors, the forbidden gap is very small as shown in the fig. 1 (b). Germanium and Silicon are the best examples of semiconductors.

In Germanium, the forbidden gap is of the order of 0.7 eV while in case of silicon, it is of the order of 1.1 eV. Actually, a semiconductor is one whose electrical properties lie between those of insulators and conductors. At 0K there are no free electrons in conduction band and valence band is completely filled.

When a small amount of energy is supplied, the electrons can easily jump from valence band to conduction band, since the forbidden gap is very small.

In semiconductors, the resistivity is of the order of 10^2 Ω m (ohm metre).

2.2.6 INSULATORS

In case of insulators, the forbidden energy band is very wide as shown in the fig 3. Due to this, electrons cannot jump from valence band to conduction band. In insulators, the valence electrons are bound very tightly to their parent atoms.

For example, in the case of material like glass, the valence band is completely full at 0K and the energy gap between valence band and conduction band is of the order of 10 eV.

Even in the presence of high electric field, the electrons cannot jump from the valence band to conduction band.

When a very large energy is supplied, an electron may jump across the forbidden gap. Increase in temperature also enables some electrons to go to the conduction band.

This explains why certain insulators become conductors at high temperature .The resistivity of insulators is of the order of 10^7 Ω m (ohm metre).

2.3 FREE ELECTRON THEORIES OF SOLIDS

There are three stages for the development of electron theory of metals; namely,

- **Classical free electron theory**
- **Quantum free electron theory**
- **Band theory or Zone theory**

2.3.1 Classical free electron theory

A classical free electron theory is a macroscopic theory proposed by Paul Drude in 1900. After the discovery of electron by JJ Thomson, this theory was elaborated by Lorentz in 1909. Hence this theory is also known as Drude & Lorentz theory. According to this theory metals contains free electrons which are responsible for the electrical conductivity in metals and obeys the laws of classical mechanics (Maxwell-Boltzmann distribution).

2.3.2 Quantum free electron theory

Quantum free electron theory is a microscopic theory developed by Sommerfeld in 1928. According to this theory, the free electrons move with a constant potential obeys quantum laws (Fermi-Dirac statistics).

2.3.3 Band theory or Zone theory

Zone theory was developed by Bloch in 1928. According to this theory, free electrons move in periodic potential provided by lattice. This theory is also known as band theory of solids.

2.4 CLASSICAL FREE ELECTRON THEORY

Free Electron Concept:

All metal atoms consists of valance electrons and they are responsible for physical properties of metals such as electrical & thermal conductivities, thermoelectricity, thermionic & Photoelectric effect ete.,

According to Drude-Lorentz theory, when a large number of atoms arranged in three dimensional lattice points to form a metal, the boundaries of the neighbouring atoms slightly overlap with each other as shown in figure.

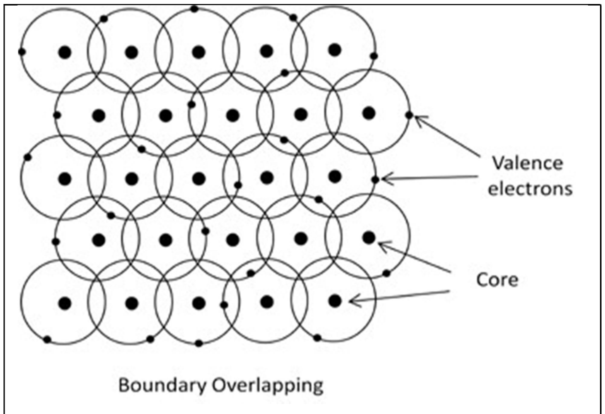


Fig 2. Arrangement of atom in solid

Due to this overlapping, the valance electrons of all the atoms are free to move within the metal lattice. These electrons are called free electrons. These free electrons are move randomly in all directions through the conductor with average speed of the order of 106 m/s. This is similar to the motion of gas molecules confined in a vessel. Since the free electrons are responsible for electrical and thermal conduction in metals, they are also called as conduction electrons.

All metals contain free electrons which act just as a gas molecules moving in every direction throughout the lattice. The average velocity due to the thermal energy is zero since the electrons are going in every direction. There is a way of affecting this free motion of electrons, which is by use of an electric field. This process is known as electrical conduction and theory is called Drude-Lorentz theory. The assumptions of the Drude-Lorentz classical theory of free electrons are the following.

2.4.1 ASSUMPTIONS OF CLASSICAL FREE-ELECTRON THEORY:

- All metals contain large number of free electrons which move freely through the positive ionic core of the metals. Since these free electrons causes conduction in metal under the application of electrical field, they are called as conduction electrons.
- The free electrons are treated as equivalent to gas molecules; the laws of classical kinetic theory of gases can be applied to them. Therefore these electrons have mean free path (λ), mean collision time (T), average speed (v).
- In the absence of the electric field, the kinetic energy associated with an electron at temperature T is given by

  $$K.E = \frac{1}{2}mv^2 = \frac{3}{2}kT = \frac{1}{2}m\bar{c}^2$$

  where, v is called thermal velocity which is equal to root mean square velocity $\bar{c}$.
- Since the motion of the electrons is random, the net current is zero in the absence of electric field. But when an electric field is applied, current is produced due to the drift velocity of the electrons.
- The electric field (or Potential) due to positive ionic cores is considered to be uniform throughout the metal and hence neglected. But the force of attraction between the electrons & lattice ions and the force of repulsion between the electrons themselves are considered to be negligible.

2.4.2 DRIFT VELOCITY, MEAN FREE PATH, MEAN COLLISION TIME, RELAXATION TIME, MOBILITY, RESISTIVITY AND CURRENT DENSITY.

Drift velocity (V_d):

It is the average velocity acquired by the electrons in a direction opposite to the direction of the applied electric field. It is denoted by the symbol $\mathbf{V_d}$.

$$V_d = \frac{\lambda}{\tau_c}$$

Where, λ be the mean free path

τ_c be the collision time

Unit: metre/second^2

Mean Free Path (λ):

The average distance travelled by the conduction electrons between two successive collisions with lattice ions is known as mean free path.

$$\lambda = V_d \, X \, \tau_C$$

It is also defined as the product of drift velocity and collision time.

Unit: metre

Mean Collision Time (τ_c):

It is the average time taken by the free electron between two successive collisions with lattice points is called as collision time.

$$\tau_c = \frac{\lambda}{V_d}$$

Unit: second

Relaxation Time (τ):

It is the time taken by the electron to reach its disturbed position to equilibrium position in the presence of electric field.

$$\tau = \frac{l}{V}$$

Where l be the length between two atoms

Unit: second

Mobility of electrons (μ):

Mobility is defined as the magnitude of the drift velocity acquired by the electrons under unit electric field applied on it. The expression for the mobility is

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

Unit: $m^2V^{-1}s^{-1}$

Electrical resistivity (ρ):

It is the property of the metal and defined as the reciprocal of electrical conductivity.

$$\rho = \frac{1}{\sigma}$$

Unit: Ωm

Current density (J):

It is defined as the ration between current flows through the material per unit area. It is represented by the symbol J.

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

In terms of electrical conductivity, current density can be written as

$$J = \sigma E$$

In terms of drift velocity, current density can be written as

$$J = neV_d$$

Unit: Am^{-2}

2.5 ELECTRICAL AND THERMAL CONDUCTIVITIES OF METALS

2.5.1 Electrical conductivity:

Definition:

The amount of electrical energy flowing through the material per unit area per unit time under unit potential gradient is known as coefficient of electrical conductivity. It is denoted as σ.

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

Unit: $\Omega^{-1}m$

Derivation of electrical conductivity

- Let us assume that, a metal which contains more number of electrons.
- Consider battery connection is given to the metal for current flow.
- When electric field is applied to the material, the electrons are moving in the opposite direction to the field direction as shown in figure.

