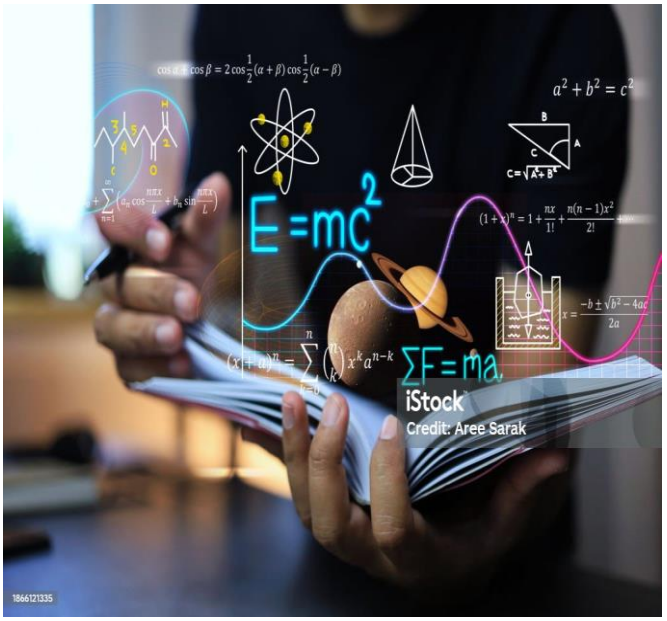

U23PHT24 PHYSICS FOR ELECTRICAL AND ELECTRONICS ENGINEERS

ONLY FOR ECE AND EEE STUDENTS

R-2023

RAJIVGANDHI S
DEPARTMENT OF PHYSICS

U23PHT24	PHYSICS FOR ELECTRICAL AND ELECTRONICS ENGINEERS (COMMON TO EEE AND ECE PROGRAMMES)	L	T	P	C
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COURSE OBJECTIVES

The main learning objective of this course is to prepare the students for:

1.	To make the students to understand the basics of crystallography and its importance in studying materials properties.
2.	To expand their knowledge in applications of magnetic and superconducting materials in small scale industries.
3.	To make the students to understand the basics of dielectric materials and insulation.
4.	To inculcate an idea of significance of new materials, nanostructures ensuing nano device applications.
5.	To know the basic building of electronic circuits using gates.

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	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 – Messiner effect-Type I and Type II Superconductors – London equations – High temperature super conductor – Applications: SQUIDS- Magnetic Levitated Train.

UNIT III	DIELECTRIC AND FERRO ELECTRIC MATERIALS	9

Introduction – Basic Definitions - Types of Polarization Mechanisms - Langevin- Debye Equation - Internal Field – Clausius - Mossotti Relation - Dielectric Loss – Dielectric Breakdown– Applications of Dielectric Materials.

Ferro Electric Materials: Properties – Ferromagnetic Hysteresis – Properties- Applications.

UNIT IV	MODERN ENGINEERING MATERIALS	9

Shape Memory Alloys – Structures – Types – Properties – Applications. Metallic Glasses – Types – Preparation, properties and Applications. Ceramics – Types - Properties and Applications.

UNIT V	NANOMATERIALS	9

Nanomaterials – quantum confined nano structures and its derivations – Properties and Applications – Preparation Techniques: Electrodeposition – Pulsed Laser Deposition. Carbon nano tubes – Structure – Types – Properties – Applications.

TOTAL: 45 PERIODS

COURSE OUTCOMES:

At the end of the course the students would be able to

CO1 :	Know basics of crystallography and its importance for varied materials properties.
CO2 :	Gain knowledge on the magnetic and superconductor properties of materials and theirapplications.

CO3:	Use the dielectric and insulating materials in electronic devices.
CO4:	Illustrate the SMA and metallic glasses.
CO5:	Get knowledge on newly developed materials in micro and nano scale.
CO6:	Summarize the different structures of CNT in Nano range

TEXT BOOKS:

1.	Charles Kittel, Introduction to Solid State Physics, Wiley India Edition, 2019.
2.	G.W.Hanson. Fundamentals of Nanoelectronics. Pearson Education (Indian Edition) 2009.
3.	Dr. P. Mani, "Physics for Electronics Engineering" Dhanam Publications, 2017.
4.	Dr. G. Senthilkumar, "Engineering Physics II" VRB Publishers, 2013.
5.	Theraja .B.L., Basic electronics solid state, S.Chand and Company Ltd (2002).

REFERENCE BOOKS:

1.	R.Balasubramaniam, Callister's Materials Science and Engineering. Wiley (Indian Edition), 2014.
2.	Robert F.Pierret, Semiconductor Device Fundamentals, Pearson, 2006.
3.	Dr. G. Senthilkumar, A. Ravikumar & S. Rajivgandhi, " Engineering Physics II", VRB Publishers, 2023
4.	Ben Rogers, Jesse Adams and Sumita Pennathur, Nanotechnology: Understanding Small Systems, CRC Press, 2017.
5.	Sedha R.S., A text book of applied Electronies, S.Chand & company Ltd (2002).
6.	S. O. Pillai, "Solid State Physics", New Age International, New Delhi, 1995

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.

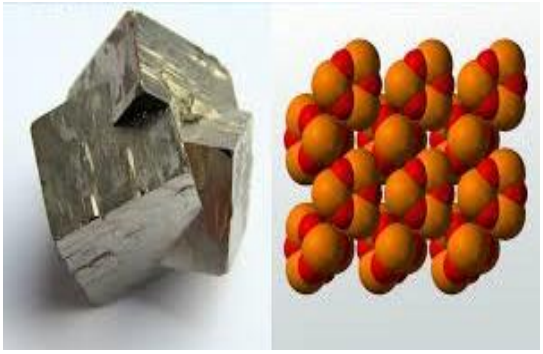


Fig 1. Solids

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.

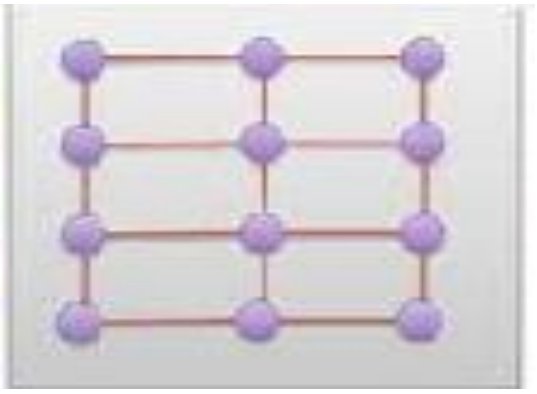


Fig 2. Crystalline Solids

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.**

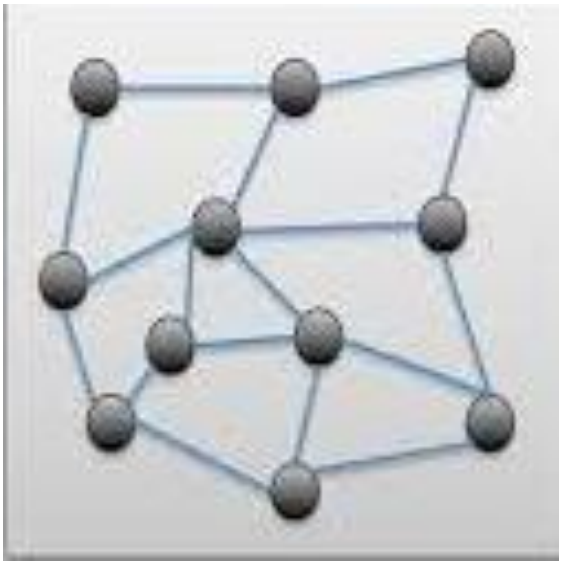


Fig 3. Amorphous Solids

Examples: Glass, Plastic and Rubber.

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.

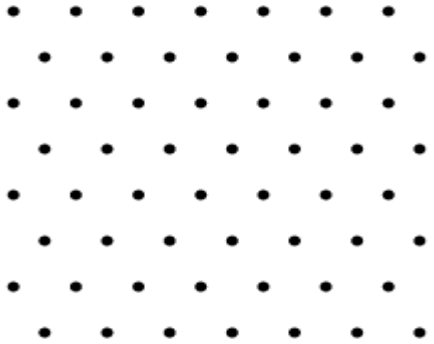


Fig 4. Lattice and Lattice Point

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.

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.

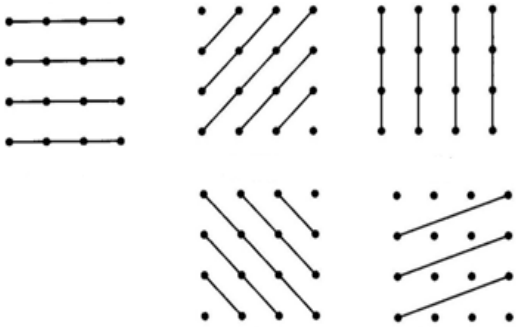


Fig 5. Lattice lines and Lattice plane

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.

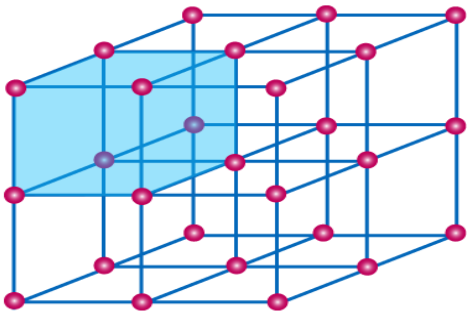


Fig 6. Space Lattice and Unit cell

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.

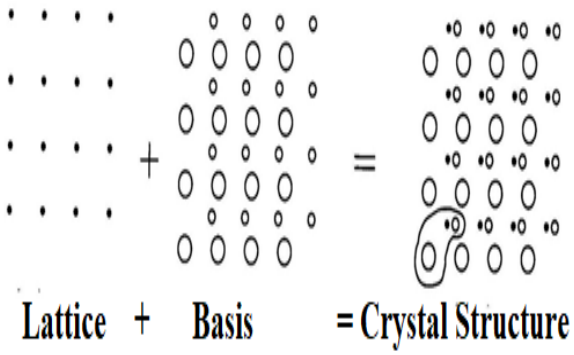


Fig 7. Basis and Crystal structure

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.

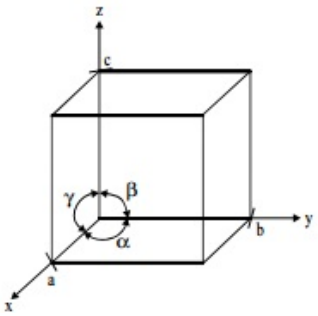


Fig 8. Lattice Parameters

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. $a \neq b \neq c$

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

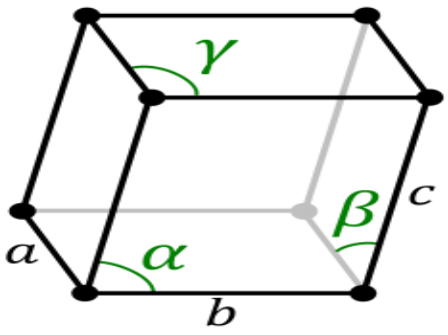


Fig9. Triclinic System

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. $a \neq b \neq c$

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

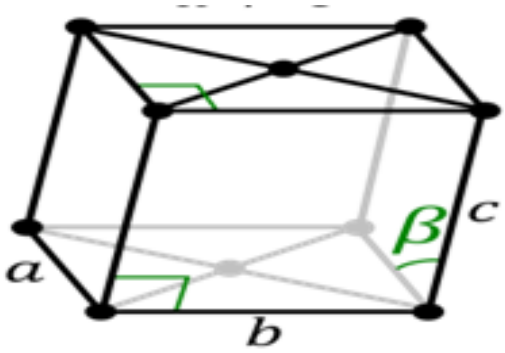


Fig10Monoclinic System

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

Orthorhombic System:

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

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

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

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

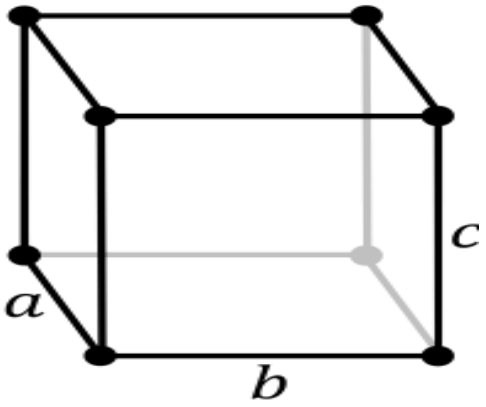


Fig 11. Orthorhombic System

Trigonal System:

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

i.e. $a = b = c$

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

Some typical examples include Ruby, Quartz,Calcite

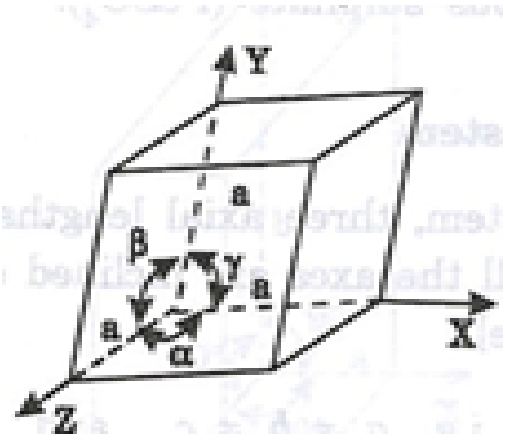


Fig 12.Trigonal

Hexagonal System:

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

The interfacial angle angles α and β are perpendicular to each other. But the angle γ = 120º

i.e.a = b ≠ c

α = β = 90º, γ = 120º

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

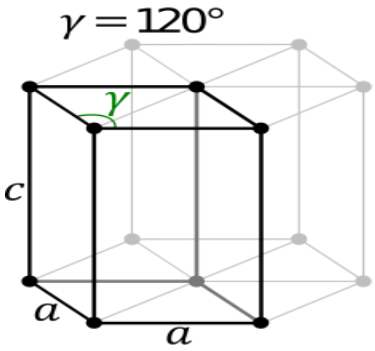


Fig. 13.Hexagonal System

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

α = β = γ = 90º

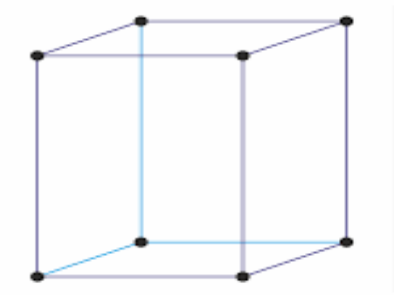


Fig. 14.Tetragonal System

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

Cubic System:

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

i.e. a=b=c

α = β = γ = 90º

Example: Silver, Garnet, Gold, and Diamond.

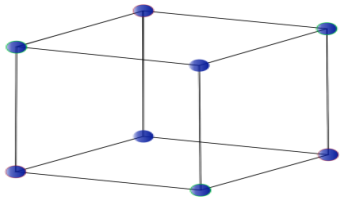


Fig. 15.Cubic System

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

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 ≠ c	$\alpha = \beta = \gamma = 90^o$	P, I	2
3.	Orthorhombic	a ≠ b ≠ c	$\alpha = \beta = \gamma = 90^o$	P, I, F, C	4
4.	Monoclinic	a ≠ b ≠ c	$\alpha = \beta = 90^o, \gamma \neq 90^o$	P, C	2
5.	Triclinic	a ≠ b ≠ 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 ≠ c	$\alpha = \beta = 90^o, \gamma \neq 120^o$	P	1
Total					**14**

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

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

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

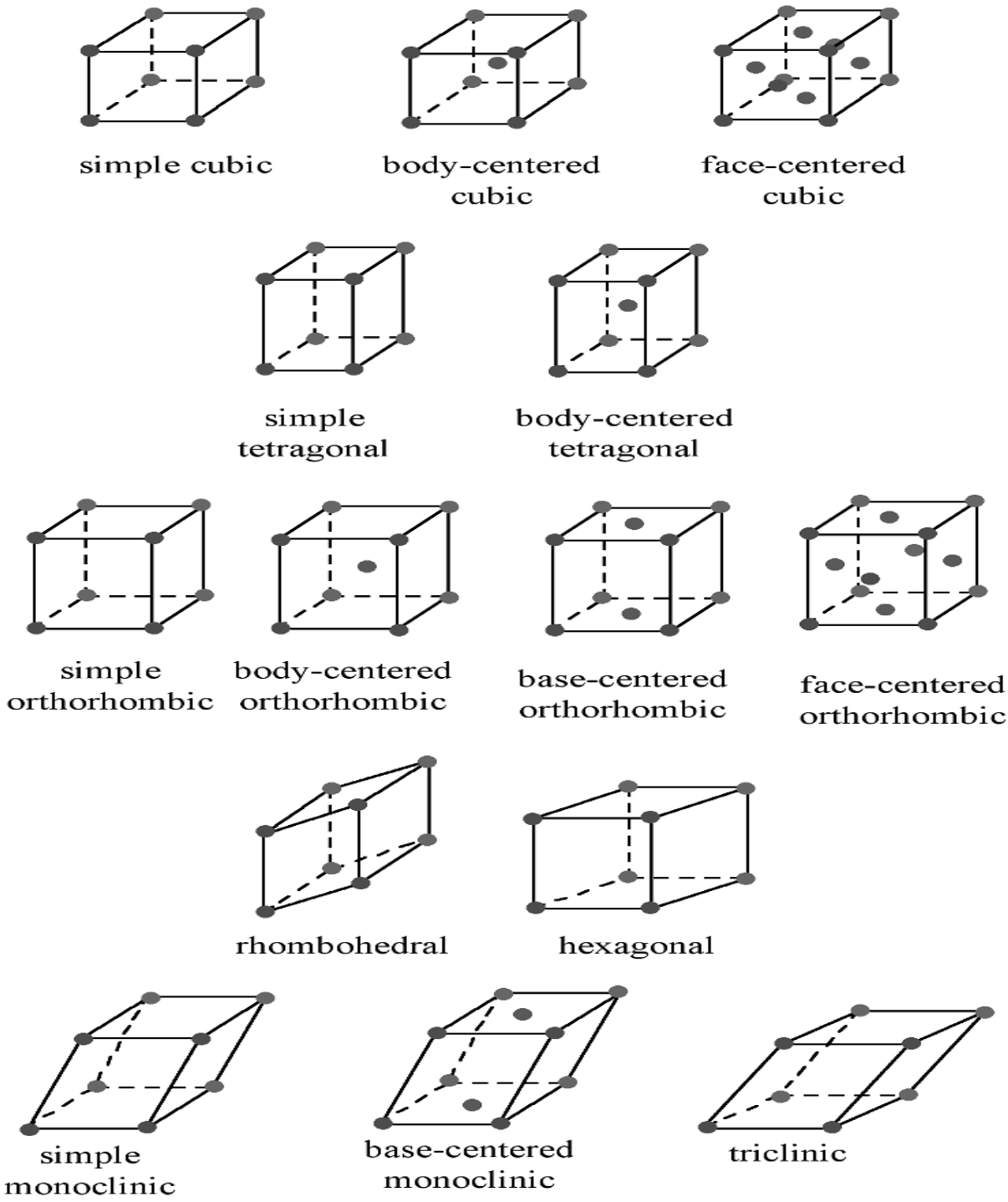


Fig 16. Bravai's Lattices

1.8 CRYSTAL PARAMETERS

1. 8.1 Number of atoms per unit cell:

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

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

1.8.2 Atomic radius or Ionic radius

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

1.8.3Coordination number

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

1.8.4 Atomic factor or atomic packing density

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

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

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

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

1.9 CUBIC CRYSTAL SYSTEMS

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

1.9.1 SIMPLE CUBIC STRUCTURE(SC)

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

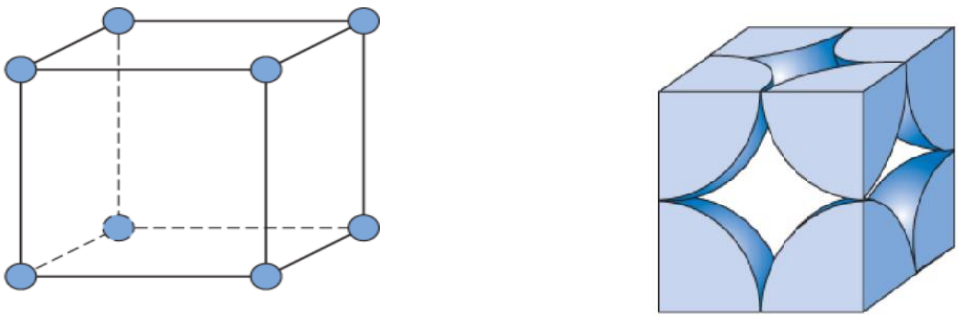


Fig 17. Simple cubic system

Number of atoms per unit cell:

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

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

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

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

Coordination number

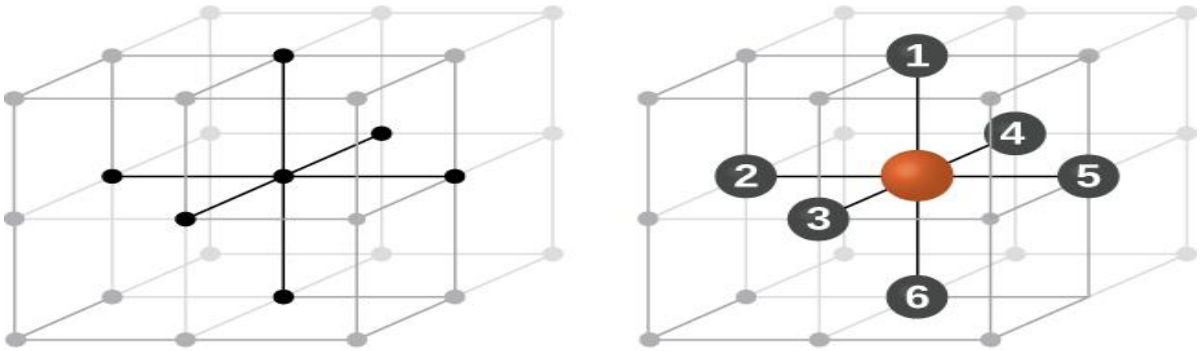


Fig 18. Coordination number

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

Atomic radius or Ionic radius

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

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

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

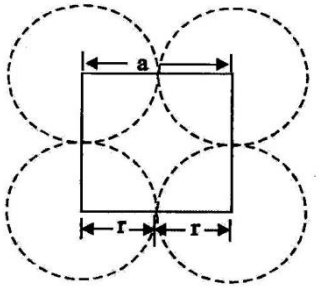


Fig 19. Atomic radius

Atomic packing factor or atomic packing density

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

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

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

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

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.

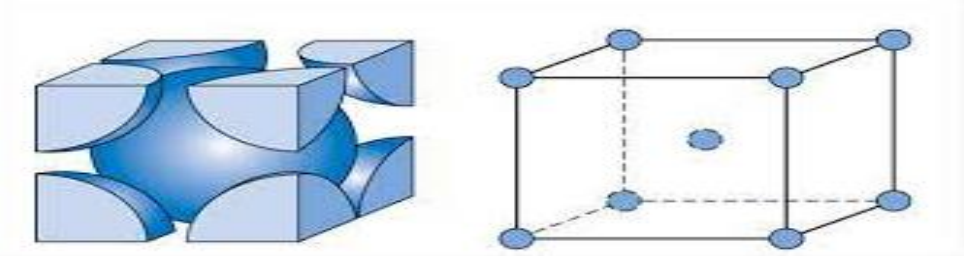


Fig 20. Body centered cubic system

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

Coordination number:

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

The co-ordination number is 8.

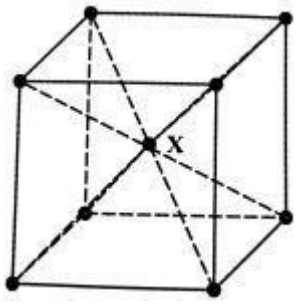


Fig 21. Coordination number of BCC

Atomic radius:

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

In the triangle ACD

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

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

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

$16r^2 = 3a^2$

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

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

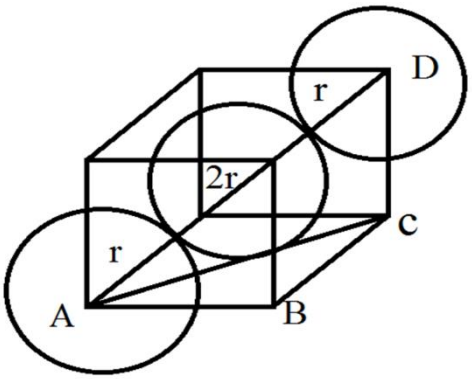


Fig 22. Atomic radius

Atomic packing factor:

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

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

No. of atom / unit cell = 2

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

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

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

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

1.9.3FACE 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.

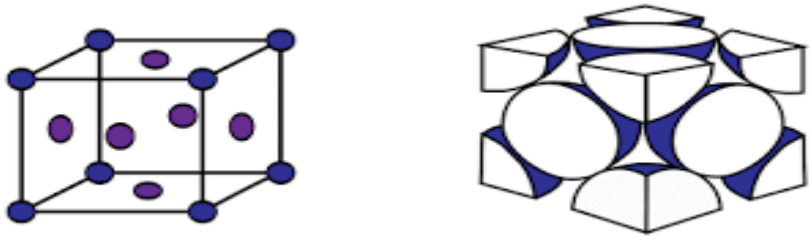


Fig 23. Face centered cubic system

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).

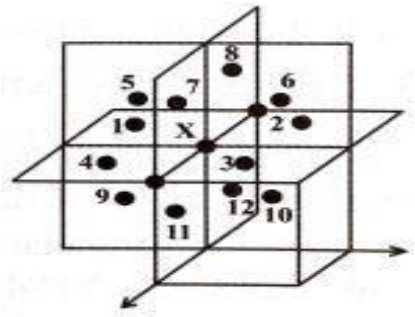


Fig 24. Coordination number of FCC

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

Atomic radius:

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

In the triangle ABC

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

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

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

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

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

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

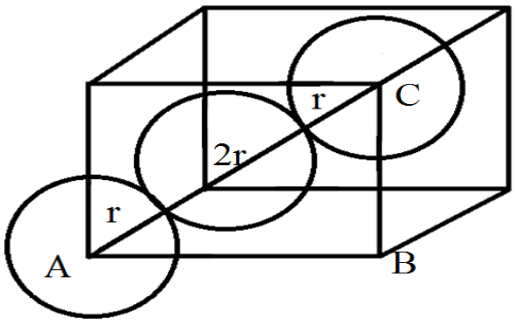


Fig 25. Atomic radius

Atomic Packing factor:x

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

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

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

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

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

1.9.4HEXAHONAL 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.

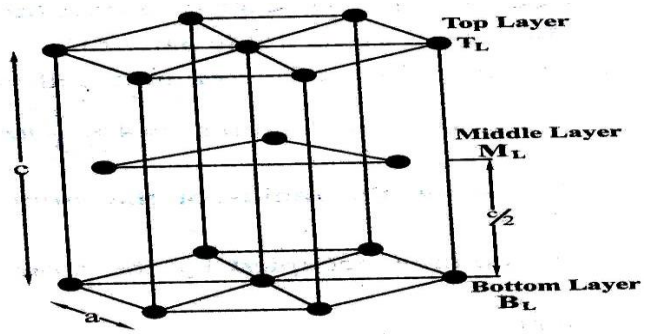


Fig 26. Hexagonal closely packed structure

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.

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

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

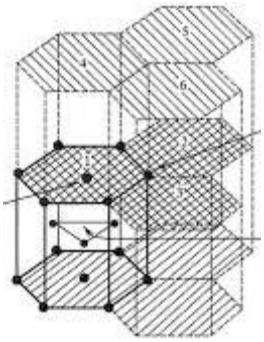


Fig 27. 6 unit cell structure

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.

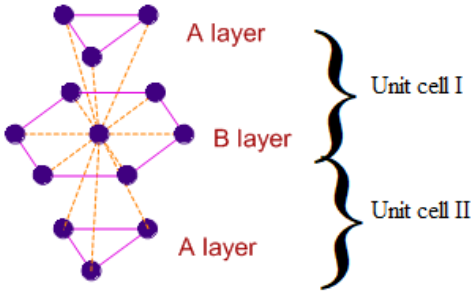


Fig 28. Coordination number

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

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

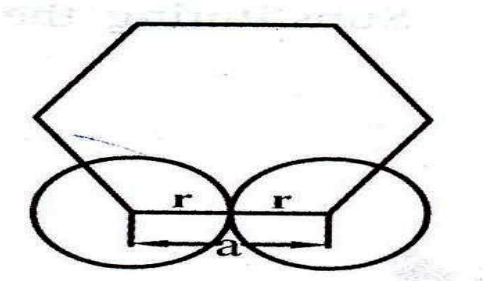


Fig 29. Atomic radius

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.

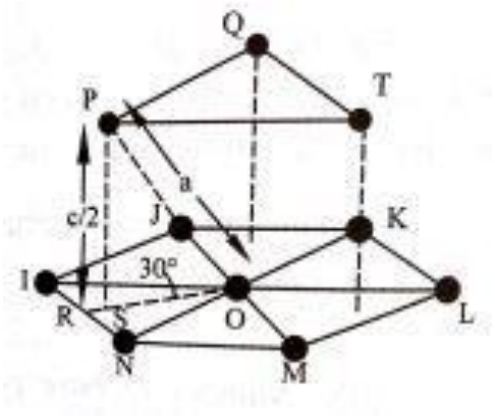


Fig 30. c/a ratio

In the triangle IRO,

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

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

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

We can write

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

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

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

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

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

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

In the triangle SOP,

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

Here, SP = c/2 and OP = a

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

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

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

Rearranging we get,

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

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

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

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

Atomic packing factor (APF):

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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.

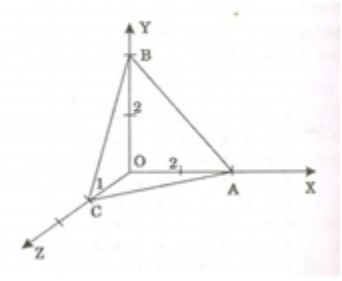


Fig 31. Example

- 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

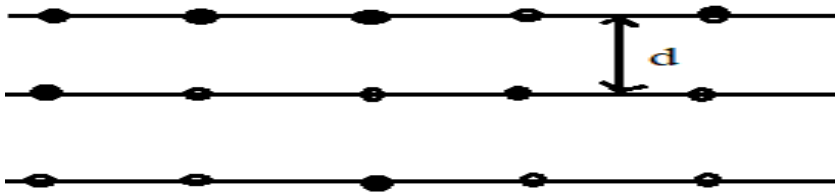


Fig 32. Interplanar spacing

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:

- 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.

$$ON = d_1$$

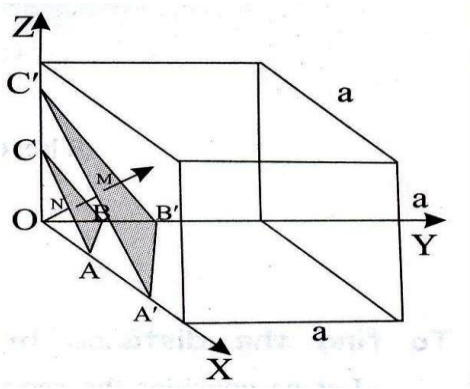


Fig 33. Interplanar spacing

- 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

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

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

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

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

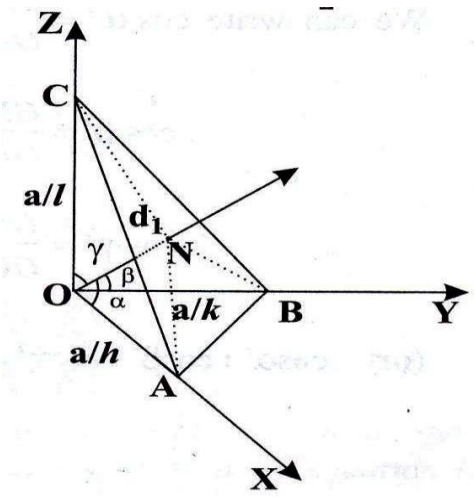


Fig 34. To find d_1

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

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

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

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

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

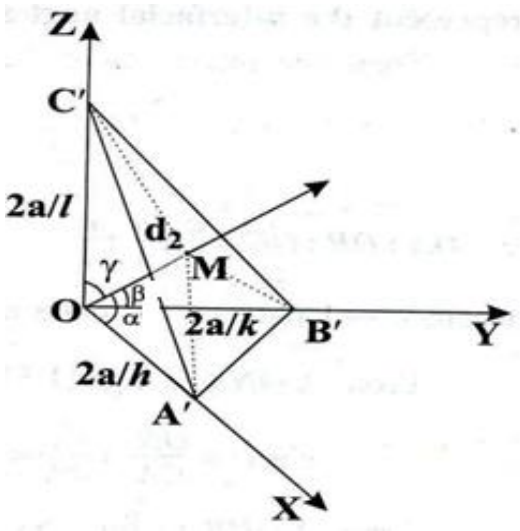


Fig 35. To find d_2

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,

$$\left(\frac{d_2h}{2a}\right)^2+\left(\frac{d_2k}{2a}\right)^2+\left(\frac{d_2l}{2a}\right)^2=1$$

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

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

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 = 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).

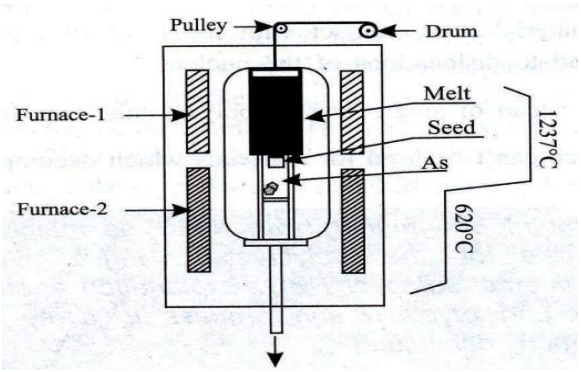


Fig 36. Bridgmann method

- 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

- 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.

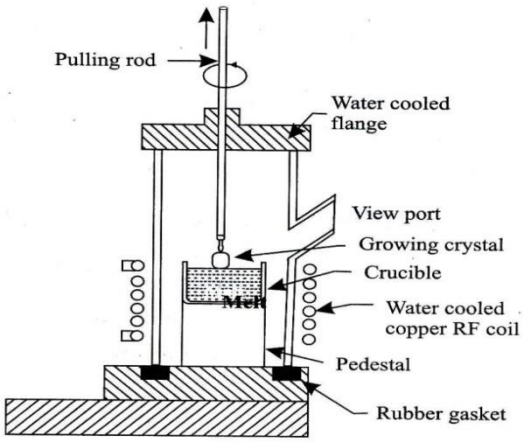


Fig 37. Czochralski method

- 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 MAGNETIC AND SUPERCONDUCTING MATERIALS

2.1 INTRODUCTION

People have been aware of magnets and magnetism for thousands of years. The earliest records date to well before the time of Christ, particularly in a region of Asia Minor called Magnesia (the name of this region is the source of words like magnetic). Magnetic rocks found in Magnesia, which is now part of western Turkey, stimulated interest during ancient times. A practical application for magnets was found later, when they were employed as navigational compasses. The use of magnets in compasses resulted not only in improved long-distance sailing, but also in the names of "north" and "south" being given to the two types of magnetic poles.

Today magnetism plays many important roles in our lives. Physicists' understanding of magnetism has enabled the development of technologies that affect our everyday lives. The iPod in your purse or backpack, for example, wouldn't have been possible without the applications of magnetism and electricity on a small scale.

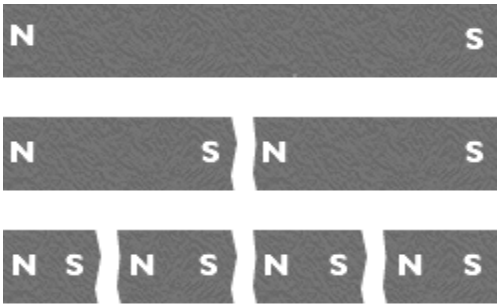


Fig 1. Magnets

The discovery that weak changes in a magnetic field in a thin film of iron and chromium could bring about much larger changes in electrical resistance was one of the first large successes of nanotechnology. The 2007 Nobel Prize in Physics went to Albert Fert from France and Peter Grunberg from Germany for this discovery of giant magneto resistance and its applications to computer memory.