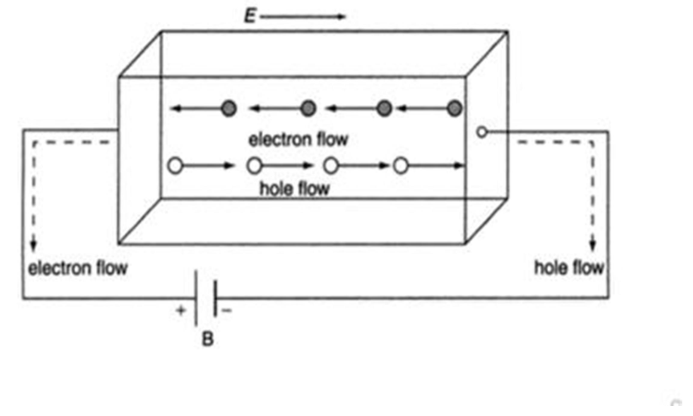


Fig 3. Electrical conductivity

The force experienced by the free electron under electric field is given by

Lorentz repulsive force, $F = eE$ --------------------------------1

According to Newton's second law of motion,

Force, $F = ma$ --------------------------------2

Equating equation 1 & 2

$$eE = ma$$

Rearranging we get,

$$a = \frac{eE}{m} \text{--------------------------------3}$$

Due to force experienced by the free electron, the electrons are accelerated toward positive potential with velocity v is given by

$$a = \frac{V_d}{\tau} \text{-------------------------------}4$$

Equating equations 3 & 4, we get

$$\frac{V_d}{\tau} = \frac{eE}{m}$$

Rearranging, $$V_d = \frac{eE}{m}\tau \text{-------------------------}5$$

We know current density in terms of drift velocity,

$$J = neV_d \text{-------------------------}6$$

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

$$J = ne\left(\frac{eE\tau}{m}\right)$$

Or $$J = \frac{ne^2\tau E}{m} \text{----------------------}7$$

The macroscopic form of Ohm's law is

$$J = \sigma E \text{-------------------------}8$$

Equating equations 7 & 8, we get

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

Or $$\sigma = \frac{ne^2\tau}{m} \text{---------------------}9$$

Equation 9 is called as coefficient of electrical conductivity based on classical theory. According to quantum mechanics, the mass of the electron at motion is not a constant. So m* replaces m in equation 9.

$$\sigma = \frac{ne^2\tau}{m^*} \text{-------------------}10$$

Where, m* be effective mass of the electron

Equation 10 is called as coefficient of electrical conductivity based on quantum theory.

Conclusions

- $\sigma \alpha\, n$: The number of free electron increases, the value of electrical conductivity increases, or otherwise decreases.
- $\sigma \alpha\, \frac{1}{m^*}$: The mass of free electron increases, the value of electrical conductivity decreases, or otherwise increases.

2.5.1 Thermal conductivity

Let us assume a cubical metal box with area "A" and thickness "x". Let T_1 and T_2 are the temperatures at hot end and cold end respectively.

Consider heat energy flowing through hot end to cold end of the metal box. Here,

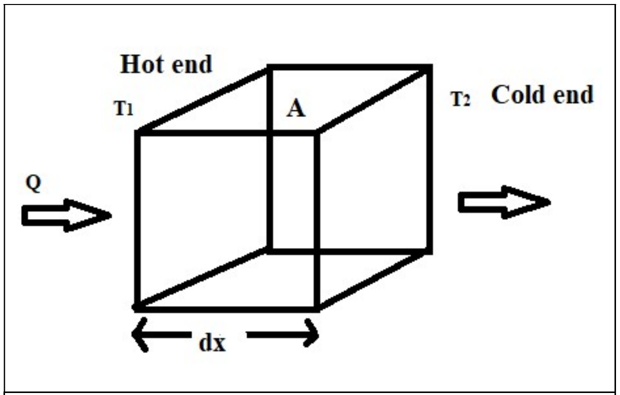


Fig 4. Thermal conductivity

Heat conduction (Q) α area (A)

α time of conduction (t)

α temperature difference between hot end and cold end (T_1-T_2)

$\alpha \ \frac{1}{Thickness(dx)}$

Combining all the terms, we get

$$Q\,\alpha\,\frac{A(T_1-T_2)t}{x}$$

Or

$$Q = K\,\frac{A(T_1-T_2)t}{dx} \text{ -----------------------1}$$

But T_1-T_2=dT

Eqn. 1 can be written as

$$Q = KA\,(\frac{dT}{dx})t \text{ ---------------------------2}$$

Assume A=1m^2, t=1 second and temperature gradient, $\frac{dT}{dx}$ =1 K/m

$$Q = K \text{ -------------------------------------3}$$

Definition:

The amount of heat energy flowing through the material per unit area per unit time under unit temperature gradient is known as coefficient of electrical conductivity. It is denoted as K.

$$K = \frac{Q}{.\left(\frac{dT}{dx}\right)} \text{ ------------------------4}$$

Derivation:

- Consider a uniform metal rod AB with length 2λ. Let T_1 &T_2 are the temperature at hot end and cold end.
- Let us assume an area of cross section C at centre with the distance of λ.
- Now we consider, heat energy passed through the material rod from hot end to cold end.

The kinetic energy of electron at hot end A (as a particle) = $\frac{1}{2}mv^2$

According to law of kinetic theory of gas, the kinetic energy of electron gas at hot end A = $\frac{3}{2}K_BT_1$ --------------------------5

The kinetic energy of electron gas at cold end B = $\frac{3}{2}K_BT_2$ --------------------6

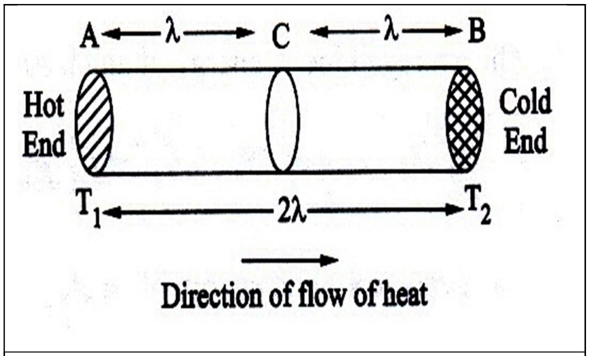


Fig 5. Thermal conductivity

Net heat energy transferred from hot end A to cold end B can be calculated as,

$$=\frac{3}{2}K_BT_1 - \frac{3}{2}K_BT_2$$

Or $$=\frac{3}{2}K_B(T_1-T_2)\text{-----------------}7$$

Assume that electrons can move in all 6 possible directions as shown in below fig.

Let n be the free electron density and v be the thermal velocity, then Number of electrons crossing per unit area per unit time through the rod AB

$$=\frac{1}{6}nv\text{------------------------}8$$

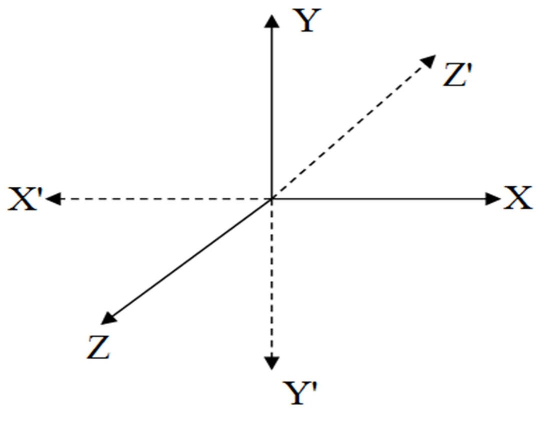


Fig 6. Probability of movement of electron

Net heat energy transferred from A to B per unit area per unit time,

Q = Number of electrons x Average kinetic energy

$$=\frac{1}{6}nv \text{ x } =\frac{3}{2}K_B(T_1-T_2)$$

$$=\frac{1}{4}nvK_B(T_1-T_2)\text{-----------}9$$

Equating eqns I & 9,

$$K\frac{(T_1-T_2)}{dx}=\frac{1}{4}nvK_B(T_1-T_2)$$

$$K=\frac{1}{4}nvK_B(T_1-T_2).\frac{dx}{(T_1-T_2)}$$

$$K=\frac{1}{4}nvK_B.dx\text{-------------}10$$

But thickness dx= 2λ

Equation 10 becomes

$$K = \frac{1}{4} n v K_B . 2\lambda$$

Or $K = \frac{1}{2} n v K_B . \lambda$ ------------------11

We know mean free path $\lambda = V_d X \tau_C$

For metal $\tau = \tau_C$

Equation 11 can be written as

$$K = \frac{1}{2} n v K_B . v . \tau$$

Or $K = \frac{1}{2} n v^2 K_B \tau$ ---------------12

Equation 12 is called as equation for coefficient of thermal conductivity.

Conclusion:

The thermal conductivity value increases with increasing of number of free electron available in metal.

2.6 WIEDEMANN-FRANZ LAW

Definition:

The ratio between thermal conductivity and electrical conductivity of the metal is directly proportional to absolute temperature of the metal.

$$\frac{K}{\sigma} \alpha \ T$$

Or $\frac{K}{\sigma} = LT$

Where, L is called Lorentz number. Its value is 2.44x10^{-8} $W\Omega K^{-2}$.

Proof:

According Classical free electron theory,

Thermal conductivity, $K = \frac{n v^2 K_B \tau}{2}$ -------------------1

Electrical conductivity, $\sigma = \frac{n e^2 \tau}{m}$ ------------------------2

$$\frac{K}{\sigma} = \frac{\frac{n v^2 K_B \tau}{2}}{\frac{n e^2 \tau}{m}}$$

$$\frac{K}{\sigma} = \frac{nv^2 K_B \tau}{2} \times \frac{m}{ne^2 \tau}$$

$$\frac{K}{\sigma} = \frac{mv^2 K_B}{2e^2} \quad \text{-------------------------3}$$

According to Kinetic theory of gases,

$$\frac{1}{2}mv^2 = \frac{3}{2}K_B T$$

$$\frac{K}{\sigma} = \frac{3}{2}\frac{K_B T K_B}{e^2}$$

$$\frac{K}{\sigma} = \frac{3}{2}\left(\frac{K_B}{e}\right)^2 T \quad \text{-------------------4}$$

$$\frac{K}{\sigma} = LT \quad \text{---------------------------5}$$

Compare 4 & 5

where

$$L = \frac{3}{2}\left(\frac{K_B}{e}\right)^2 = \frac{3}{2}\left(\frac{1.38x10^{-23}}{1.602x10^{-19}}\right)^2$$

$$L = 1.22 \times 10^{-8}\ W\Omega K^{-2}$$

The value of Lorentz number is only one half of the experimental value. This discrepancy is rectified by quantum theory.

According quantum free electron theory,

Thermal conductivity,

$$K = \frac{\pi^2}{3}\frac{nT K_B{}^2 \tau}{m^*} \quad \text{--------------------6}$$

Electrical conductivity,

$$\sigma = \frac{ne^2 \tau}{m^*} \quad \text{-----------------------7}$$

$$\frac{K}{\sigma} = \frac{\left(\frac{\pi^2}{3}\frac{nT K_B{}^2 \tau}{m^*}\right)}{\left(\frac{ne^2 \tau}{m^*}\right)}$$

$$\frac{K}{\sigma} = \frac{\pi^2}{3}\frac{K_B{}^2}{e^2}T$$

$$\frac{K}{\sigma} = LT$$

Where, $$L = \frac{\pi^2}{3}\frac{K_B{}^2}{e^2} = \frac{(3.14)^2}{3}\frac{(1.38x10^{-23})^2}{(1.602x10^{-19})^2}$$

$$L = 2.44 \times 10^{-8}\ W\Omega K^{-2}$$

2.7 LORENTZ NUMBER:

Definition:

It is defined as the ratio between thermal conductivity and product of electrical conductivity and absolute temperature of the material.

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

Its value is 2.44x10^{-8} $W\Omega K^{-2}$.

2.7 SUCCESSFUL OF CLASSICAL FREE ELECTRON THEORY

- It verifies Ohm's law.
- It explains the electrical and thermal conductivity of metals.
- It is used to derive Wiedemann – Franz law.
- The optical properties of metals can be explained by using this theory.

2.8 DRAWBACKS OF CLASSICAL FREE ELECTRON THEORY

- It is a macroscopic theory.
- It could not explain the hyperfine structure of Hydrogen atom
- Classical theory states that all the electrons will absorb energy but quantum theory states that only few electrons will absorb energy.
- This theory cannot explain the Compton Effect, Photoelectric Effect, blackbody radiation etc…
- Different kinds of magnetic materials could not be explained.
- The theoretical and experimental values of specific heat are not matched.
- It could not explain classification of material as conductor, semiconductor and insulator.
- The Lorentz number by classical theory does not have good agreement with the experimental value and it is rectified by quantum theory.
- The classical free electron theory fails to explain dependence of T on σ.
- The theoretical value of mean free path is 2.85 nm. The experimental value of λ is found to be 0.285 nm, which is 10 times less than the value obtained from classical free electron theory. Hence classical free electron theory fails to explain λ.

2.8. QUANTUM FREE ELECTRON THEORY (SOMMERFELD THEORY):

To overcome the drawbacks of classical free electron theory, Sommerfeld proposed quantum free electron theory. He treated electron as a quantum particle. He retains the vital features of classical free electron theory and included the Pauli Exclusion Principle & Fermi-Dirac statistics. The following are the assumptions of quantum free electron theory.

- The free electrons in a metal can have only discrete energy values. Thus the energies are quantized.
- The electrons obey Pauli's Exclusion Principle, which states that there cannot be more than two electrons in any energy level.
- The distribution of electrons in various energy levels obey the Fermi-Dirac quantum statistics.
- Free electrons have the same potential energy everywhere within the metal, because the potential due to ionic cores is uniform throughout the metal.
- The force of attraction between electrons & lattice ions and the force of repulsion between electrons can be neglected.
- Electrons are treated as wave-like particles.

There are three statistics in physics are;

1. **Maxwell-Boltzmann Statistics:**

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

   - Deals with particles which has no spin
   - Eg. : Gaseous particles

2. **Bose-Einstein Statistics:**

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

   - Deals with particles which has integral spin
   - Known as Bosons
   - Eg. : Photons. Gluons, ^{4}He atoms… etc

3. **Fermi-Dirac Statistics:**

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

   - Deals with particles which has half integral spin
   - Also known as Fermions
   - Eg. : Electrons, Protons, Neutrons, Quarks, Neutrinos etc.,

2.9 DENSITY OF ENERGY STATES

Definition:

Density of states Z (E) dE is defined as the number of available energy states with in the energy interval E and E + dE per unit volume.

Density of states = Number of available energy states between E and E + dE / volume

$$N(E)dE = \frac{Z(E)dE}{V} \text{-------------------------------}1$$

Derivation:

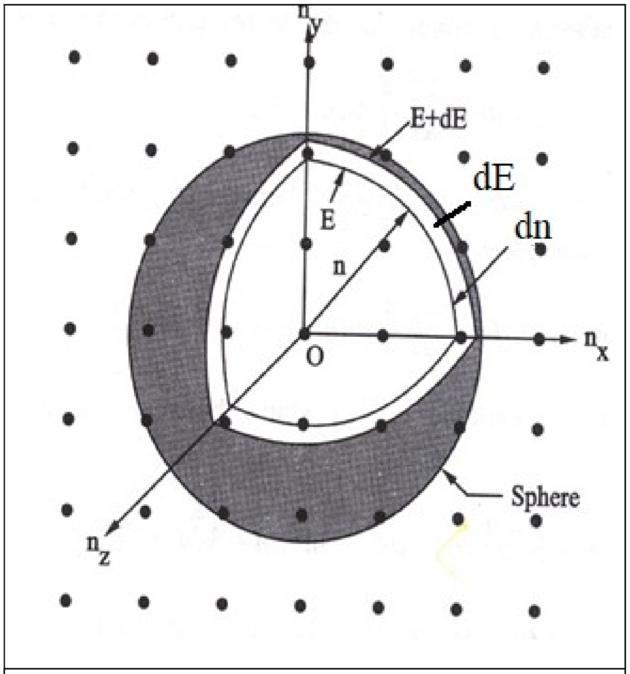


Fig 10. Density of states

- Consider a cubical metal piece
- n_x, n_y & n_z – Coordinate axes in three dimensional space
- $n^2 = n_x^2 + n_y^2 + n_z^2$
- Consider a sphere within the cubical metal piece
- The sphere is divided into many shells. Let us consider two shells.
- E – Energy value of the inner shell
- E + dE – Energy value of the outer shell
- n – Radius of the inner shell
- n + dn – Radius of outer shell
- O be the origin
- The sphere is cut in to 8 equal pieces. We have taken one piece for calculation