All electric motors, with uses as diverse as powering refrigerators, starting cars, and moving elevators, contain magnets. Generators, whether producing hydroelectric power or running bicycle lights, use magnetic fields. Recycling facilities employ magnets to separate iron from other refuse. Hundreds of millions of dollars are spent annually on magnetic containment of fusion as a future energy source. Magnetic resonance imaging (MRI) has become an important diagnostic tool in the field of medicine, and the use of magnetism to explore brain activity is a subject of contemporary research and development. The list of applications also includes computer hard drives, tape recording, detection of inhaled asbestos, and levitation of high-speed trains.

Magnetism is used to explain atomic energy levels, cosmic rays, and charged particles trapped in the Van Allen belts. Once again, we will find all these disparate phenomena are linked by a small number of underlying physical principles.

2.2 BASIC DEFINITIONS

Magnetic Dipole

A system consists of equal and opposite poles which are separated by small distance d is called magnetic dipole.

Magnetic Dipole moment (M)

The dipole moment is defined as the product of magnetic pole strength and length of the magnet. It is given by

M = m X d.

Unit: Amp m^2

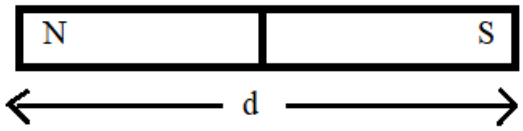


Fig 2. Magnetic dipole

Magnetic Field

The space around which the magnetic lines of forces exist is called as magnetic field. Magnetic field is produced by permanent magnets such as a horse shoe magnet and temporarily by elelctromagnets (or) superconducting magnets.

Magnetic Lines of Force

The continuous curve in a magnetic field that exists from North Pole to South Pole is called as magnetic lines of force.

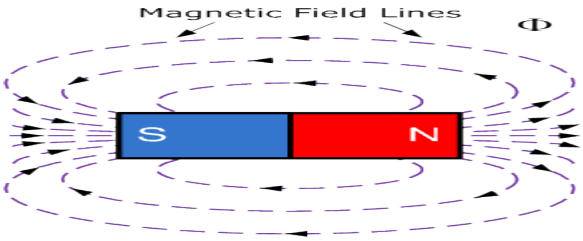


Fig 3. Magnetic lines of forces

Magnetic Flux (ϕ)

The total number of magnetic lines of force passing through a surface of the material.

Unit: weber

Magnetic Induction (B) (or) Magnetic Flux Density

It is the number of magnetic lines of force passing through unit area of cross section.

Magnetic induction, $B = \frac{\phi}{A}$

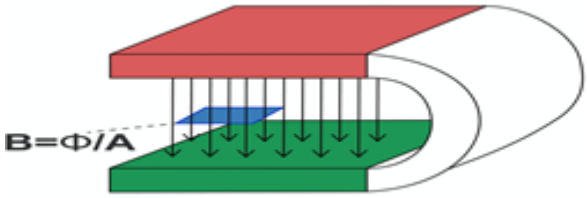


Fig 4. Magnetic flux density

Unit: weber $metre^{-2}$ or Tesla

Magnetic Field Strength (or) Magnetizing Field (H)

It is the force experienced by a unit North Pole placed at a given point in a magnetic field.

The magnetic induction B due to the magnetic field of intensity H applied in vacuum is related by

$$B = \mu_0 H$$

Unit: Amp/m

Intensity of Magnetization (I)

Magnetization is the process of converting a non-magnetic material in to a magnetic material.

It is also defined as the magnetic moment per unit volume.

$$I = \frac{M}{V}$$

Unit: web m^{-2}.

Magnetic Permeability (μ)

It is ratio of the magnetic induction (B) to the applied magnetic field intensity (H).

$$\mu = \frac{B}{H}$$

Unit: Henry m^{-1}

It is the measure of ability of the material to permit magnetic lines of force.

Relative Permeability (μ_r)

It is defined as the ratio of permeability of the medium to the permeability of the free space (μr).

$$\mu_r = \frac{\mu}{\mu_0}$$

Magnetic Susceptibility (χ)

It is defined as the ratio of intensity of magnetization (I) and intensity of magnetic field (H).

$$\chi = \frac{I}{H}$$

The sign and magnitude of χ are used to determine the nature of the magnetic materials.

Orbital magnetic moment

This magnetic moment is due to the orbital motion of electron around nucleus.

Spin magnetic moment

If magnetic moment arises due to spin of electrons itself around the nucleus. Then,

Example: The earth around the sun.

Bohr Magnetron (μ_B)

The orbital magnetic moment and the spin magnetic moment of an electron in an atom can be expressed in terms of atomic unit of magnetic moment called as Bohr magnetron.

$$1\,\text{Bohr magneton} = \frac{eh}{4\pi m} = \mu_B = 9.27x10^{-24}\,Am^2$$

Relation between susceptibility (χ) and Relative permeability (μ_r)

We know that when a current is supplied through a coil, magnetic field is developed. When a magnetic material is placed inside a external magnetic field, the magnetic flux density (B) arises due to applied magnetic field (H) and also due to the induced magnetization (I).

i.e., the total flux density,

$$B = \mu_0 (I + H) \text{ ----------1}$$

We know, $\mu = \frac{B}{H}$

Rearranging $B = \mu H$ ----------2

Equating eqns 1&2

$$\mu H = \mu_0 (I + H)$$

Dividing by H, we get

$$\mu = \mu_0 (\frac{I}{H} + 1) \text{ ----------3}$$

We know, $\chi = \frac{I}{H}$

Eqn 3 can be written as

$$\mu = \mu_0 (\chi + 1)$$

Or $\frac{\mu}{\mu_0} = (\chi + 1)$

We know, $\mu_r = \frac{\mu}{\mu_0}$

$$\mu_r = (\chi + 1) \text{ ----------4}$$

Equation 4 gives the relation between relative permeability and magnetic susceptibility.

Retentivity or Remanence

When an external field is applied to the specimen it is magnetized and when the field is removed it is demagnetized. But some materials do not completely demagnetize when field is removed. There is some magnetism left out in the specimen. “This residual magnetism which is left out even after the removal of the external magnetic field” is called as the Retentivity or Remanence.

Coercivity

The residual magnetism can be removed completely from the material by applying a reverse magnetic field. “The reverse magnetic field which is used to completely remove the residual magnetism” is called as the coercivity.

2.3. ORIGIN OF MAGNETIC MOMENT

The macroscopic magnetic properties of a substance are a consequence of magnetic moments associated with individual electrons. Each electron in an atom has magnetic moments that originate from the following two sources

1. Orbital magnetic moment of electrons
2. Spin magnetic moment of electrons.

We know that the electrons in an atom revolve around the nucleus in different orbits. Basically, there are three contributions for the magnetic dipole moment of an atom.

The motion of electrons in the closed orbits around the nucleus is called as orbital magnetic moment. Its magnitude is always small. Spin motion of the electrons (i.e. due to electron spin angular momentum) and it is called as spin magnetic moment.

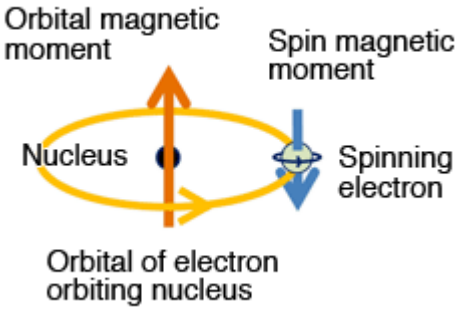


Fig 5. Orbital and Spin magnetic moment

The contribution from the nuclear spin (i.e., due to nuclear spin angular momentum). Since this is nearly 10^3 times smaller than that of electron spin, it is not taken into consideration.

For all practical purposes, we assume that the magnetic moment arises due to the electron spin ignoring the orbital magnetic moments and the nuclear magnetic moments as their magnitudes are small.

We may note that permanent magnetic moments can also arise from spin magnetic moments of the nucleus. Of all the three, the spin dipole moments of electrons are important in most magnetic materials.

Orbital angular momentum

This corresponds to permanent magnetic dipole moments. Let us consider an electron describing a circular orbit of radius ‘r’ with a stationary nucleus at the centre. Let the electron rotate with a constant angular velocity of ‘w’ radians per second.

Electron revolving in any orbit may be considered as current carrying circular coil producing magnetic field perpendicular to its plane. Thus the electronic orbits are associated with a magnetic moment. The orbital magnetic moment of an electron in an atom can be expressed in terms of atomic unit of magnetic moment called Bohr Magnetron, defined as

$$1\,\text{Bohr magneton} = \frac{eh}{4\pi m} = \mu_B = 9.27x10^{-24}\,Am^2$$

Electron spin magnetic moment

The concept of the electron having an angular momentum has been introduced in order to explain the details of atomic spectra. This angular momentum of the electron is referred to as the spin of the electron. Since the e- has a charge, its spin produces a magnetic dipole moment.

According to quantum theory, the spin angular momentum along a given direction is

$$\frac{+h}{4\pi} \quad \text{or} \quad \frac{-h}{4\pi}$$

Hence the spin dipole moment components along an external field are

$$1\,\text{Bohr magneton} = \mu_B = \frac{eh}{4\pi m}$$

Or $$-1\,\text{Bohr magneton} = -\mu_B = -\frac{eh}{4\pi m}$$

In a many electron atom, the individual spin magnetic moments are added in accordance with certain rules. Completely filled shells contribute nothing to the resultant spin moment.

Nuclear magnetic moment

The angular momentum associated with the nuclear spin is also measured in units of $\frac{h}{2\pi}$. The mass of the nucleus is larger than that of an e- by the order of 10^3. Hence nuclear spin magnetic moment is of the order of 10^{-3} Bohr magnetrons.

2.4. CLASSIFICATION OF MAGNETIC MATERIALS

There are 11 types of magnetic materials are available in universe. Same important types of magnetic materials are explained below.

Based on presence of permanent dipole moment, the magnetic materials are classified as follows:

- The material have no permanent dipole moment,
  - Dia magnetic materials
- The material have permanent dipole moment,
  - Para magnetic materials
  - Ferro magnetic materials
  - Anti Ferro magnetic materials
  - Ferri magnetic materials

Based on magnetization, the magnetic materials are classified as follows:

- Soft magnetic materials
- Hard magnetic materials

2.4.1. DIA MAGNETIC MATERIALS

Definition

In a diamagnetic material the electron orbits are randomly oriented and the orbital magnetic moments get cancelled. Similarly, all the spin moments are paired i.e., having even number of electrons. Therefore, the electrons are spinning in two opposite directions and hence the net magnetic moment is zero. It is also called as weak magnetic materials.

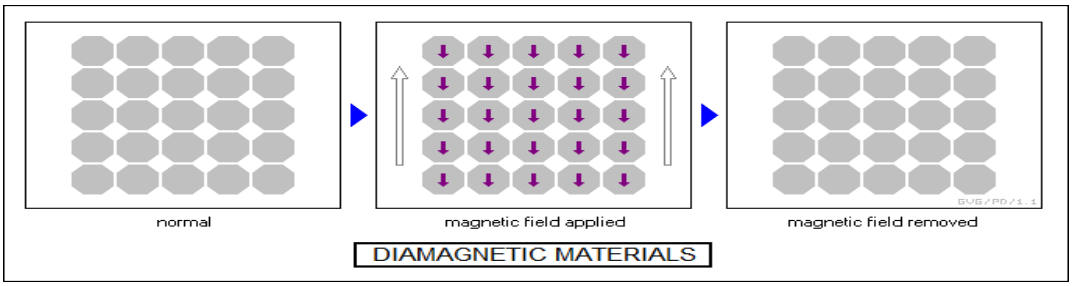


Fig 6. Diamagnetism

Effect of magnetic field

When an external magnetic field is applied, the electrons re-orient and align perpendicular to the applied field, i.e., their magnetic moment opposes the external magnetic field.

In the diagram, there is no penetration of magnetic lines through the diamagnetic material.

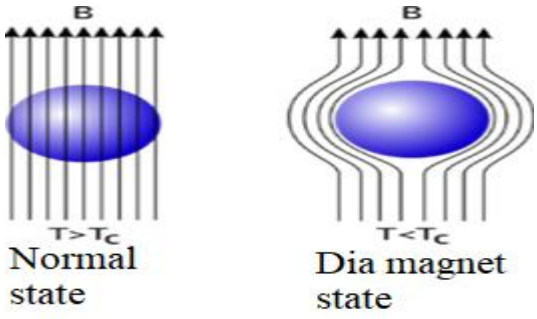


Fig 7. Effect of magnetic field in dia magnetic material

Properties

- They repel the magnetic lines of force, if placed in a magnetic field as shown in figure 7.
- The susceptibility is negative and it is independent to temperature and applied field strength. (χ = –ve)
- The permeability is less than one (μ <1)
- There is no permanent dipole moment.

- When the temperature is greater than the critical temperature diamagnetic becomes normal material.
- It has superconducting property.

Examples: Gold, germanium, silicon, antimony, bismuth, silver, lead, copper, hydrogen, Water and alcohol.

2.4.2 PARA MAGNETIC MATERIALS

Definition

Para magnetism is due to the presence of few unpaired electrons which gives rise to the spin magnetic moment. In the absence of external magnetic field, the magnetic moments (dipoles) are randomly oriented and possess very less magnetization in it.

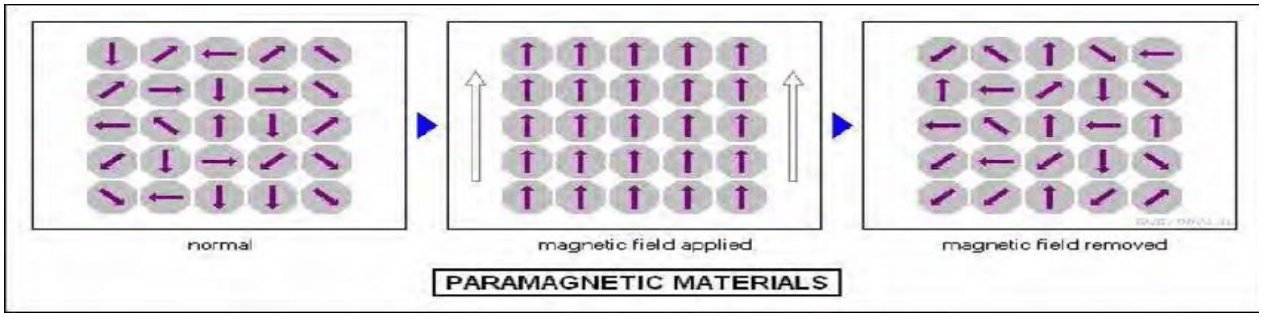


Fig 8. Para magnetic material

Effect of magnetic field

When an external magnetic field is applied to paramagnetic material, the magnetic moments align themselves along the field direction and the material is said to be magnetized. This effect is known as paramagnetism.

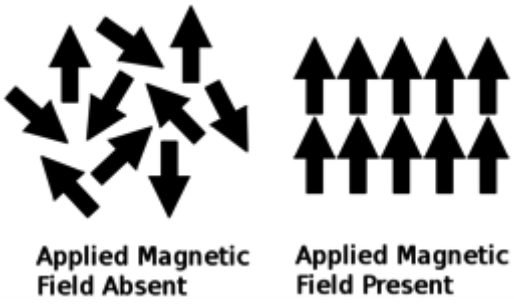


Fig 9. Effect of magnetic field in Para magnetic material

Thermal agitation disturbs the alignment of the magnetic moments with an increase in temperature, the increase in thermal agitation tends to randomize the dipole direction thus leading to decrease in magnetization.

This implies that the paramagnetic susceptibility decreases with increase in temperature. It is observed that the paramagnetic susceptibility varies inversely with temperature.

$$\chi \alpha \frac{1}{T} \qquad \text{or} \qquad \chi = \frac{C}{T}$$

Where, χ be the magnetic susceptibility

C be the Curie constant

T be the absolute temperature

This relation is known as Curie law of para magnetism.

Properties

- The magnetic lines of force pass through the materials.
- The susceptibility is positive and is given by $\chi = \frac{C}{T-\theta}$ (Curie-Weiss law)
- The permeability is greater than one (μ>1)
- There is a permanent magnetic moment.
- When the temperature is less than the Curie temperature, paramagnetic materials become diamagnetic materials.
- It spin alignment is random in nature.

Examples: Platinum, $CuSO_4$, $MnSO_4$,Al etc

2.4.3 FERROMAGNETIC MATERIALS

Definition

Ferromagnetism is due to the presence of more unpaired electrons. Even in the absence of external field, the magnetic moments align parallel to each other. So that it has large magnetism. This is called spontaneous magnetization. It is also called as strong magnetic materials.

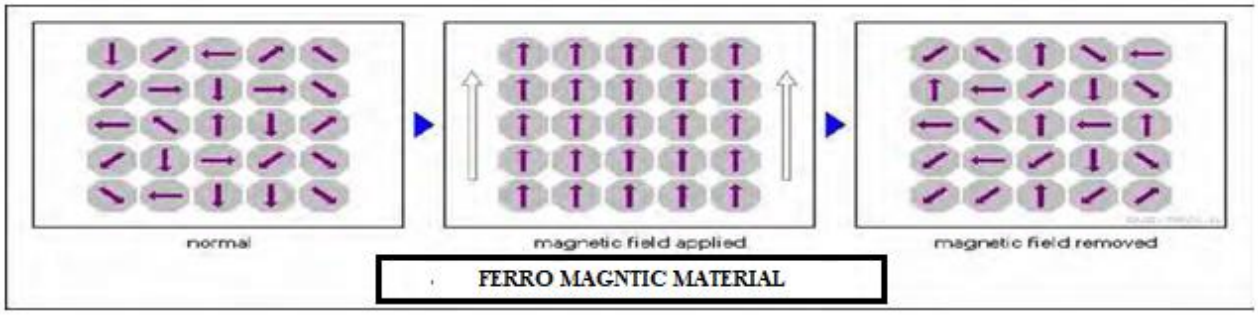
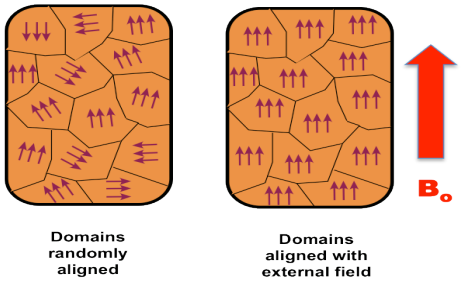


Fig 10. Ferro magnetic material



Effect of magnetic field **Fig 11. Effect of magnetic field in Ferro magnetic material**

In the absence of magnetic field, the material shows magnetization due to parallel alignment of dipoles with in small region so called domain. Here, dipoles are aligned to a particular direction with in a domain, but directions of dipoles differ from one domain to another domain.

If a small external magnetic field is applied, all the magnetic dipoles are aligned in particular direction which is parallel to the field direction and become very strong magnets.

Properties

- All the magnetic lines of force pass through the material.
- Its susceptibility is high positive and it is given by $\chi = \frac{C}{T-\theta}$
- The permeability is very much greater than one (μ>>1)
- They have enormous permanent dipole moment.
- When the temperature is greater than the Curie temperature, the Ferromagnetic material becomes paramagnetic material.
- The ferromagnetic material has equal magnitude dipole lying parallel to each other.

Examples: Nickel, iron, Cobalt, Steel, etc.

Curie temperature:

The temperature below which a material can acts as ferromagnetic material and above which it can acts as paramagnetic material is called Curie temperature.

2.4.4 COMPARISION BETWEEN DIA, PARA AND FERRO MAGNETIC MATERIALS

Properties	Diamagnetic Materials	Paramagnetic Materials	Ferromagnetic Materials
State	They can be solid, liquid or gas.	They can be solid, liquid or gas.	They are solid.
Effect of Magnet	Weakly repelled by a magnet.	Weakly attracted by a magnet.	Strongly attracted by a magnet.
Behaviour under non-uniform field	It tends to move from high to low region.	It tends to move from low to high field region.	It tends to move from low to high field region.
Behaviour under external field	They do not preserve the magnetic properties once the external field	They do not preserve the magnetic properties once the external field	They preserve the magnetic properties after the external field is

	is removed.	is removed.	removed.
Effect of Temperature	No effect.	With the rise of temperature, it becomes a diamagnetic.	Above curie point, it becomes a paramagnetic.
Permeability	Little less than unity	Little greater than unity	Very high
Susceptibility	Little less than unity and negative	Little greater than unity and positive	Very high and positive
Examples	Copper, Silver, Gold	Lithium, Tantalum,	Iron, Nickel, Cobalt

2.5 DOMAIN THEORY OF FERROMAGNETISM

This theory was proposed by Weiss in 1907. It explains the hysteresis and the properties of ferromagnetic materials.

Magnetic Domains

A ferromagnetic material is divided into a large number of small region is called domains. (0.1 to 1 of area), each direction is spontaneously magnetized. The direction of magnetization varies from domain to domain and the net magnetization is zero, in the absence external magnetic field. The boundary line which separates two domains is called domain wall or Block wall. When the magnetic field is applied to the Ferromagnetic material, the magnetization is produced by two ways.

1. By the motion of domain walls.
2. By the rotation of domains.

Process of Domain magnetization

There are two ways to align a random domain structure by applying an external magnetic field.

1. **By the motion of Domain walls**

Consider magnetic dipoles are aligned in parallel direction within a domain when no field is applied.

When a small amount of magnetic field is applied, the walls of the domains are shifted to new position. (Fig.12 (b))

2. **By the rotation of Domains**

If the applied magnetic field is further increased, the domains are rotated parallel to the field direction by the rotation of domains. (fig.12 (c))

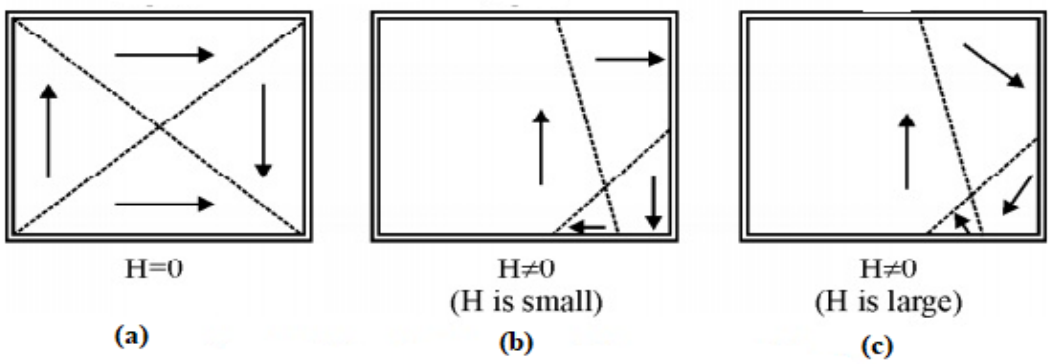


Fig 12. Effect of magnetic field in Ferro magnetic domain

4.6 ENERGIES INVOLVED IN THE DOMAIN GROWTH (OR) ORIGIN OF DOMAIN THEORY OF FERROMAGNETISM

We can understand the origin of domains from the thermodynamic principle i.e., in equilibrium, the total energy of the system is minimum.

The total internal energy of the domain structure in a ferromagnetic material is made up from the following contributions.

1. Exchange energy (or) Magnetic field energy.
2. Crystalline energy (or) Anisotropy energy.
3. Domain wall energy (or) Bloch wall energy.
4. Magnetostriction energy

2.6.1 Exchange energy (or) Magnetic Field energy

"The interaction energy which makes the adjacent dipoles align themselves" is the called exchange energy (or) magnetic field energy.

The interaction energy makes the adjacent dipoles align themselves. It arises from interaction of electron spins. It depends upon the inter atomic distance. This exchange energy also called magnetic field energy is the energy required in assembling the atomic magnets into a single domain and this work done is stored as potential energy. The size of the domains for a particular domain structure may be obtained from the principle of minimum energy. The volume of the domain may very between say, say, 10^{-2} to 10^{-6} cm^3.

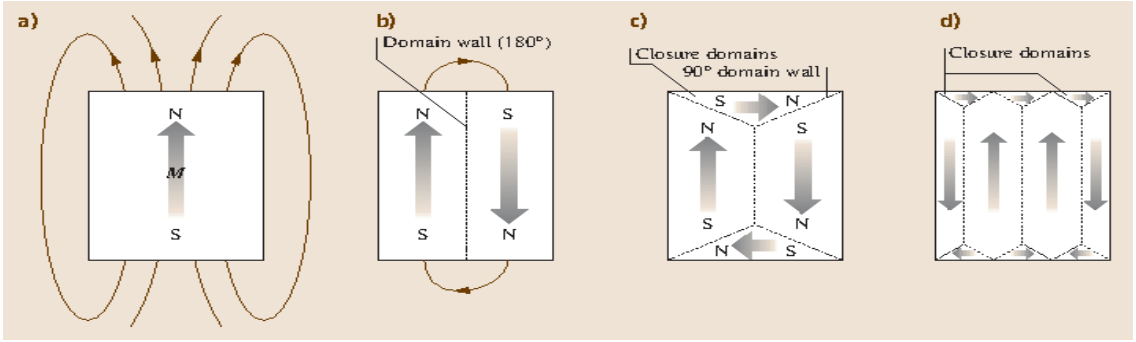


Fig 13. Exchange energy

2.6.2 Anisotropy energy or crystalline energy

The excess energy required to magnetize a specimen in particular direction over that required to magnetize it along the easy direction is called the crystalline anisotropy energy.

In ferromagnetic materials there are two types of directions of magnetization namely,

a) Easy direction and b) hard direction.

In easy direction of magnetization, weak field can be applied and in hard direction of magnetization, strong field should be applied.

Crystalline anisotropy energy is energy of magnetization which is the function of crystal orientation. As shown in figure magnetization curves for iron with the applied field along different crystallographic direction crystallographic directions have been drawn.

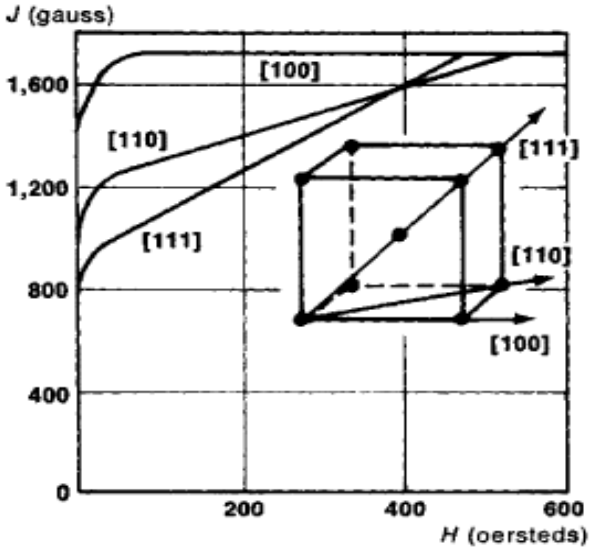


Fig 14. Crystalline energy

For example, in BCC iron the easy direction is [100], the medium direction is [110], and the hard direction [111]. The energy difference between hard and easy direction to magnetize the material is about. This energy is very important in determining the characteristic domain boundaries.

2.6.3 Domain wall energy or Bloch wall energy

A thin boundary or region that separates adjacent domains magnetized in different directions is called domain wall or Bloch wall.

The size of the Bloch walls is about 200 to 300 lattice constant thickness. In going from one domain to another domain, the electron spin changes gradually. The energy of domain wall is due to both exchange energy and anisotropic energy.

Based on the spin alignments, two types of Bloch walls may arise, namely

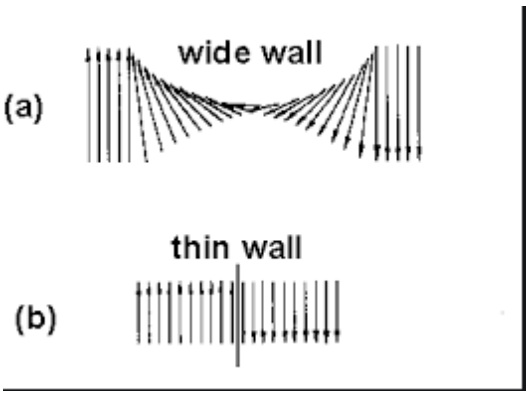


Fig 15. Domain wall energy

Thick wall:

When the spins at the boundary are misaligned and if the direction of the spin changes gradually as shown figure 15 (a), it leads to a thick Bloch wall. Here the misalignments of spins are associated with exchange energy.

Thin wall:

When the spins at the boundaries changes abruptly, then the anisotropic energy becomes very less. Since the anisotropic energy is directly proportional to the thickness of the wall, this leads to a thin Bloch wall. It is shown in fig 15 (b).

2.6.4 Magnetostriction energy

When a material is magnetized, it is found that it suffers a change in dimensions. This phenomenon is known as Magnetostriction. This deformation is different along different crystal directions. So if the domains are magnetized in different directions, they will either expand or shrink. This means that work must be done against the elastic restoring forces. The work done by the magnetic field against these elastic restoring forces is called magneto-elastic energy or Magnetostrictive energy.

2.7 HYSTERESIS

Hysteresis means "Lagging" i.e., The Lagging of intensity of magnetization (I) behind the intensity of magnetic field (H).

Experimental Determination

A graph is drawn between the intensity of magnetization [I] and the intensity of magnetic field [H], for a cycle of magnetization. The experimental setup consists of solenoid coil through which current is passed and the material is magnetized. By varying the value of current we can get different values of Intensity of magnetization [I] due to the magnetic field (H) in the solenoid.

Here, $H \alpha I$,

$H = n.I.l$

Where n – no of turns in the coil

l – Length of the coil and

I–Current through the circuit.

1. When the intensity of magnetic field 'H' is increased from O to F, the value of Intensity of magnetization T if also increases from O to A, at 'A' the material reaches the saturation value of Intensity of magnetization. Then the value of I is constant.

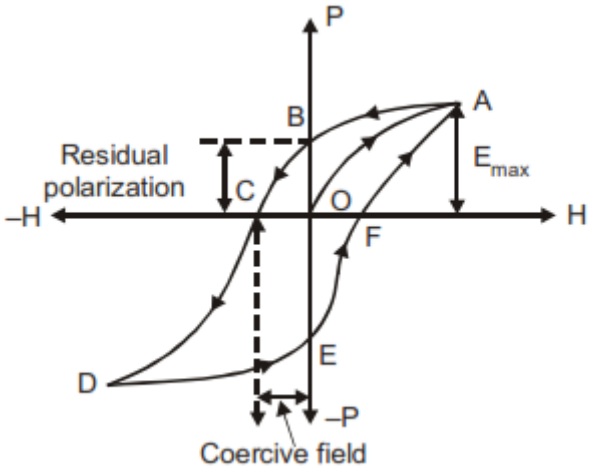


Fig 16. Hysteresis

2. When intensity of magnetic field 'H' is decreased from G to O, the value of Intensity of magnetization 'I' also decreases from A to B, but not to zero (0). Now the material retains [stores] some amount of magnetism known as Retentivity, even though the intensity of magnetic field 'H' is zero. It is represented as 'OB' in the graph.
3. When intensity of magnetic field 'H' is increased in reverse direction from O to C, the value of Intensity of magnetization 'I' decreases from B to C. i.e., the value of 'I' reaches zero.
4. The amount of intensity of magnetic field 'H' applied in the reverse direction to remove the retentivity is known as Coercivity or Coercive force. It is represented as 'OC' in the graph.
5. Further repeating the process the remaining portion [CDEFA] in the graph is obtained. The closed loop [OABCDEFA] is called Hysteresis loop (or) (I – H) curve. For one cycle of magnetization.
6. Now the material is taken out. After a cycle of magnetization, there is some expenditure (loss) of energy.
7. This loss of energy is radiated in the form of heat energy in the material.
8. This loss of energy is directly proportional to the area of the loop.
9. From the Hysteresis graph, we can select soft and hard magnetic materials depending upon the purpose.

Energy product

It is the product of residual magnetism B_r and coercivity which HC gives the maximum amount of energy stored in the specimen.

Energy product = B_r X H_c

Hysteresis loss

When the specimen is taken through a cycle of magnetization. There is a loss of energy in the form of heat. This loss of energy is known as Hysteresis loss.

2.7.1 Explanation of hysteresis on the basis of Domains

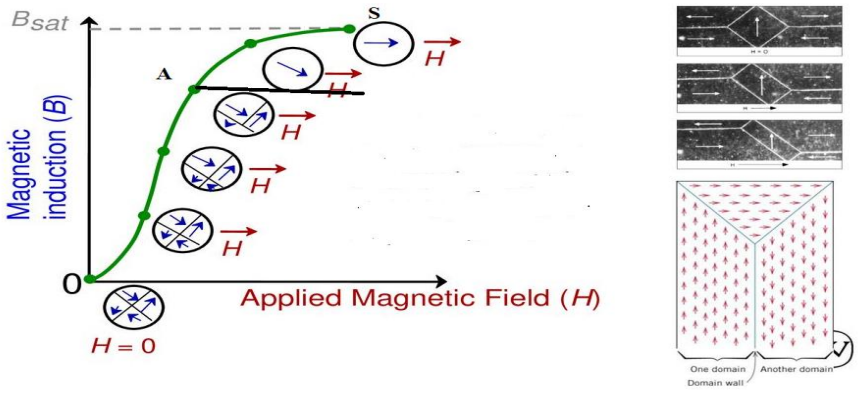


Fig 17. Hysteresis based on domain concept

OA - Due to smaller reversible domains wall movement.

AB - Due to larger irreversible domain wall movement.

BS - Due to smaller irreversible domain rotation

S - Point of saturation.

1. When a field is applied, for small H, the domain walls are displaced and gives rise to small value of magnetization. [OA in the graph]. Now, the field is removed, the domains return to its original state known as reversible domains.
2. When the field is increases, a large number of domains contribute to the magnetization and I increases rapidly with H.
3. Now, when the field is removed the domain boundaries do not come back to the original position due to the domain wall movement to a very large distance (AB in the graph). These domains are called irreversible domains.
4. Now if the field is further increased, domains start rotating along the field direction and anisotropic energy is stored and it is represented as BC in the graph.
5. Thus the specimen is said to attain maximum magnetization at this position even after the removal of the field. The material is having magnetism called Retentivity. This Retentivity can be destroyed by applying a high reverse magnetic field called coercivity.
6. Thus the reversible and irreversible domain wall movements give rise to hysteresis in the Ferromagnetic materials.

2.8 HARD AND SOFT MAGENTIC MATERIAL

In Hysteresis, after a cycle of magnetization, there is some expenditure (loss) of energy. This loss of energy is radiated in the form of heat energy in the material and it is directly proportional to the area of the loop. From the Hysteresis graph, we can select the soft and hard magnetic materials.

2.8.1 Hard Magnetic Materials

The materials which are very difficult to magnetize and demagnetize are called hard magnetic materials. These materials can be made by heating the magnetic materials and then cooling it suddenly. It can also be prepared by adding impurities.

The above hysteresis loop is very hard and has a large loop area for a hard magnetic material, therefore the loss is also large. Domain wall does not move easily and require large value of H for magnetization. Its coercivity and retentivity values are large. Its eddy current loss is also high due to its low resistivity, the magnetostatic energy is large. It has low susceptibility and permeability. The hard magnetic materials have large amount of impurities and lattice defects.

Examples : Tungsten steel, Carbon steel, Chromium steel, Alnico etc.,

Properties

- It is easilly magnetised and demagnetised.
- They hysteresis area is very small and hence, the hysteresis loss is also small, as shown in figure.
- The coercivity and rentenivity are very small.