The number of available energy states within the sphere of radius ‘n’ is given by

$$= \frac{4}{3}\pi n^3$$

The number of available energy states within the sphere of radius ‘n’ within one octant is given by

$$= \frac{1}{8}\left[\frac{4}{3}\pi n^3\right] \text{-------------------}2$$

The number of available energy states within the sphere of radius ‘n+dn’ within one octant is given by

$$= \frac{1}{8}\left[\frac{4}{3}\pi (n+dn)^3\right] \text{-----------}3$$

The number of energy states within the sphere of radius ‘*dn*’ is

$$Z(E)\,dE=\frac{1}{8}\left[\frac{4}{3}\pi\left(n+dn\right)^{3}\right]-\frac{1}{8}\left[\frac{4}{3}\pi n^{3}\right]$$

$$Z(E)\,dE=\frac{1}{8}\frac{4}{3}\pi\left[\left(n+dn\right)^{3}-n^{3}\right]$$

$$Z(E)\,dE=\frac{1}{8}\frac{4}{3}\pi\left[n^{3}+dn^{3}+3n\,dn^{2}+3n^{2}dn-n^{3}\right]$$

Since dn is very small. So dn^2, dn^3 are neglected.

$$Z(E)\,dE=\frac{1}{8}\frac{4}{3}\pi\left[3n^{2}dn\right]$$

$$Z(E)\,dE=\frac{\pi}{2}n^{2}dn\Rightarrow\frac{\pi}{2}n\left(n\,dn\right)\text{------------------}4$$

According to particle in a one dimensional box problem, the energy of the electron in a box of length ‘l” is given by

$$E=\frac{n^{2}h^{2}}{8ml^{2}}$$

$$n^{2}=\frac{8ml^{2}E}{h^{2}}\text{--}5$$

$$n=\left[\frac{8ml^{2}E}{h^{2}}\right]^{\frac{1}{2}}\text{-------------------------------------}6$$

Differentiate (5) on both sides

$$2n\,dn=\frac{8ml^{2}}{h^{2}}dE$$

$$n\,dn=\frac{8ml^{2}}{2h^{2}}dE\text{-----------------------------------}7$$

Sub. (6) & (7) in (4)

$$Z(E)\,dE=\frac{\pi}{2}\left[\frac{8ml^{2}E}{h^{2}}\right]^{\frac{1}{2}}\left[\frac{8ml^{2}}{2h^{2}}dE\right]$$

$$Z(E)\,dE=\frac{\pi}{2}\frac{1}{2}\left[\frac{8ml^{2}E}{h^{2}}\right]^{\frac{1}{2}}\left[\frac{8ml^{2}}{h^{2}}dE\right]$$

$$Z(E)\,dE=\frac{\pi}{4}\left[\frac{8ml^{2}}{h^{2}}\right]^{\frac{3}{2}}E^{\frac{1}{2}}\,dE$$

$$Z(E)\,dE=\frac{\pi}{4}\left[\frac{8m}{h^{2}}\right]^{\frac{3}{2}}l^{3}E^{\frac{1}{2}}\,dE\text{ -------}8$$

l^3 – Volume of the sphere (V),

(8) Becomes

$$N(E)dE = \frac{Z(E)dE}{V} = \frac{\pi}{4}\left[\frac{8m}{h^2}\right]^{\frac{3}{2}} E^{\frac{1}{2}}\, dE \text{-------}9$$

According to Pauli’s exclusion principle, electron has 2 spins.

$$N(E)\,dE = 2\times\frac{\pi}{4}\left[\frac{8m}{h^2}\right]^{\frac{3}{2}} E^{\frac{1}{2}}\, dE$$

$$N(E)\,dE = \frac{\pi}{2}\left[\frac{8m}{h^2}\right]^{\frac{3}{2}} E^{\frac{1}{2}}\, dE \text{-----------------}10$$

Equation 10 is the expression for density of states per unit volume.

Carrier concentration in metals

It is defined as product of density of states and Fermi function.

N = N (E) dE. F(E)--11

N (E) dE – Number of filled energy states per unit volume

F(E) – Fermi function

Sub. Eqn. (10) in (11)

$$N = \frac{\pi}{2}\left[\frac{8m}{h^2}\right]^{\frac{3}{2}} E^{\frac{1}{2}}\, dE.F(E) \text{----------------------------------}12$$

Equation 12 is the expression for carrier concentration (or) density of electrons in metals.

Fermi energy at 0 Kelvin

At 0 Kelvin, Fermi energy *F(E) = 1*.

The density of electrons in metals is

$$N = \frac{\pi}{2}\left[\frac{8m}{h^2}\right]^{\frac{3}{2}} E^{\frac{1}{2}}\, dE.F(E)$$

Integrate within the limits 0 to E_{F_0}

$$N = \int_0^{E_{F_0}} \frac{\pi}{2}\left(\frac{8m}{h^2}\right)^{3/2} E^{1/2} dE\,.F(E)$$

$$N = \frac{\pi}{2}\left(\frac{8m}{h^2}\right)^{3/2} \int_0^{E_{F_0}} E^{1/2} dE \qquad [F(E) = 1]$$

$$N = \frac{\pi}{2}\left(\frac{8m}{h^2}\right)^{3/2} \left[\frac{E^{3/2}}{3/2}\right]_0^{E_{F_0}}$$

$$N = \frac{\pi}{2}\frac{2}{3}\left(\frac{8m}{h^2}\right)^{3/2} \left(E_{E_{F_0}}^{3/2} - 0\right)$$

$$N=\frac{\pi}{3}\left(\frac{8m}{h^2}\right)^{3/2} E_{E_{F0}}^{3/2} \text{ ---13}$$

Equation 13 is the expression for carrier concentration (or) density of electrons in metals in terms of Fermi energy.

DIELECTRIC MATERIALS

2.10 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 isoccurs
- It shows Piezo, pyro and Ferro electric properties
- All the dielectrics are insulators, but all the insulators are not a dielectrics

2.11 BASIC DEFINITIONS

Electric dipole

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

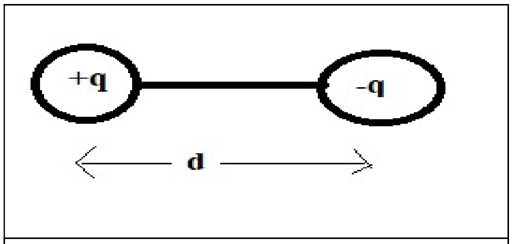


Fig.1 Electric dipole

Dipolemoment (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.

$$\mu=q.d$$

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.

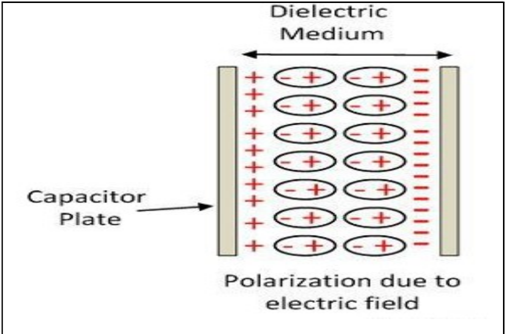


Fig.2 Polarization

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.

$$P \infty E$$

$$P = \varepsilon_0 \chi_e E$$

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, $$P \infty E$$

$$P = \varepsilon_0 \chi_e E$$

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

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 $$\varepsilon_0 E \left(\varepsilon_r - 1\right) = P \quad \text{-----------------------3}$$

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 BETWEENPOLAR AND NON-POLARMOLECULES

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.

2.12 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

2.12.1 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.

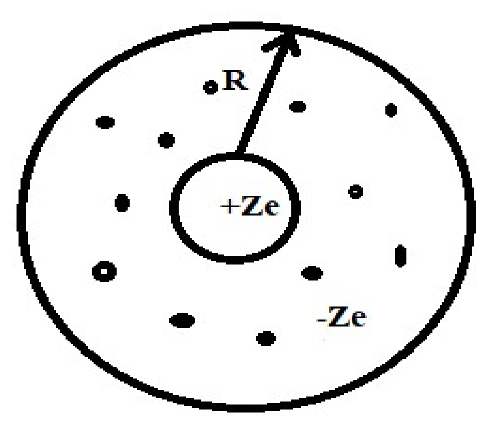


Fig.3 Without field

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

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

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

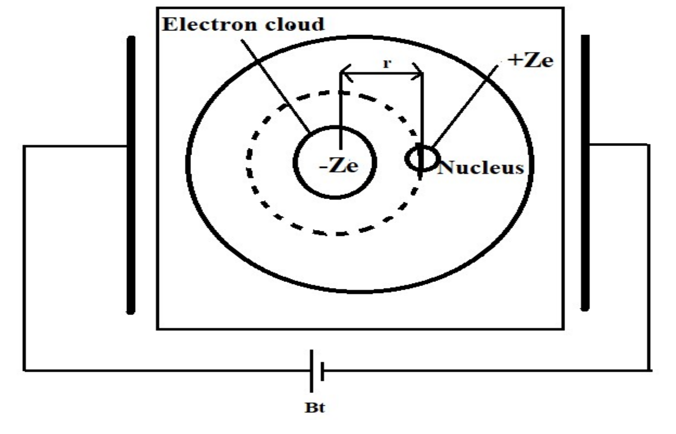


Fig.4 With field

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,

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

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

At equilibrium condition, Lorentz force = Coulomb force

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

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

Rearranging, we get, $r = \frac{4\pi\varepsilon_0 R^3 E}{Ze}$ ----------------------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

μ_e= Ze X r-----------------------------8

Subs. Eqn. 7 in 8 $\mu_e = Ze.\frac{4\pi\varepsilon_0 R^3 E}{Ze}$

Or $\mu_e = 4\pi\varepsilon_0 R^3 E$ ----------------------9

Comparing eqn.1 & 9, we get $\alpha_e = 4\pi\varepsilon_0 R^3$ ------------------------10

Eqn. 10 represents electronic polarizability.