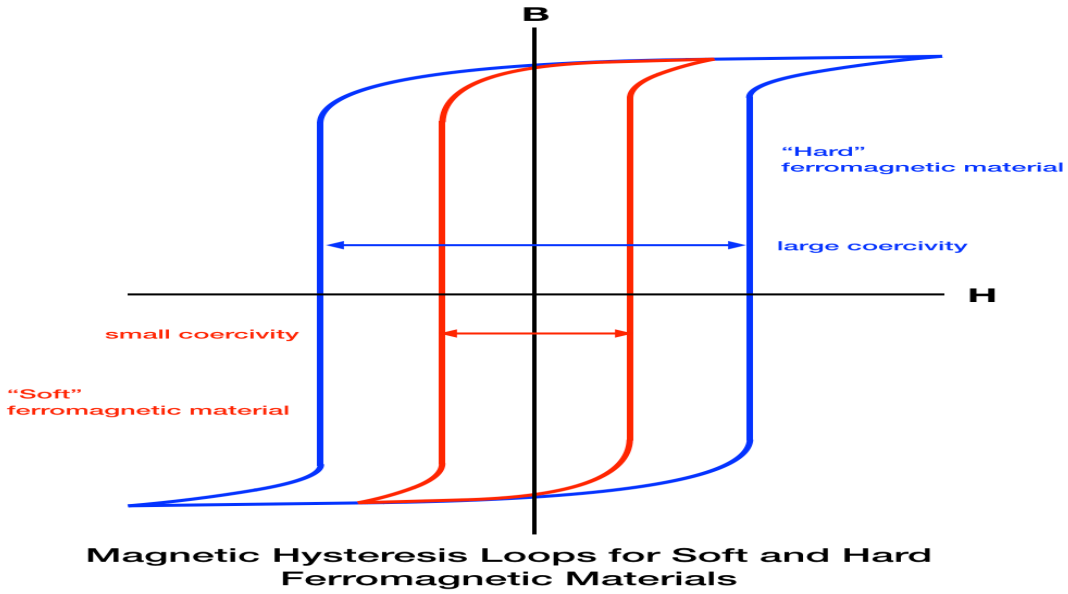


Fig 18. Hysteresis for Soft and Hard magnetic materials

- These materials have large values of susceptibility and permeabilty.
- Their magnetostatic energy is very small.
- The eddy current loss is very small

Applications

- Iron-Silicon alloys are used in electrical equipment and magnetic cores of transformes.
- Cast iron is used in the structure of electical machinery and the frame work of D.C machine.
- Nickel alloys are used to manufacture inductors, relays and small motors.
- It is also used for computer and data storage devices.

2.8.2 Soft Magnetic Materials

The materials which are easily magnetized and demagnetized are called soft magnetic materials. These materials can be made by heating the magnetic materials and then cooling it slowly to attain an ordered structure of atoms.

The above hysteresis loop is very small and has a less loop area for a soft magnetic materials. Therefore the loss is also small. Domain wall move easily and require small value of H for magnetization. Its coercivity and retentivity values are small, its eddy current loss is small due to its high resistivity. The magnetostatic energy is less, it has high value of susceptibility and permeability. The soft magnetic materials do not have impurities and lattice defects.

Examples: Iron-Silicon alloys, Nickel-Iron alloys and Iron-cobalt alloys.

Properties

- It is very hard to magnetize and also demagnetize.
- The hysteresis cure is very broad and has a large as shown in figure.
- The coercivity and retentivity values are large.
- These materials have low value of susceptibility and permeability.
- The magnetostatic energy is large.
- The eddy current loss is very high.

Applications

- Magnets made by carbon steel are used for manufacturing the toys and compass needle.
- Tungsten steel is used in making permanent magnets for D.C motors.
- It is also used for making a small size of magnets.

2.8.3 Comparison between Soft Magnetic Materials and Hard Magnetic Materials

Sr.No.	Soft Magnetic Materials	Hard Magnetic Materials
1	Soft magnetic materials are those materials which have a smaller area enclosed by their Hysteresis loop	Hard magnetic materials are those materials which have a Larger area enclosed by their Hysteresis loop
2	They have low remnant magnetization	They have high remnant magnetization
3	They have low coercivity	They have high coercivity
4	They have high initial permeability	They have low initial permeability
5	Hysteresis loss is less	Hysteresis loss is higher
6	Eddy current loss is less	Eddy current loss is more for metallic types and low for ceramic types.
7	Used in transformer cores, motors, generators, electromagnets, etc.	Used in making permanent magnets, magnetic separators, magnetic detectors, speakers, microphones, etc.
8	Tungsten steel, Carbon steel, Chromium steel, Alnico etc.,	Iron-Silicon alloys, Nickel-Iron alloys and Iron-cobalt alloys

SUPER CONDUCTING MATERIALS

2.9 INTRODUCTION

It was thought that the electrical resistance of a conductor becomes zero only at absolute zero temperature. But in 1911, H. Kammerlingh Onnes studied the properties of mercury at very low temperature using liquid helium and is found that the resistivity of mercury drops to zero at 4.2 K and changes into a superconducting material.

Definition

The ability of certain metals and alloys exhibit almost zero electrical resistivity when they are cooled to below critical temperature is known as superconducting. (ie., maximum conductivity with zero resistance at zero Kelvin)

Each of these parameters is very dependent on the other two properties present.

Critical temperature (T_C) (or) Transition Temperature

The temperature at which a normal conductor loses its resistivity and becomes a superconductor is known as critical temperature (or) Transition temperature. Every superconductor has its own critical temperature at which it passes over into superconducting state. Depending on the transition temperature, superconductors are classified into two groups are

Low temperature superconductors (LTS):

The superconductors which have low transition temperature (below 30K) are known as low temperature superconductors.

Example: Tin (3.2 K), Mercury (4.15 K).

High temperature superconductors (HTS):

The superconductors which have high transition temperature (above 30K) is known as high temperature superconductors.

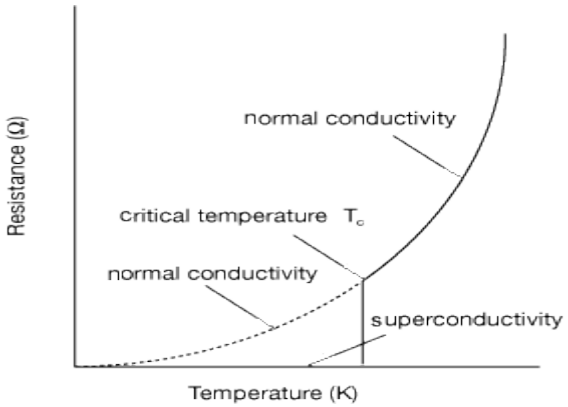


Fig 19. Variation of resistance with temperature

Example: Barium - Lanthanum - Copper - Oxide (BLCO) - 35 K

Yttrium - Barium - Copper - Oxide - (Y Ba_2 Cu_3 O_4) - 92 K

2.10 PROPERTIES OF SUPERCONDUCTORS

Zero Electric Resistance or Infinite Conductivity

In Superconducting state, the superconducting material shows the zero electric resistance (infinite conductivity). When the sample of a superconducting material is cooled below its

critical temperature/transition temperature, its resistance reduces suddenly to zero. For example Mercury shows zero resistance below 4k.

Meissner Effect (Dia magnetic property)

A Superconductor, when it is cooled below the critical temperature Tc), expel the magnetic field and doesn't allow the magnetic field to penetrate inside it. This phenomenon in superconductors is called Meissner effect. The meissner effect is shown in figure.

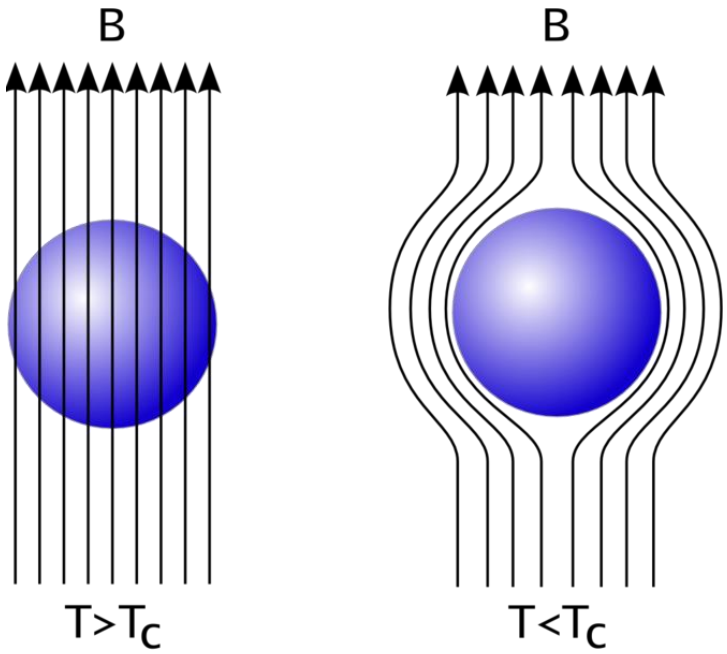


Fig 20. Meissner effect

Proof:

We know the relation between B, H and I,

$$B = \mu_0 (I + H)$$

For super conductor, B=0

So, $0 = \mu_0 (I + H)$

Dividing by H, we get, $0 = (\frac{I}{H} + 1)$

We know, $\frac{I}{H} = \chi$, $\chi + 1 = 0$, $\chi = -1$

In magnetic materials, dia magnetic materials only have negative susceptibility. So, all the superconductors are perfect dia magnets.

Critical Temperature/Transition Temperature

Critical temperature of a superconducting material is the temperature at which the materials changes from normal conducting state to superconducting state. This transition from normal conducting state (phase) to superconducting state (phase) is sudden / sharp and complete. The transition of mercury from normal conducting state to superconducting state is shown in figure.

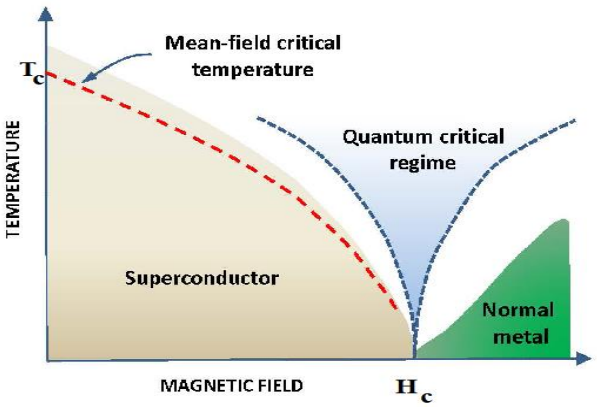


Fig 21. H_c Vs T_c

Critical Magnetic Field

The superconducting state / phase, of a superconducting material, breaks when the magnetic field (either external or produced by current flowing superconductor itself) increases beyond a certain value and sample starts behaving like an ordinary conductor. This certain value of magnetic field beyond which superconductor returns back to ordinary state, is called Critical magnetic field. The value of critical magnetic field depends on temperature. As the temperature (below the critical temperature) reduces the value of critical magnetic field increase. The variation in critical magnetic field with temperature is shown in figure.

Persistent Current

If a ring made of a superconductor is placed in a magnetic field above its critical temperature, now cool the ring of superconductor below its critical temperature and now if we remove the magnetic field a current is induced in ring due to its self-inductance. By Lenz law the direction of this induced current is such that it opposes the change in flux passing through the ring. As the ring is in superconducting state (zero resistance), the current induced is ring will be continue to flow this current is called the persistent current. This persistent current produce a magnetic flux which makes the magnetic flux passing through the ring constant.

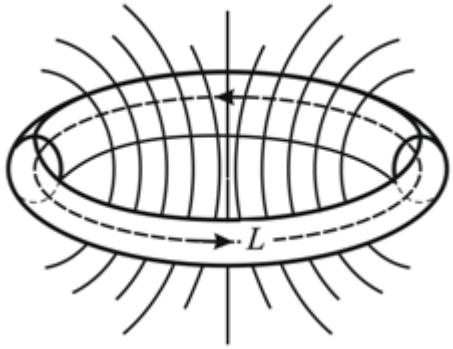


Fig 21. Persistent current

Josephson Current

If two superconductors are separated by a thin film of insulating material, which forms a low resistance junction, it is found that the cooper pairs (formed by phonon interaction) of electrons, can tunnel from one side of junction to the other side. The current, due to flow of such cooper pairs, is called Josephson Current.

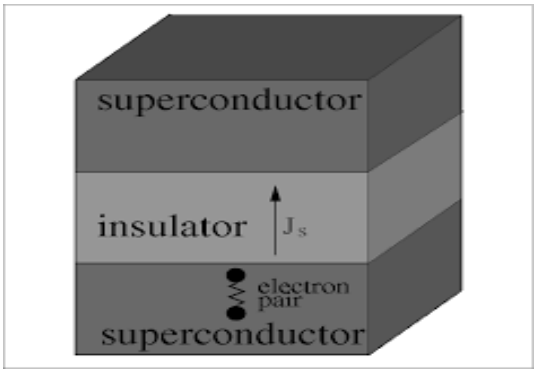


Fig 22. Josephson current

Critical Current

When a current is passed through a conductor under superconducting state, a magnetic field is developed. If the current increase beyond certain value the magnetic field increased up to critical value at which conductor returns to its normal state. This value of current is called critical current.

Effect of heavy Current

The superconducting property disappears when a heavy current flows, since current flow will set up a magnetic field.

According to Silsbee's rule, for a superconducting wire, the induced current to destroy the superconducting property is given by,

$$I_c = 2\pi r H_c$$

Where r be the radius of the super conductor

H_c be the critical field

Effect of pressure

If pressure increases, the critical temperature also increases. Therefore certain materials are brought into the superconducting state by increasing the pressure. Research is going on to get the superconducting state at room temperature by applying heavy pressure.

Isotope effect

The presences of isotopes in superconductor change the transition temperature of the superconductor. The transition temperature is found to be inversely proportional to the square root of the atomic weight of the isotope (M).

$$T_C \alpha \frac{1}{\sqrt{M}}$$

Or $$T_C = \frac{cons\tan t}{\sqrt{M}}$$

Or $$T_C \sqrt{M} = cons\tan t$$

The transition temperature of the heavier isotope is less than that of the lighter isotope.

General properties

- There is no change in elastic properties, photo electric properties and crystal structure.
- The transition temperature is unchanged with the frequency variation.

2.11 TYPES OF SUPER CONDUCTORS

Superconductors are classified as follows

Based on the value of H_C we have,

- Type I (or) Soft superconductors
- Type II (or) Hard superconductors

Based on the value of T_C we have,

- High temperature superconductors
- Low temperature superconductors

Type I Superconductor

In type I superconductor, the magnetic field is completely excluded from the material below the critical magnetic field and the material loses its superconducting property abruptly at critical magnetic field.

Characteristics

- They exhibit complete Meissner Effect
- They have only one critical magnetic field value.
- Below the material behaves as superconductor and above the material behaves as normal conductor.
- These are called as Soft superconductors.

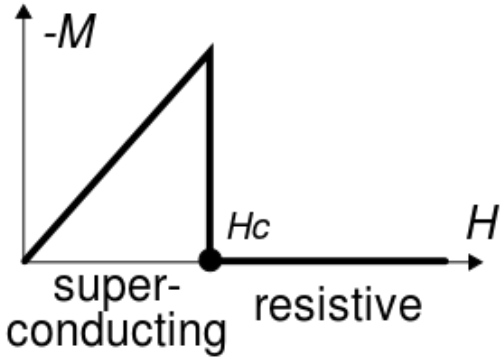


Fig 23. Type I super conductor

Type II Superconductor

In type II superconductor, the magnetic field is excluded from the material and the material loses its superconducting property gradually rather than abruptly.

Characteristics

- They do not exhibit a complete Meissner Effect.
- They have two critical magnetic field values. Lower critical magnetic filed [H_{Cl}] and Higher critical magnetic field [H_{C2}]
- Below HC1 the material behaves as superconductor and above the material behaves as normal conductor. The region in between [H_{Cl}] and [H_{C2}] is called mixed state or vortex region.
- These are called as hard superconductors.

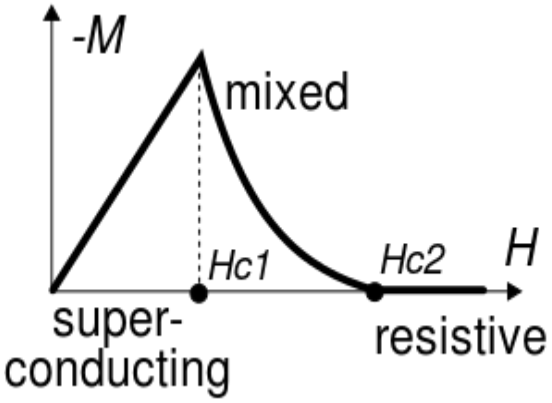


Fig 24. Type II super conductor

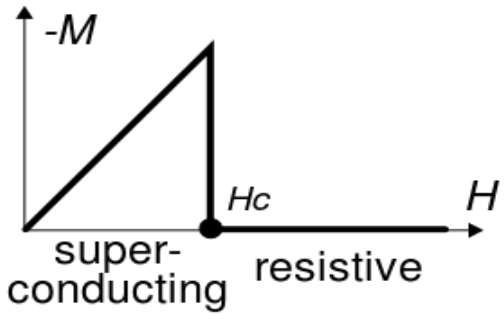
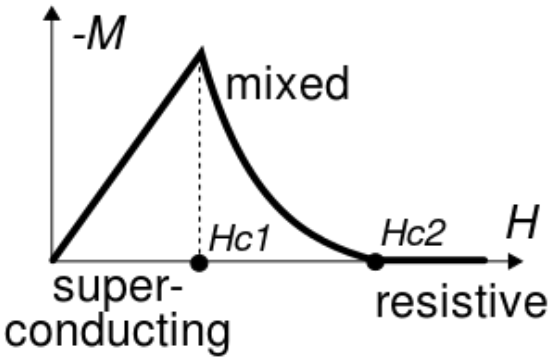
Low T_C Superconductors

- The superconductors having the critical temperature less than 20 K are known as low T_C Superconductors or elemental superconductors.
- The Superconductors by BCS theory.
- It is explained by BCS theory.
- It is not so useful due to its low temperature maintenance.
- It is called as N-type superconductor.