Conclusion:

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

2.12.2 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.

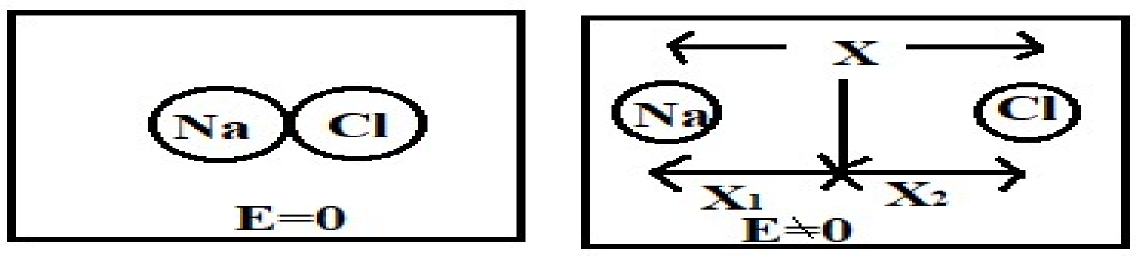


Fig.5 Ionic polarization

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_2be the displacement of positive and negative ions respectively. The total displacement,

$X=X_1+X_2$--2

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

For + ion, $F \infty X_1$

$F = K_1 X_1$ --3

For - ion, $F \infty X_2$

$F = K_2 X_2$ ---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,

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

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

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

$$\mu = \frac{e^2 E}{\omega_0^2}\left(\frac{1}{M_1}+\frac{1}{M_2}\right) \text{---------------------}14$$

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.

2.12.3 Orientation (or) dipolar polarization

Definition:

When an electric field is applied on the dielectric medium with polarmolecules, the electric field tries to align these dipoles along its fielddirection 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

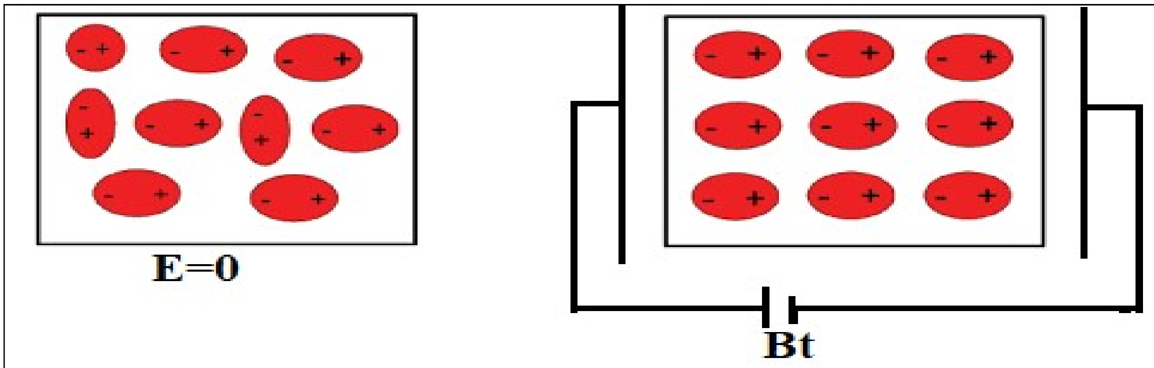


Fig.6 Orientation polarization

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:

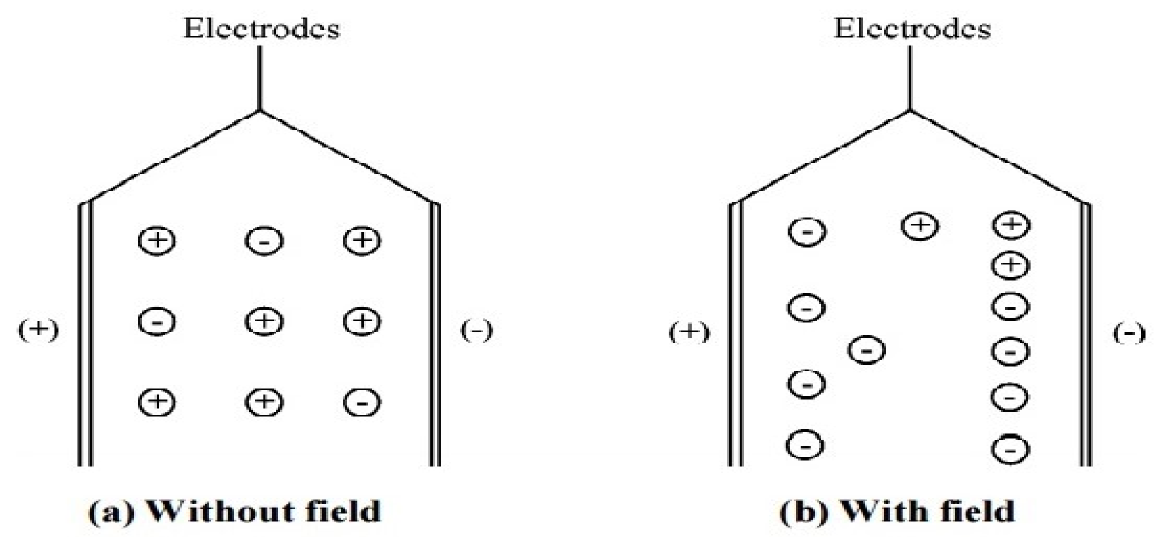
- Orientation polarization change with temperature
- It is temperature dependent

2.12.4 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.



(a) Without field (b) With field

Fig.7 Space charge polarization

It occurs in some semiconducting materials and ferrites.

The space charge polarization is very small. So, it is negligible (α_s=0)

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, $P=NE\alpha$

$$P = NE\left[4\pi\varepsilon_0 R^3 + \frac{e^2}{\omega_0^2}\left(\frac{1}{M_1}+\frac{1}{M_2}\right) + \frac{\mu^2}{3KT}\right] \text{ ------5}$$

Equation 5 is called as ‘Langevin-Debye equation.

UNIT IV PHYSICS OF SEMICONDUCTOR

4.1 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.

4.2 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.

4.3 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

4.3.1 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

4.3.2 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,

4.3.3 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.

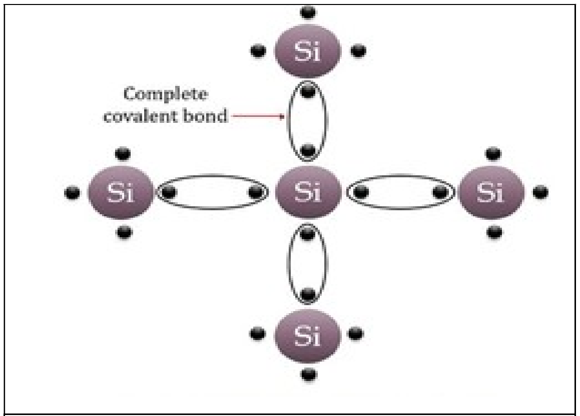


Fig 1 Intrinsic semi-conductor

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.