High TC Superconductors

- The superconductors having the critical temperature greater than 100 K are known as high TC Superconductors or ceramic or oxide superconductors.
- The Superconductors is due to hole states.
- It is explained by RVB theory proposed by Anderson.
- It is very useful for commercial and engineering purposes.
- It is called as P-type superconductor.

Differences between Type I and Type II super conductors

Type – I Superconductors	Type – II Superconductors
Low critical temperature (typically in the range of 0K to 10K)	High critical temperature (typically greater than 10K)
Low Critical magnetic field (Typically in the range of 0.0000049 T to 1T)	High Critical magnetic field (Typically greater than 1T)
Perfectly obey the Meissner effect: Magnetic field cannot penetrate inside the material.	Partly obey the Meissner effect but not completely: Magnetic field can penetrate inside the material.
Exhibits single critical magnetic field.	Exhibits two critical magnetic field
Easily lose the superconducting state by low-intensity magnetic field. Therefore, type-I superconductors are also known as soft superconductors.	Does not easily lose the superconducting state by external magnetic field. Therefore, type-II superconductors are also known as hard superconductors.
	
Due to the low critical magnetic field, type-I superconductors cannot be used for manufacturing electromagnets used for producing strong magnetic field.	Due to the high critical magnetic field, type-II superconductors can be used for manufacturing electromagnets used for producing strong magnetic field.
Type-I superconductors are generally pure metals.	Type-II superconductors are generally alloys and complex oxides of ceramics.

The transition from a superconducting state to a normal state due to the external magnetic field is sharp and abrupt for type-I superconductors.	The transition from a superconducting state to a normal state due to the external magnetic field is gradually but not shape and abrupt. At lower critical magnetic field (HC1), type-II superconductor starts losing its superconductivity. At upper critical magnetic field (HC2), type-II superconductor completely loses its superconductivity. The state between lower critical magnetic field and upper magnetic field is known as an intermediate state or mixed state.
BCS theory can be used to explain the superconductivity of type-I superconductors.	BCS theory cannot be used to explain the superconductivity of type-II superconductors.
These are completely diamagnetic.	These are not completely diamagnetic
These are also called as Soft Superconductors.	These are also called as Hard Superconductors.
These are also called as Low-temperature Superconductors.	These are also called as High-temperature Superconductors.
No mixed state exists in type-I Superconductors.	A mixed state exists in type-II Superconductors.
Slight impurity does not affect the superconductivity of type-I superconductors.	Slight impurity greatly affects the superconductivity of type-II superconductors.
Due to the low critical magnetic field, type-I superconductors have limited technical applications.	Due to the high critical magnetic field, type-II superconductors have wider technical applications.
Examples: Hg, Pb, Zn,etc.	Examples: NbTi, Nb3Sn, etc.

2.11. APPLICATIONS OF SUPERCONDUCTORS

General Applications

- Electric generators can be made by using superconductors with smaller size, less weight and low energy consumption.
- Superconductors can be used for the transmission of power over very long distances.
- Superconductors can be used in switching Devices.
- The superconductors can be used in sensitive electrical instruments.
- It can be used as a memory or storage element in computers.
- These are used in NMR (Nuclear Magnetic Resonance) imaging equipments which is used for scanning purposes.
- Superconductors are used for the detection of brain tumor, defective cells, etc.,

- Superconducting solenoids are used in magneto hydrodynamic power generation to maintain the plasma in the body.
- These are used to design Cryotron, Maglev, Josephson Devices and SQUID.
- DC superconducting motors are used in ship propulsion and in large mills.

Cryotron

It is a magnetically operated current switch. The superconducting property disappears when the magnetic field is greater than critical field.

It consists of a superconducting material [A] and it is surrounded by a super conducting coil of wire [B].

When the critical magnetic field of wire B exceeds or less than that of a Superconducting material A, the current in A can be controlled by the current in the material B, it can act as relay or switching elements and it can be used as memory or storage element in computers.

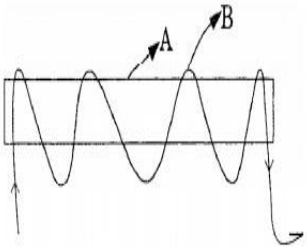
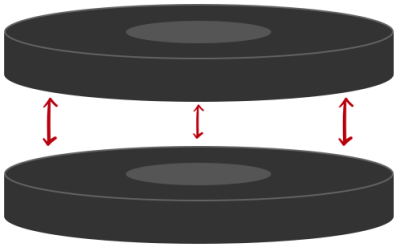


Fig. 28 Cryotron

MAGLEV Train (MAGnetic LEVitated Train)

- The first known commercial use of MAGLEV train was in the year 1984 in Birmingham, England, and the train was named MAGLEV itself. But due to less reliability, the train was stopped by 1994.
- The most famous commercial MAGLEV train is the Shanghai MAGLEV train in Shanghai, China. The train can go in a top speed of 270 miles/hour with an average speed of 160 miles/hour.
- Since these trains move on a cushion of air, there is no friction at all [except air friction]. The trains are also aerodynamically designed which enables them to reach great speeds like 300 miles/hour and so on. At 300 miles/hour you can travel from Rome to Paris in about 2 hours.



Principle **Fig. 29 Magnetic Levitation**

Maglev is a magnetic levitated train, its works under the principle of Electromagnetic induction.

Magnetic levitated effect is also the principle of MAGLEV Train i.e. a super conducting magnet floating over another super conducting magnet.

Construction

It consists of series of superconducting bar magnets which act as a guiding media. Bottom side of the train also made by superconducting bar magnets. The guiding media is connected with power supply to change the pole continuously. A propulsion motor is fixed at front of the train. It is used to give initial velocity to the train

Working

The train will be floating about 10mm above the magnetic guiding track. The train will be propelled to move by the guide way itself. Thus, there is no need of any engine inside he train. The detailed working of MAGLEV train is shown in the figure below. The train is propelled by the changing in magnetic fields. As soon as the train starts to move, the magnetic field changes sections by switching method and thus the train is again pulled forward. The whole guide way is run by electromagnets so as to provide the magnetic effect.

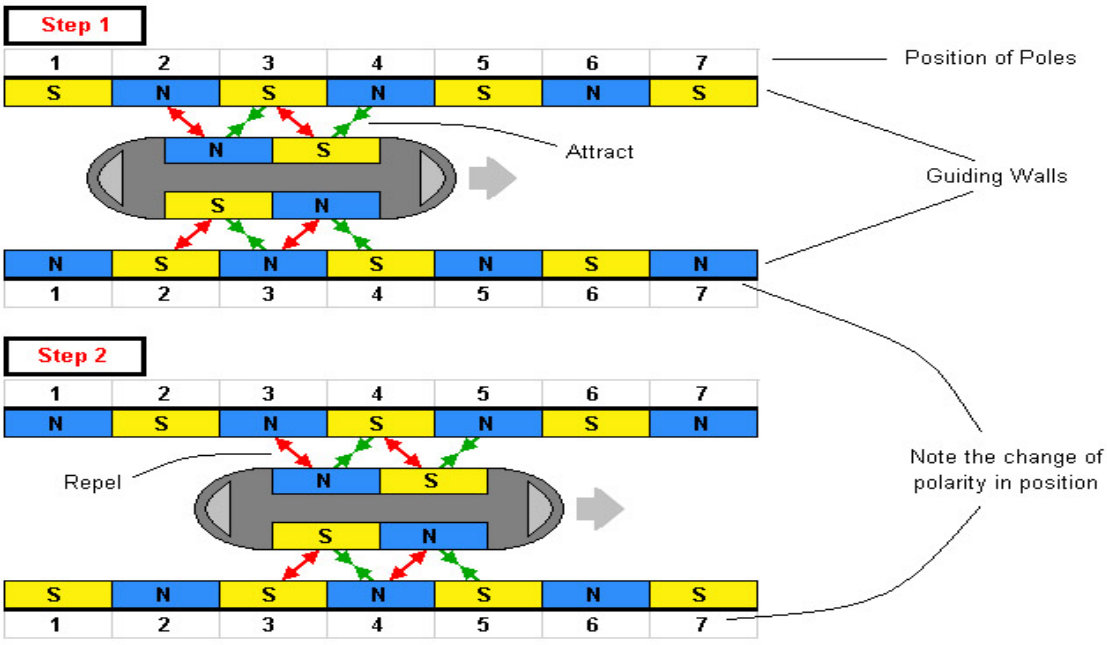


Fig.30. Magnetic Levitated Train

Thus the power needed for the whole process is less when compared to a conventional electric train. Amongst the power used, only a little is used for the levitation process. But a higher percentage of power is needed to overcome air friction.

Advantages of MAGLEV

- The main advantage is maintenance. There is no contact between the guide way and the train which lessens the number of moving parts. Thus the components that wear out is little.
- Another advantage is the reduction in noise. As there are no wheels running along there is no wheel noise. However noise due to air disturbance will still be there.
- The next advantage is high speed. As there are no frictional contacts, the train is prone to have more speed.
- Another advantage is that the guide way can be made a lot thicker in uphill places, after stations and so on. This will help in increasing the speed of the train further.

Disadvantages of MAGLEV

- The initial cost of MAGLEV trains is highly costly. The guide paths are also supposed to be more costly than conventional steel railways.

UNIT III DIELECTRIC AND FERROELECTRIC MATERIALS

3.1 INTRODUCTION

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

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

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

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

3.2 PROPERTIES OF DIELECTRICS

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

3.3 BASIC DEFINITIONS

Electric dipole

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

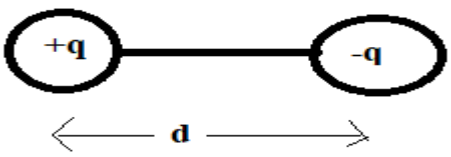


Fig.1 Electric dipole

Dipole moment (μ)

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

It is represented by the symbol μ.

$$\mu = q.d$$

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**.**

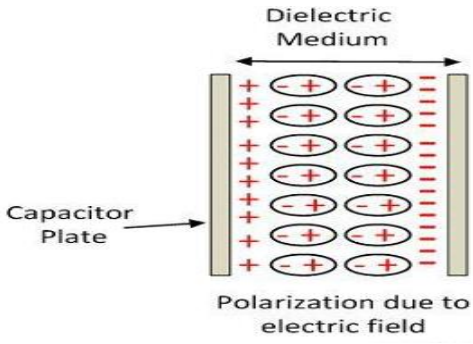


Fig.2 Polarization

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

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.

$$Ɛ = Ɛ_0 Ɛ_r$$

Relative Permittivity ($Ɛ_r$)

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

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

Electric susceptibility (χ_e)

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

$$P \propto E$$

$$P = \varepsilon_0 \chi_e E$$

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

Where, χ_e is called as electric susceptibility.

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

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

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

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

Subs. Eqn. 3 in 2 we get

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

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

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

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

Subs, eqn. 4 in 1 we get

$$D = P + \varepsilon_0 E$$ ----------5

Equation 5 gives the relation between P and D.

Relation between $\vec{P}$ and χ_e

We know, $P \propto E$

$$P = \varepsilon_0 \chi_e E$$

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

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

Comparing eqn. 1 and 2

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

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

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

Polar molecules

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

Example: H_2O, HCl, CO_2

Non Polar molecules

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

Example: O_2, H_2, N_2

COMPARISION BETWEEN POLAR AND NON POLAR MOLECULES

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

Surface Tension, Boiling And Melting Point	It has high surface tension, melting point & boiling point.	It has low surface tension, melting and boiling point.
Interaction With Other Molecules	It interacts with other polar molecules.	It does not interact with other Nonpolar molecules.
Examples	Water, ammonia and ethanol	Oil, benzene, methane.

3.4 TYPES OF POLARIZATION

There are four different types of polarization.

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

3.4.1 Electronic (or) induced polarization

Definition

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

This type of polarization occurs in all materials.

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

Derivation

a. Without field

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

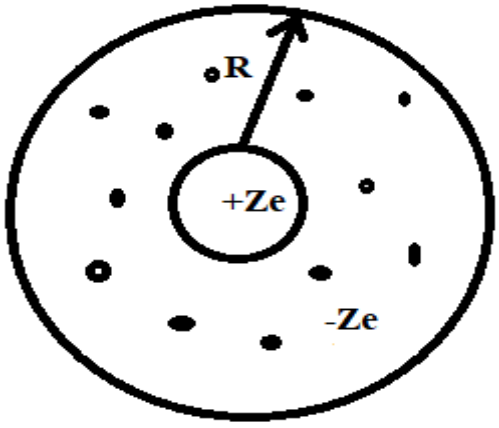


Fig.3 Without field

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

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

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

b. With field

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

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.

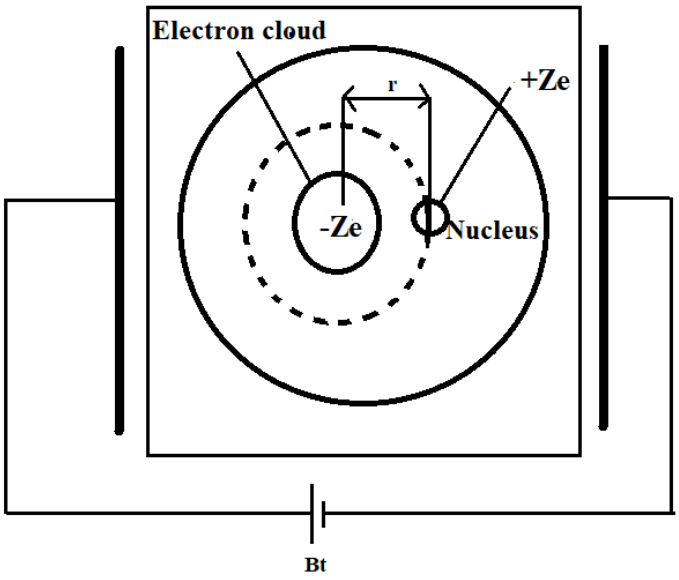


Fig.4 With field

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

Lorentz repulsive force is given by,

$$F_L = -Ze.E$$ ----------3

Coulomb attraction force

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

Total negative charge within the sphere of radius

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

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

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

Subs. Eqn.5 in 4 we get,

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

$$F_C = \frac{-Z^2e^2r}{4\pi\varepsilon_0 R^3}$$ ----------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 depends on radius of the atom
- It is temperature independent

3.4.2 Ionic (or) atomic polarization

Definition

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

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

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

Derivation:

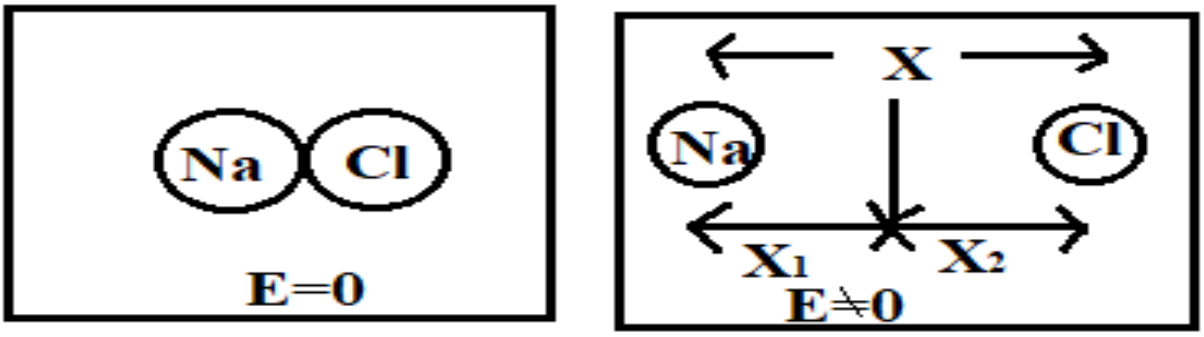


Fig.5 Ionic polarization

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

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

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

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

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

For + ion, $F \propto X_1$

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

For - ion, $F \propto X_2$

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

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

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

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

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

Eqns. 3 & 4 can be written as,

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

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

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

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

Equating eqn. 7 & 9, we get,

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

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

Equating eqn. 8 & 9, we get,

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

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

Subs. 10 & 11 in eqn, 2

Displacement, $X = X_1 + X_2$

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

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

We know, dipole moment = charge X displacement

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

Subs eqn. 12 in 13

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

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

Comparing, eqn. 1 & 14, we get,

$$\alpha_i = \frac{e^2}{\omega_0^2}\left(\frac{1}{M_1} + \frac{1}{M_2}\right) \text{----------15}$$

Equation 15 represents ionic polarizability.

Conclusion:

- Ionic polarisability is depends on square of angular frequency and mass of the ion.
- It is temperature independent.

3.4.3 Orientation (or) dipolar polarization

Definition:

When an electric field is applied on the dielectric medium with polar molecules, the electric field tries to align these dipoles along its field direction as shown in figure. Due to this there is a resultant dipole moment in that material and this process is called orientation polarization.

The orientation polarization is due to the existence of a permanent dipole moment (polar molecule) in the dielectric medium. Polar molecules have permanent dipole even in the absence of an electric field.

It occurs only in polar molecules.

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

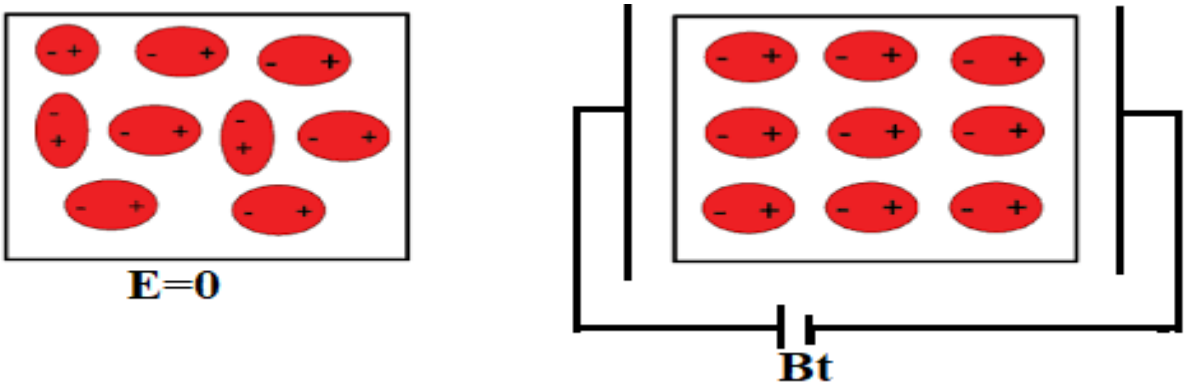


Fig.6 Orientation polarization

Derivation:

According to Langevin theory of paramagnetism, the intensity of magnetization is given by,

$$I = \frac{N\mu^2 B}{3KT}$$

Where, N be the number of molecule,

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

$$\alpha_o = \frac{\mu^2}{3KT}$$ ----------4

Equation 4 represents orientation polarization.