4.3.4 Extrinsic semiconductor

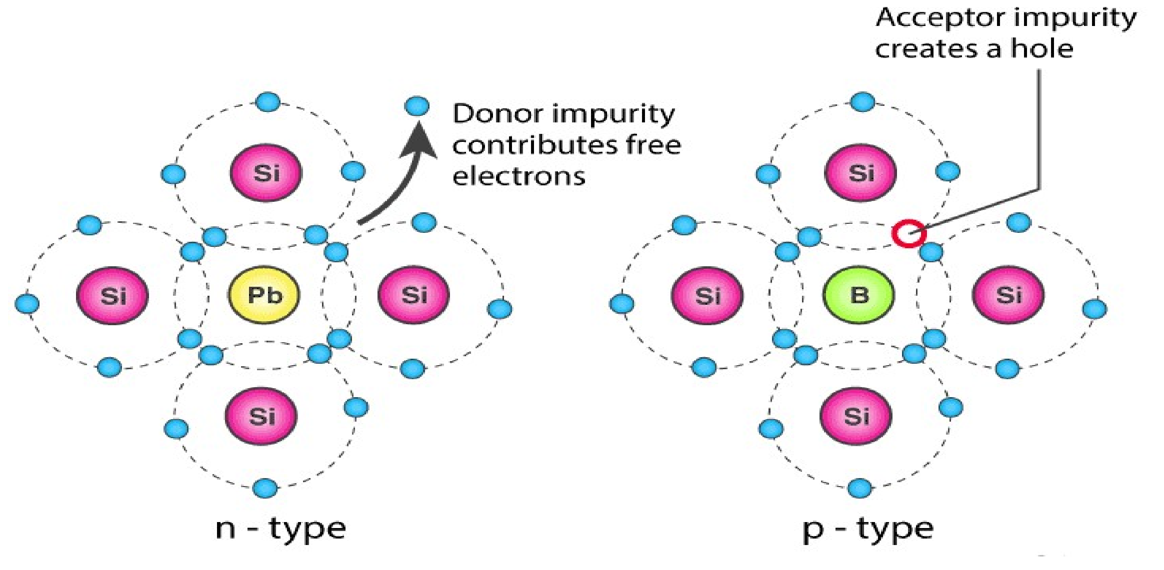


Fig 2. Extrinsic semi-conductor

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 added 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.

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.

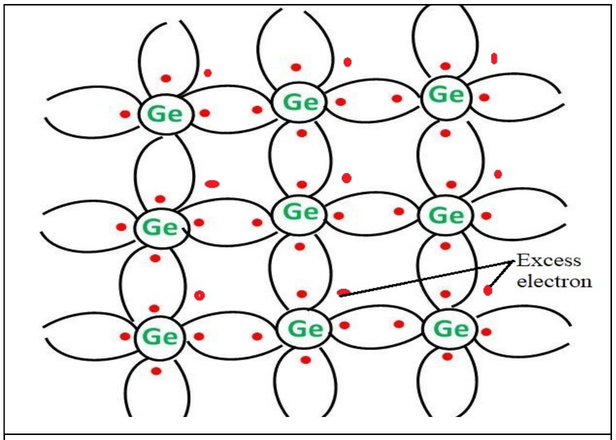


Fig 3. N type semi-conductor

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.

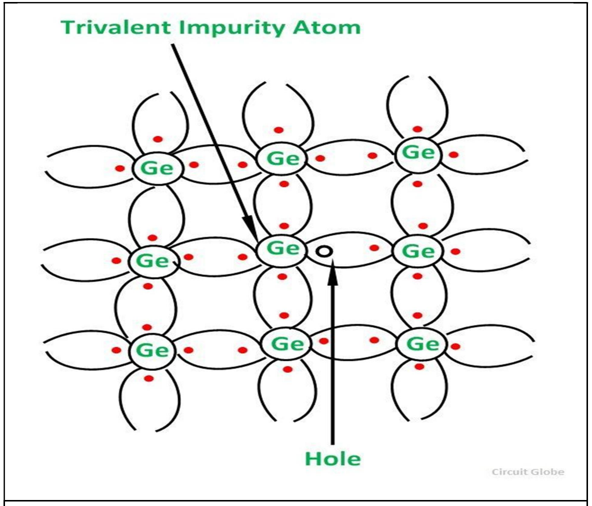


Fig 4. P type semi-conductor

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.

4.3.5 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.

4.4 CARRIER CONCENTRATION IN AN INTRINSIC SEMICONDUCTOR

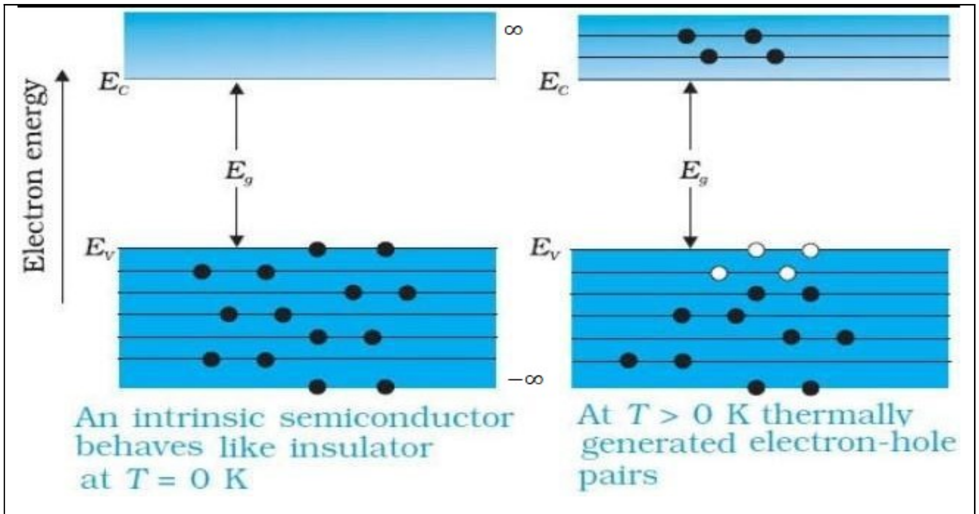


Fig 6. Energy level diagram for intrinsic semi-conductor

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 ∞.

4.4.1 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 $$1+\exp\left[\frac{E-E_F}{KT}\right] \approx \exp\left[\frac{E-E_F}{KT}\right] \text{--6}$$

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

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

------------8

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

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.

4.4.2 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, $N(E)dE = \frac{\pi}{2}\left(\frac{8m}{h^2}\right)^{\frac{3}{2}} E^{\frac{1}{2}} dE$ 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, $x = E_V - E$	Put, $x = E_V - E$	
$E = E_V - x$	$E = E_V - x$	
Differentiating we get	Differentiating we get	--------------------20
$dE = -dx$	$dE = -dx$	
Lower limit $E=-\infty$	upper limit $E=E_V$	
Subs. $x = E_V - (-\infty)$	Subs. $x = E_V - E_V$	
$x = \infty$	$x = 0$	

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.

4.4.3 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.

4.5 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.

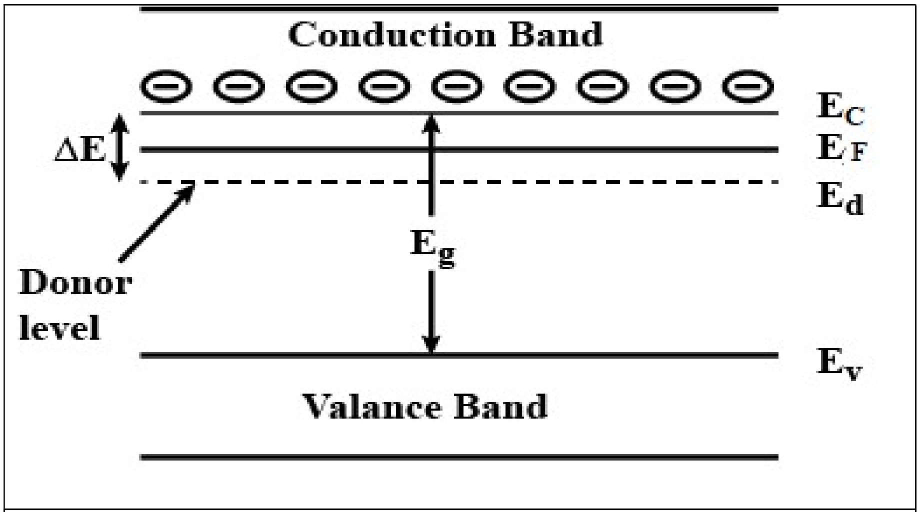


Fig 8. Energy level diagram of N type semiconductor

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

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

Or

If T=0K

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

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

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

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

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

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

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

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

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

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

-------------------------------------9

Subs. ‘x’ value in eqn.9 we get,

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

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

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

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

------------------------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.

4.6 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.

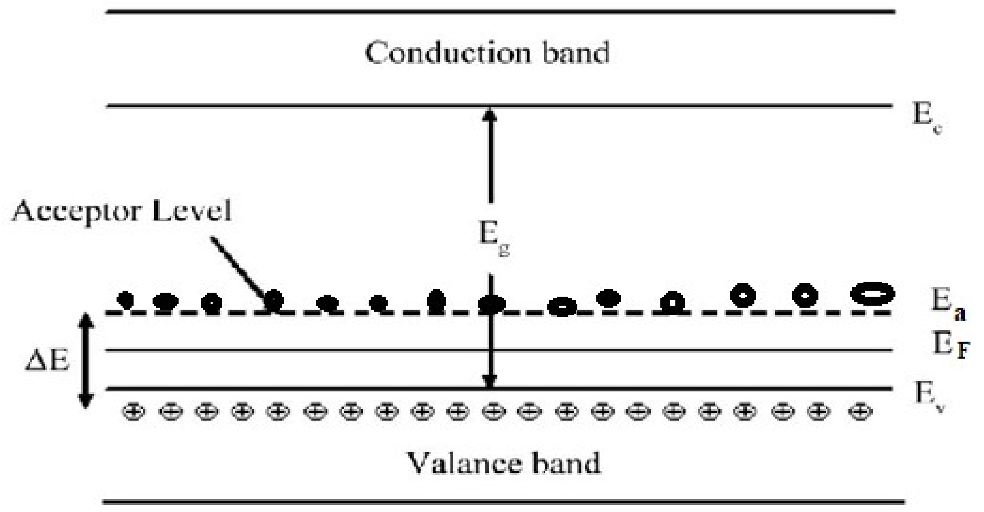


Fig 9. Energy level diagram of P type semiconductor

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

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

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

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

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

Where, N_a represents number of electrons in acceptor energy level

We know,

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

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

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

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

Or ------------------------------------7

If T=0K

$$E_F=\frac{(E_V+E_a)}{2}$$

---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.

4.7 HALL EFFECT

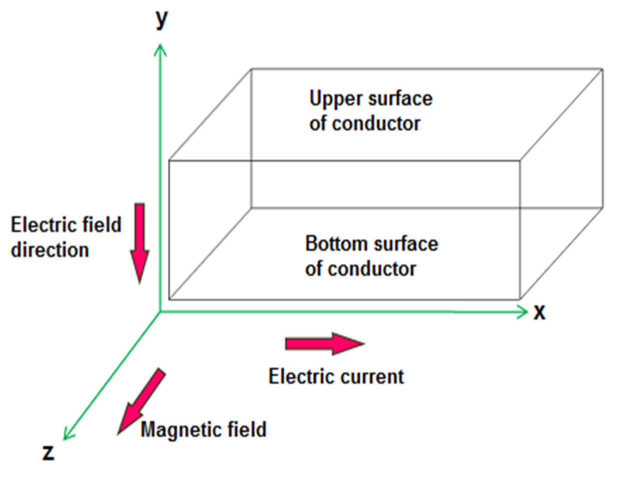


Fig 10. Hall Effect

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.

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.

4.7.1 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.

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.

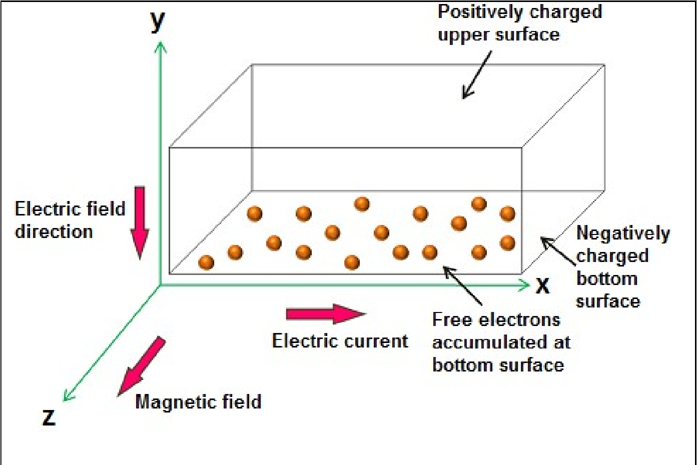


Fig 11. Hall Effect in N type semiconductor

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.

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

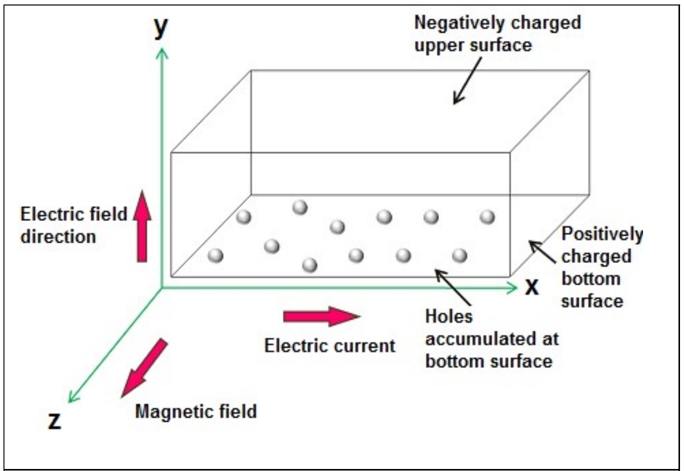


Fig 12. Hall Effect in P type semiconductor

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.

4.7.2 EXPERIMENTAL DETERMINATION OF HALL COEFFICIENT

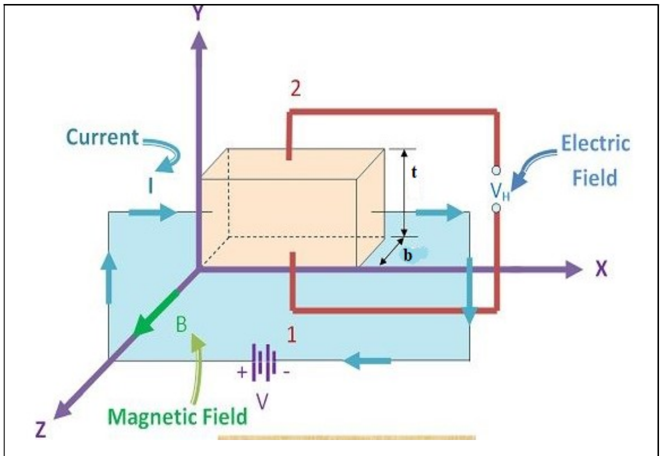


Fig 13. Hall Effect -experiment

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

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.

4.7. 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.

UNIT III MODERN ENGINEERING MATERIALS

5.1 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.

5.2 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.

5.3 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.

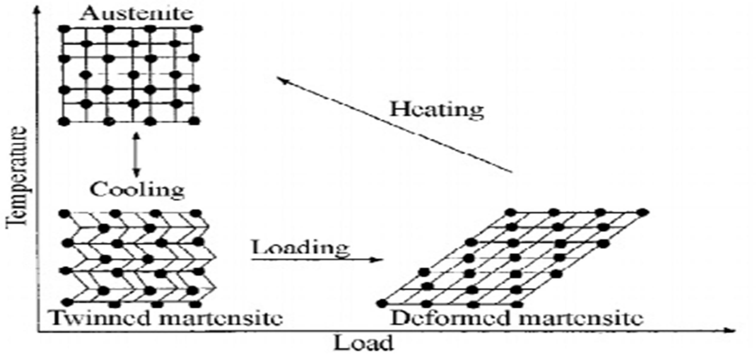


Fig. Material crystalline arrangement during shape memory effect

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.

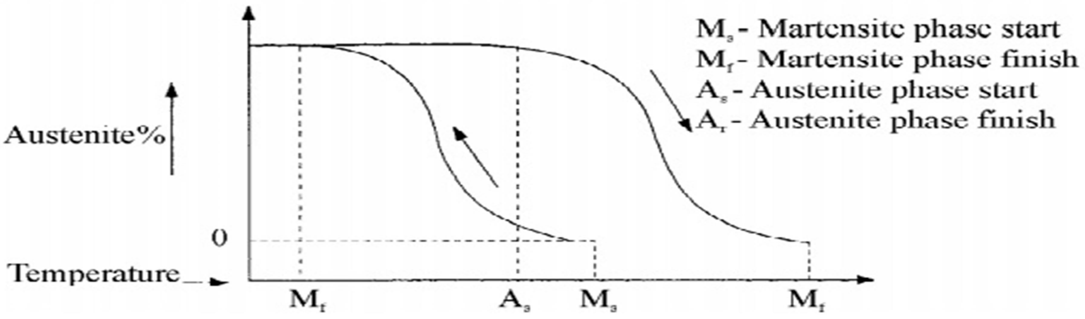


Fig. Hysteresis curve for SMA's

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).