Conclusion:

- Orientation polarization change with temperature
- It is temperature dependent

3.4.4 Space-charge polarization or interfacial polarization

Definition

Interfacial or space charge polarization occurs when there is an accumulation of charge at an interface between two materials or between two regions within a material because of an external field.

This can occur when there is a compound dielectric, or when there are two electrodes connected to a dielectric material. This type of electric polarization is different from orientational and ionic polarization because instead of affecting bound positive and negative charges i.e. ionic and covalent bonded structures, interfacial polarization also affects free charges as well. As a result interfacial polarization is usually observed in amorphous or polycrystalline solids. Figure 7 shows an example of how free charges can accumulate in a field, causing interfacial polarization. The electric field will cause a charge imbalance because of the dielectric material's insulating properties. However, the mobile charges in the dielectric will migrate over maintain charge neutrality. This then causes interfacial polarization.

It occurs in some semiconducting materials and ferrites.

The space charge polarization is very small. So it is negligible ($\alpha_s=0$)

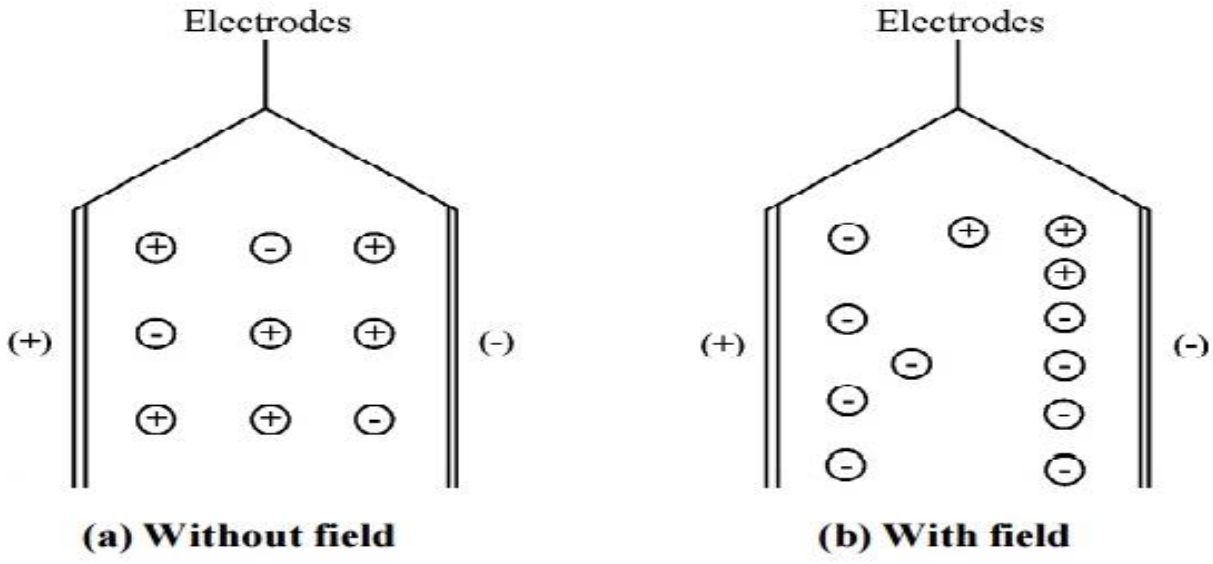


Fig.7 Space charge polarization

2.4.5 Total polarization

It can be calculated by summing the all four types of polarization.

$$P=P_e+P_i+P_o+P_s \text{ ----------1}$$

Polarizabilities are $\alpha = \alpha_e + \alpha_i + \alpha_o + \alpha_s$ ----------2

$\alpha_s = 0$

$$\alpha = \alpha_e + \alpha_i + \alpha_o \text{ ----------3}$$

$$\alpha = 4\pi\varepsilon_o R^3 + \frac{e^2}{\omega_0^{\ 2}}\left(\frac{1}{M_1}+\frac{1}{M_2}\right)+\frac{\mu^2}{3KT} \text{ ----------4}$$

Polarization, $P=NE\alpha$

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

Equation 5 is called as 'Langevin-Debye equation.

3.5 FREQUENCY AND TEMPERATURE DEPENDENCE OF POLARIZATION

Frequency dependence

On application of an alternating field across the material, the polarization occurs as function of time

$$P(t) = P_m(1-\exp\left(\frac{-t}{t_r}\right))$$

Where, P_m is the maximum polarization attained due to applied field and t is the relaxation time. Which is the time taken for a polarization process to reach 0.63 of the maximum value. The relaxation times are different for different kinds of polarization mechanisms.

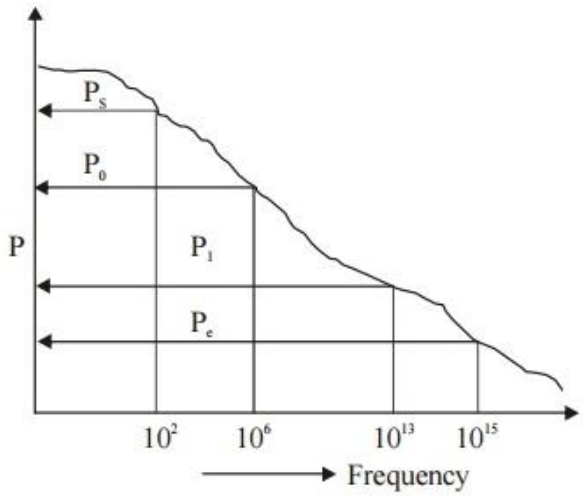


Fig.7 Frequency dependence of polarization

1. **Electronic polarization** is very fast and is completed at any instant of time even when the frequency of the voltage is very high in the optical range (10^{15} Hz). Thus it occurs at all frequencies.
2. **Ionic Polarization** is slower and the ions do not respond when the voltage corresponds to visible optical frequencies, i.e., the electric field changes in polarity at very fast, so that the ions are not able to reorient themselves due up to the field. So the ionic polarization does not occur at visible optical frequencies. It occurs only at frequencies less than 10^{13} Hz.

3. **Orientation Polarization** is even slower than ionic polarization and occurs only at electrical frequencies (audio and radio frequencies 10^6 Hz).
4. **Space-charge polarization** is the slowest process because the ions have to diffuse (jump) over several inter atomic distances. This occurs at very low frequencies of 50 - 60 Hz (power frequencies).

Thus at low frequencies all the four polarizations will occur and the total polarization is very high, but at high frequencies, the value of the total polarization is very small. The following graphs show the frequency dependence of polarization mechanism and the corresponding power losses at those frequencies.

Temperature dependence

Electronic and ionic polarizations are independent of temperature and the orientation and space charge polarizations are dependent of temperature. Orientation polarization is inversely proportional to the temperature.

Orientation polarization decreases when temperature increases. Because, the random nature decreases the tendency of permanent dipoles to align along the field direction. Thus the dielectric constant increases.

Space charge polarization is directly proportional to the temperature. The space charge polarization increases with increase the temperature. It is because of the fact that the thermal energy helps to overcome the activation barrier and the ions diffuse easily, this results in decrease of dielectric constant.

3.5 INTERNAL FIELD OR LORENTZ LOCAL FIELD

Definition

In dielectric solids, the atoms or molecules experience not only the external applied electric field but also the electric field produced by the dipoles. The resultant electric field acting on the atoms or molecules of dielectric substance is called the local field or an internal field.

To find an expression for local electric field on a dielectric molecule or an atom, we consider a dielectric material in the electric field of intensity *E*, between the capacitor plates so that the material is uniformly polarized, as a result opposite type of charges are induced on the surface of the dielectric near the capacitor plates. The local field is calculated by using the method suggested by Lorentz. It is represented by $E_{i.}$

$$E_i = E + \frac{P}{3\varepsilon_o}$$

Where, E be the applied field

P be the polarization

ε_o be the permittivity of free space

Derivation

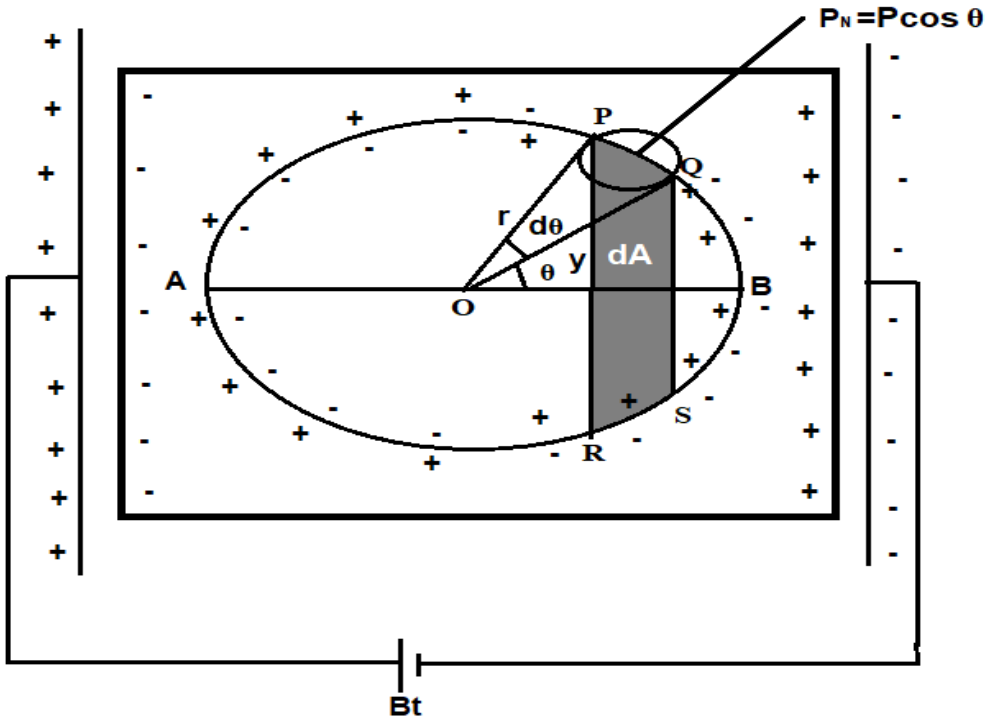


Fig.8 Internal field

The dielectric material which is placed in between two plates of a parallel plate capacitor is uniformly polarized as shown in Figure.8.

Let r be the radius of the spherical sphere considered. Y be the radius of small element taken. Let dA be the small area considered.

Let θ and dθ be the angle subtended.

Assume an imaginary small spherical cavity around an atom for which the internal field must be calculated at its centre.

The internal field E_i at the atom site (0) can be considered to consist of components namely E_1, E_2, E_3 and E_4.

$$E_i = E_1 + E_2 + E_3 + E_4 \text{----------1}$$

Where, E_1 is the field due to charges over the metal plates

E_2 is the field due to charges inside the dielectric

E_3 is the field due to charges over spherical cavity considered

E_4 is the field due to charges inside the spherical cavity considered

Macroscopically, we can take $E = E_1 + E_2$ i.e., the field externally applied (E_1) and the field induced on the plane surface of the dielectric (E_2) can be considered as a single field (E).

If we consider the dielectric which is highly symmetric, then the field due to the dipoles present inside the imaginary cavity will cancel each other. Therefore, the electric field due to permanent dipoles $E_4=0$.

Eqn.1 becomes $E_i = E + E_3$ ----------2

To find E_3

The normal component of polarization is given by,

$P_N = \frac{Charge}{Area} = P\cos\theta$

$P_N = P\cos\theta = \frac{q}{dA}$

Rearranging,

$$q = P\cos\theta dA \text{----------3}$$

The electric field intensity can be written as,

$$E = \frac{q}{4\pi\varepsilon_O r^2}$$

Subs. Eqn. 3 in 4

$$E = \frac{P\cos\theta dA}{4\pi\varepsilon_O r^2} \text{----------4}$$

The electric field intensity along x axis can be written as,

$$E_x = E\cos\theta \text{----------5}$$

Subs. Eqn. 4 in 5

$$E_x = \frac{P\cos\theta dA}{4\pi\varepsilon_O r^2}.\cos\theta$$

$$E_x = \frac{P\cos\theta^2 dA}{4\pi\varepsilon_O r^2} \text{----------6}$$

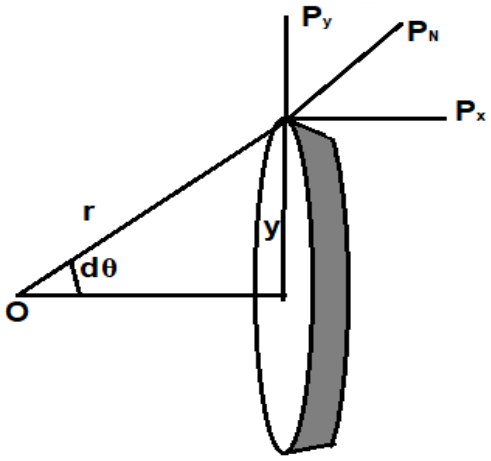


Fig.9 Internal field

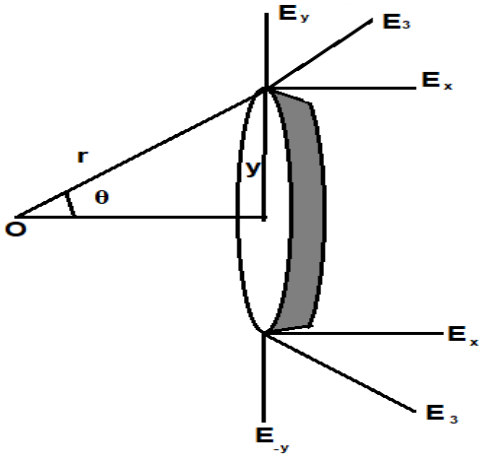


Fig.10 Internal field

The electric field intensity is in opposite direction along y axis. They are cancelled out each other. So the parallel components alone are taken into consideration.

Smallest area, dA=circumference X thickness----------7

Circumference of the circle with radius y is, 2πy----------8

Thickness of smallest area can be calculated as, y = r.dθ----------9 (Fig.9)

Subs. Eqns. 8&9 in eqn. 7, we get

dA=2πy. r.dθ----------10

From fig.10.

$$\sin\theta = \frac{y}{r} \quad \text{or} \quad y = r.\sin\theta \text{----------11}$$

Subs. Eqn.11 in 10

dA=2πr.sinθ. r.dθ

$$dA = 2\pi r^2 . \sin\theta . d\theta$$ ----------12

Subs. Eqn. 12 in 6 we get

$$E_x = \frac{P\cos^2\theta}{4\pi\varepsilon_O r^2}.2\pi r^2 \sin\theta d\theta$$

$$E_x = \frac{P\cos^2\theta \sin\theta d\theta}{2\varepsilon_O}$$ ----------13

Equation 13 represents the electric field over the spherical cavity at a point. Total electric field can be calculated by integrating equation 13 within the limit 0 to π.

$$E_3 = \int_0^{\pi} \frac{P\cos^2\theta \sin\theta d\theta}{2\varepsilon_O}$$

$$E_3 = \frac{P}{2\varepsilon_0}\int_0^{\pi} \cos^2\theta \sin\theta d\theta$$ ----------14

Put, $x = \cos\theta$

Differentiating, $dx = -\sin\theta . d\theta$

Limits: if x=0, cos 0=1,

x=π, cos 0=-1

Eqn. 14 can be written as

$$E_3 = \frac{P}{2\varepsilon_0}\int_1^{-1} x^2(-dx)$$

$$E_3 = -\frac{P}{2\varepsilon_0}\left[\frac{x^3}{3}\right]_1^{-1} = -\frac{P}{2\varepsilon_0}\left[-\frac{1}{3}-\frac{1}{3}\right] = -\frac{P}{2\varepsilon_0}\left[-\frac{2}{3}\right] = \frac{P}{2\varepsilon_0}\left[\frac{2}{3}\right]$$

$$E_3 = \frac{P}{3\varepsilon_0}$$ ----------15

Subs. eqn. 15 in 2,

$$E_i = E + \frac{P}{3\varepsilon_0}$$ ----------16

This equation (16) shows that E_i is different from E. The local intensity E_i is larger than the macroscopic intensity E. So the molecules are more effectively polarised.

DEDUCTION: CLAUSIUS MOSOTTI RELATION

If N be the number of molecules, α be the polarizability and E_i be the internal field, then,

Polarization vector, $P=N\alpha E_i$

Or $$E_i = \frac{P}{N\alpha} \text{ ----------17}$$

We know, $$D = P + \varepsilon_0 E$$

$$D = \varepsilon E$$

From above 2 equation, $$\varepsilon E = P + \varepsilon_0 E$$

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

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

$$E = \frac{P}{(\varepsilon - \varepsilon_0)} \text{ ----------18}$$

Subs. eqn.18 in 16 we get,

$$E_i = \frac{P}{(\varepsilon - \varepsilon_0)} + \frac{P}{3\varepsilon_0}$$

$$E_i = P\left(\frac{1}{\varepsilon - \varepsilon_0} + \frac{1}{3\varepsilon_0}\right)$$

$$E_i = P\left(\frac{3\varepsilon_0 + (\varepsilon - \varepsilon_0)}{3\varepsilon_0(\varepsilon - \varepsilon_0)}\right)$$

$$E_i = \frac{P}{3\varepsilon_0}\left(\frac{\varepsilon + 2\varepsilon_0}{(\varepsilon - \varepsilon_0)}\right) \text{ --------19}$$

We know $\varepsilon = \varepsilon_0 \varepsilon_r$

Eqn. 19 becomes

$$E_i = \frac{P}{3\varepsilon_0}\left(\frac{\varepsilon_o \varepsilon_r + 2\varepsilon_0}{\varepsilon_o \varepsilon_r - \varepsilon_o}\right)$$

$$E_i = \frac{P}{3\varepsilon_0}\left(\frac{\varepsilon_o(\varepsilon_r + 2)}{\varepsilon_o(\varepsilon_r - 1)}\right)$$

$$E_i = \frac{P}{3\varepsilon_0}\left(\frac{(\varepsilon_r + 2)}{(\varepsilon_r - 1)}\right) \text{ ----------20}$$

Equating eqn. 17 and 20

$$\frac{P}{N\alpha} = \frac{P}{3\varepsilon_0}\left(\frac{(\varepsilon_r + 2)}{(\varepsilon_r - 1)}\right)$$

$$\frac{1}{N\alpha} = \frac{1}{3\varepsilon_0}\left(\frac{(\varepsilon_r + 2)}{(\varepsilon_r - 1)}\right)$$

Rearranging, $$\frac{N\alpha}{3\varepsilon_0} = \frac{\varepsilon_r - 1}{\varepsilon_r + 2}$$ ----------21

Eqn.21 represents Clausius Mosotti realtion. This equation relates dielectric constant and polarizability.