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.

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.

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.

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.

5.4 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.

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.

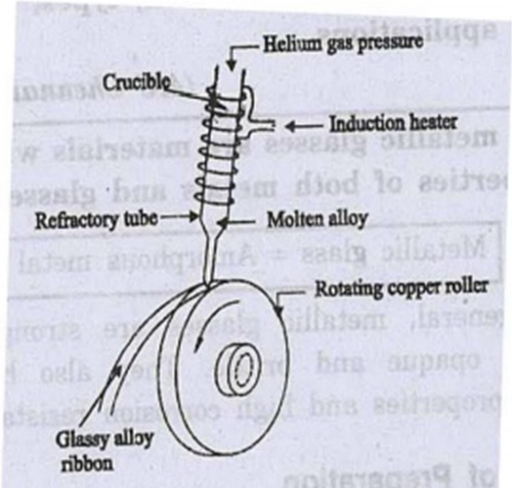


Fig. Melt spinning unit

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.

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

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.

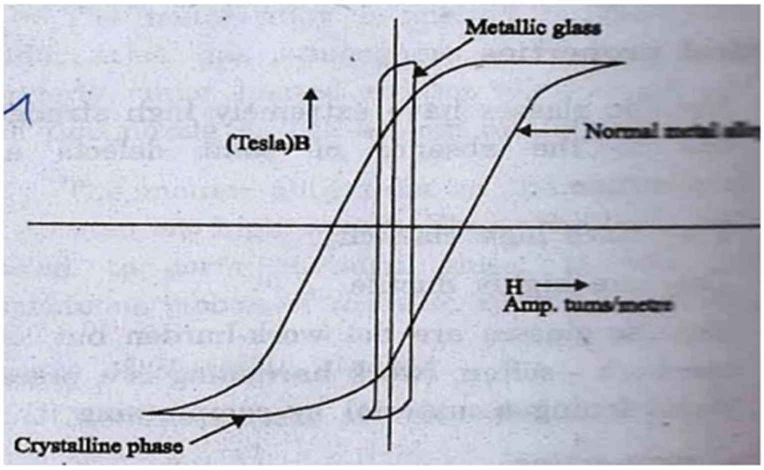


Fig. Hysteresis loop of iron-based alloy in crystalline and metallic glassy phase.

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.

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.

5.5 Definition of Nano System

Nano phase materials are newly developed materials with grain size at the nanometre 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.

Different Forms of Nanomaterials

Nano-structured material

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

Nano particles

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

Nano dots

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

Nanorods

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

Nanotubes

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

Nanowires

Nanowires are nanorods which especially conduct electricity.

Fullerenes

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

Nanocomposites

Composite structures whose characteristic dimensions are found at nanoscale.

Cluster

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

Colloids

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

5.5 Preparation of Nano Phase Materials

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

- Top – down approach
- Bottom – up approach

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.

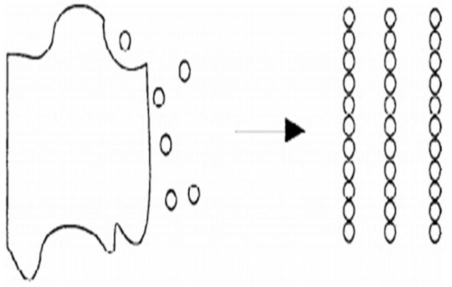


Fig 5.5. Top down approach

Types of Top – down Methods

- Ball Milling
- Lithographic
- Machining

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.

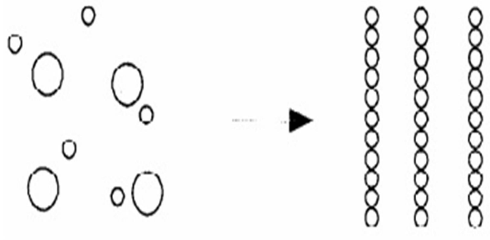


Fig 5.5. Bottom up approach

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]

5.6 Synthesis Methods

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.
- 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

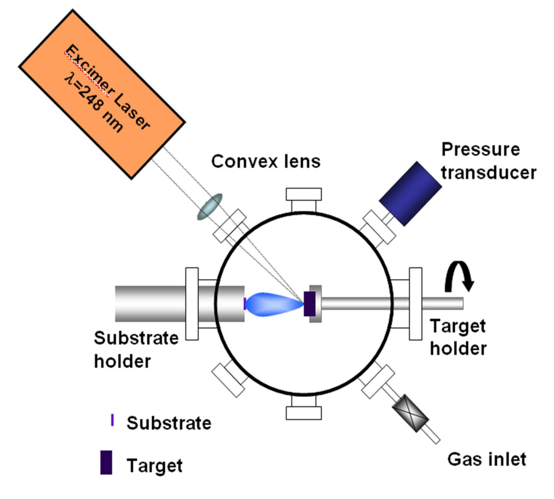


Fig 5.6. Schematics of PLD

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.

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.

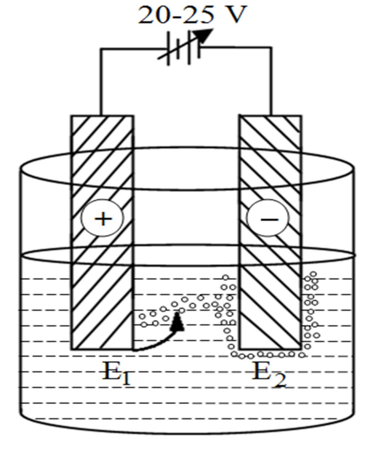


Fig 5.9. Schematics of Electro deposition

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.

5.7 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.

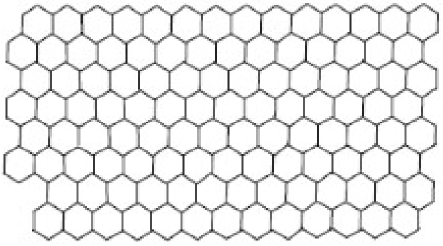


Fig 5.10. Graphene sheet

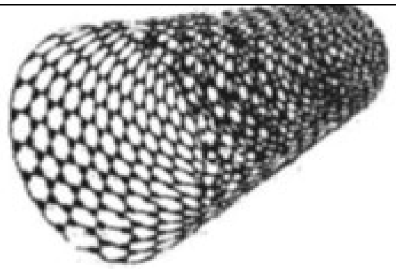


Fig 5.11. Rolled Graphene sheet

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.

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.

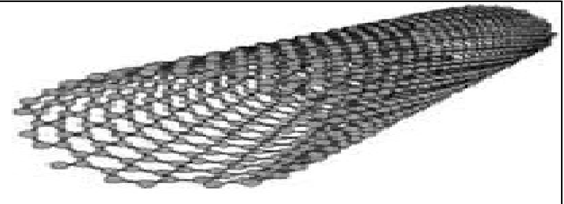


Fig 5.12. SWCNT

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.

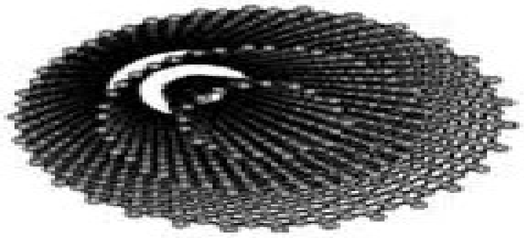


Fig 5.13. MWCNT

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.

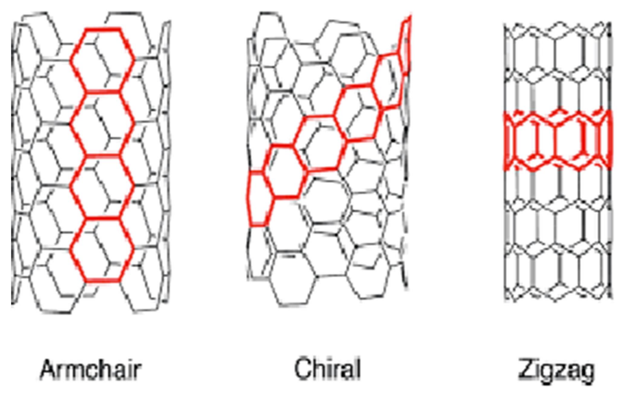


Fig 5.14.

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.

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