3.6 DIELECTRIC BREAKDOWN

Definition

When a dielectric material is subjected to large amount of electric field, at $E>E_C$, the material lose its dielectric property and becomes good conductor. This phenomenon is called as dielectric breakdown.

Dielectric strength

Dielectric strength is the voltage that an insulating material can withstand before breakdown occurs. It usually depends on the thickness of the material and on the method and conditions of the test.

Dielectric strength $= \frac{\text{Voltage}}{\text{Thickness}} = \frac{V}{d}$

Types of dielectric breakdown

- Intrinsic breakdown
- Thermal breakdown.
- Electrochemical breakdown.
- Defect breakdown.
- Discharge breakdown.

1. Intrinsic breakdown

When a dielectric material is subjected to large electric field, a large number of electrons are transferred from the valence band to the conduction band. Thus the dielectric material loses its insulating property and becomes a conductor. This is known as intrinsic breakdown.

Further the conducting electrons may collide with the atoms and release some of the valence electrons. These electrons may collide with some more atoms and may release more electrons. This becomes a chain process resulting in a large current. It is known as avalanche breakdown.

Characteristics

- This type of breakdown occurs at room temperature and low temperatures.
- This requires relatively large electric fields
- This kind of breakdown occurs in all materials.

2. Thermal breakdown

Thermal breakdown occurs in dielectric when the rate of heat generation is greater than the rate of heat dissipation.

When a dielectric is subjected to an electric field, heat is generation. The generation heat is dissipated by the dielectric material. When the amount of heat generation is higher than the amount of heat dissipation, the temperature inside like dielectric increases and this causes the breakdown called thermal breakdown.

Characteristics:

- This can occur only at high temperatures.
- The Thermal breakdown time is of the order of few milliseconds.
- This requires moderate electric fields.
- It depends on size and shape of dielectric material.
- Since the dielectric loss its directly proportional to frequency, the electric field strength to create this dielectic breakdown will be smaller for a.c fields and higher d.c fields.

3. Electrochemical breakdown

When temperature increases, mobility of ions increases and hence leakage curent also increases. This decreases the insulation resistance and finally creates a dielectric breakdown. Hence this type of breakdown is called electrochemical breakdown.

Characteristics

- This is used to determine the leakage current, density of ions and dipoles inside the material.
- They are accelerated by high temperatures
- This occurs only at low temperature
- This type of breakdown occurs even in absence of elcetric field also.

4. Discharge breakdown

This type of breakdown occurs when the insulator contains occluded gas bubbles. When the dielectic is subjected to an electric field, the gas present in the material will be easily ionized than the solids. The ionized gas particles bombarded with the solid dielectric and produce large ionization current called discharge breakdown.

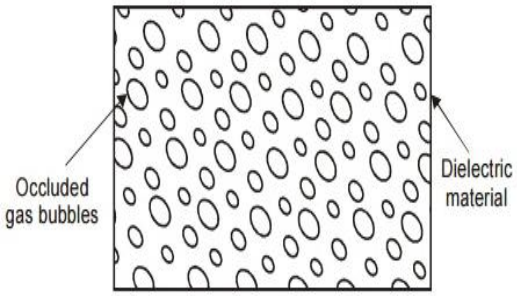


Fig.12 Discharge break down

Characteristics

- This is possible at low voltages where, there are large number of occluded gas bubbles is present in the material.
- The life time of the material depends upon the number of discharge taking place inside the material
- This occurs due to presence of gas bubbles.

5. Defect breakdown

If the surface of the dielectric material has defects such as cracks, pores, etc. Moisture and other impurities can fill at these places leading to breakdown, this type of breakdown called Defect breakdown.

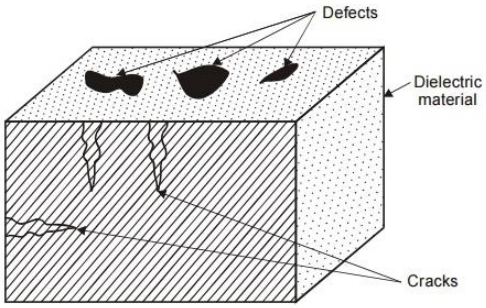


Fig.12 Discharge break down

Remedies to Avoid Breakdown Mechanisms

To avoid breakdown, the dielectric material should have the following properties

- It should have high resistivity.
- It must have low dielectric loss and less density.
- If should have sufficient mechanical strength.
- Thermal expansion should be small.
- It should be fire proof.
- It must in pure form and not have any defects.

3.8 APPLICATIONS OF DIELECTRIC MATERIALS

Some of the applications of dielectrics are as follows-

- These are used for energy storage in capacitors.
- To enhance the performance of a semiconductor device, high permittivity dielectric materials are used.
- Dielectrics are used in Liquid Crystal Displays.
- Ceramic dielectric is used in Dielectric Resonator Oscillator.
- Barium Strontium Titanate thin films are dielectric which are used in microwave tunable devices providing high tunability and low leakage current.
- Parylene is used in industrial coatings acts as a barrier between the substrate and the external environment.
- In electrical transformers, mineral oils are used as a liquid dielectric and they assist in the cooling process.
- Castor oil is used in high-voltage capacitors to increase its capacitance value.

- Electrets, a specially processed dielectric material acts as electrostatic equivalent to magnets.
- In the substation equipment where medium and high voltages flow this type of insulating material is used.
- Practically, for the high voltage is driven transformers bushes are coated with such insulating materials as well as on switch gears.
- The exposable components for example cables are firmly coated with dielectrics so that they are protected from hazardous effects.
- Even Resin and varnish are used in electrical pieces of equipment such that its working life will be increased.
- The liquid type of dielectrics is the cooling medium for the transformers, Rheostats, and Capacitors.

3.10. FERRO ELECTRIC MATERIALS

Definition

Ferroelectricity is the phenomenon where spontaneous electric polarization of the material takes place. The reverse electric polarization is possible by applying an electric field.

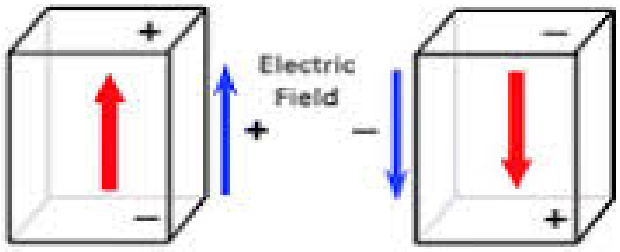


Fig.16 Ferro electrics

Ferroelectric materials are materials that exhibit Ferroelectricity. Ferroelectricity is the ability of the material to have a spontaneous electric polarization. This polarization can be reversed by the application of an external electric field in the opposite direction. Ferroelectricity (and hence Ferroelectric materials) was discovered by Rochelle salt by Valasek in 1921.

The reversal of polarity of a ferroelectric material via the application of an external electric field is called “switching”.

Ferroelectric materials can maintain the polarisation even once the electric field is removed. Ferroelectric materials have some similarities over ferromagnetic materials, which reveal permanent magnetic moment. The hysteresis loop is almost the same for both materials.

Since there are similarities, the prefix is the same for both materials. But all the ferroelectric material must not have Ferro (iron).

All the ferroelectric materials exhibit a piezoelectric effect. The opposed properties of these materials are seen in antiferromagnetic materials.

Examples of Ferroelectric Materials

- $BaTiO_3$

- $PbTiO_3$
- Lead Zirconate Titanate (PZT)
- Triglycine Sulphate
- PVDF
- Lithium tantalite etc.

Properties

- The lattice structure in Ferroelectric Materials shows crystal symmetry
- They possess spontaneous polarization
- The dielectric constant of these materials does not vary with respect to temperature.
- The dielectric constant reaches maximum value only at a particular temperature called Curie temperature.
- The properties of these materials exist only below a definite phase conversion temperature. Above this temperature, the material will become para electric materials.
- The polarization does not vary linearly with respect to electric field and hence these materials are also called as non-linear dielectrics.
- Ferroelectric materials exhibit hysteresis similar to ferromagnetic materials.

Dielectric Hysteresis

The ferro electrics are known as non –linear dielectrics. Such materials exhibit hysteresis curve similar to that of ferro magnetic materials.

The lagging of polarization 'P' behind the applied electric field E is called dielectric hysteresis.

When a ferro – electric material is subjected to external electric field (E) the polarization (P) increases with respect to the field applied and it reaches the maximum value 'OA'.

If now the applied electric field is reduced, the polarization also decreases from a, and when E becomes zero a small amount of polarization exists in the material is called spontaneous (or) residual polarization.

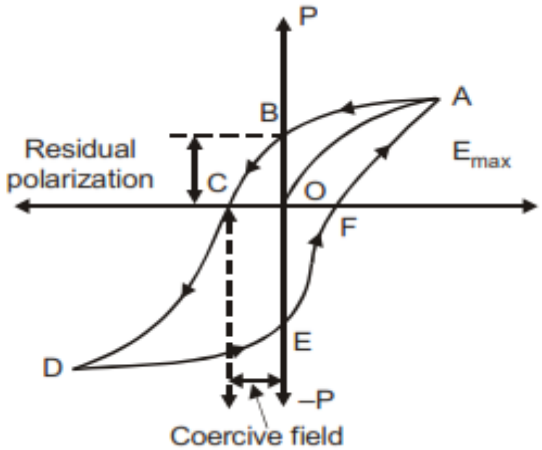


Fig.17 Dielectric hysteresis

In order to reduce the value of polarization to zero, a reversing electric field oc should be applied. This field is known as coercive field.

Thus the variation of P with respect to E traced along the closed path OABCDEFA in one full cycle of polarization and depolarization is called hysteresis or the hysteresis curve.

Application of Ferroelectric Materials

Ferroelectric materials have many applications, including:

- Thermistors
- Oscillators
- Non-volatile memory
- Filters
- Capacitors
- Light deflectors
- Transchargers
- Electro-optic materials
- Modulators
- Piezoelectrics
- Display etc

UNIT IV MODERN ENGINEERING MATERIALS

4.1 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.

4.2 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.

4.3 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.

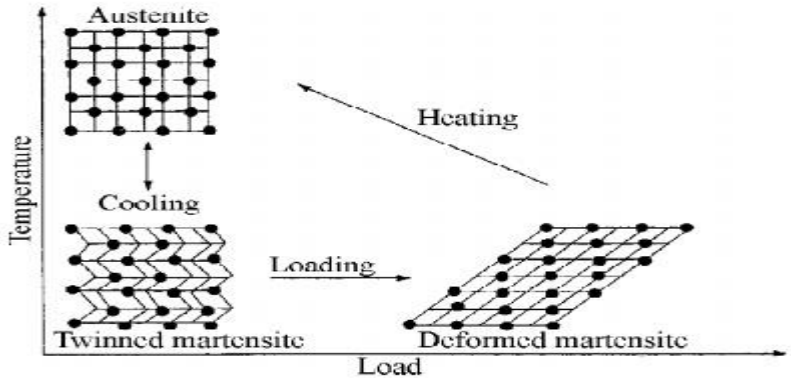


Fig. Material crystalline arrangement during shape memory effect

4.4 Characteristics of SMA

1. Hysteresis

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

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

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

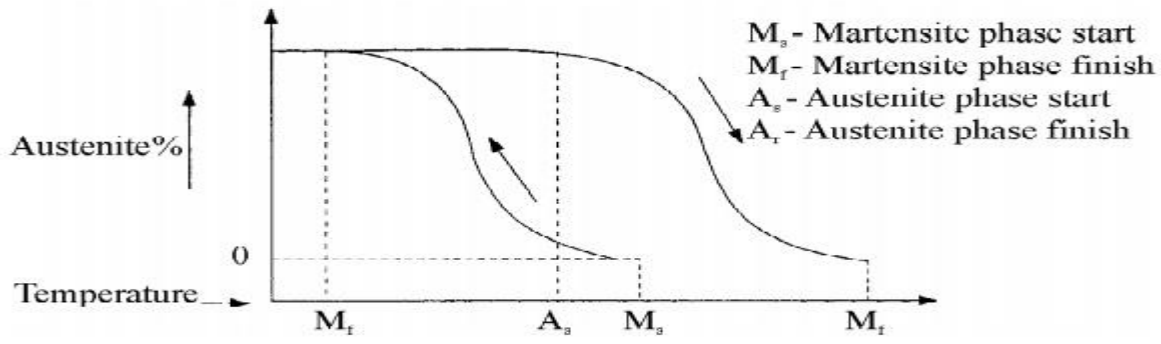


Fig. Hysteresis curve for SMA's

2. Pseudo elasticity

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

3. Super elasticity

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

4.5 Properties of Ni – Ti alloy

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

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

4.5 Advantages of SMA's

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

4.6 Disadvantages of SMA's

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

4.7 Applications of SMA

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

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

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

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

Medical Applications of SMA's

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

Engineering Applications of SMA's

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

4.8 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.

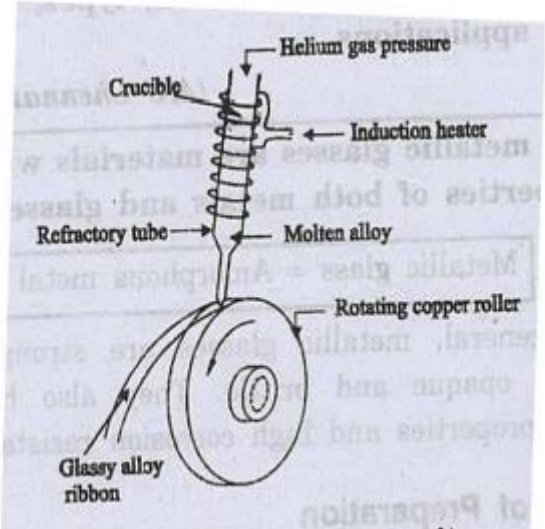


Fig. Melt spinning unit

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.

Examples: Metals Metalloids

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.

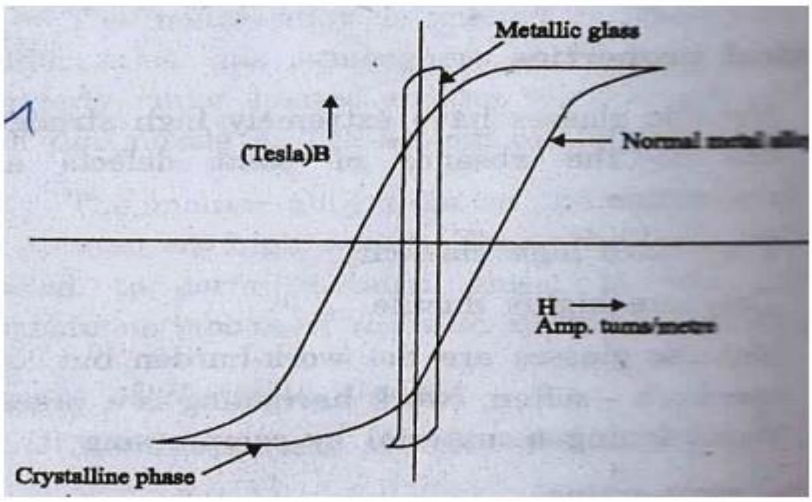


Fig. Hysteresis loop of iron-based alloy in crystalline and metallic glassy phase.

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.

Metallic glasses as transformer core materials

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

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

Nuclear reactor engineering

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

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

Bio-medical Industries

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

CERAMICS

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

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

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

Types of ceramics

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

1. Crystalline ceramics
2. Non-crystalline ceramics

They can also be classified into three different material categories.

1. Oxides
2. Non-oxides
3. Composites

Examples of ceramics

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

Properties of ceramics

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

Applications of ceramics

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

UNIT V NANO MATERIALS

5.1 INTRODUCTION

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

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

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

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

5.2 DEFINITION OF NANO SYSTEM

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

5.3 DIFFERENT FORMS OF NANOMATERIALS

5.3.1 Nano-structured material

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

5.3.2 Nano particles

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

5.3.3 Nano dots

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

5.3.4 Nanorods

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

5.3.5 Nanotubes

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

5.3.6 Nanowires

Nanowires are nanorods which especially conduct electricity.

5.3.7 Fullerenes

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

5.3.8 Nanocomposites

Composite structures whose characteristic dimensions are found at nanoscale.

5.3.9 Cluster

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

5.3.10 Colloids

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

5.4 Nano electronics

Nanoelectronics refers to the use of nanotechnology in electronic components, especially transistors.

It often refers to transistor devices that are so small that inter-atomic interactions and quantum mechanical properties need to be studied extensively. Besides, being small and allowing more transistors to be packed into a single chip, the uniform and symmetrical structure of nanotubes allows a higher electron mobility, a symmetrical electron/hole characteristic.

Need for Nanotechnology in Electronics

Today microelectronics are used and they solve our most of the problems.

The two exceptional disadvantages of micro electronics are:

- Physical size
- Increasing cost of fabrication of integrated circuits.

To overcome these disadvantages, nanotechnology is used.

Advantages of Using Nanotechnology in Electronics

- Increasing the density of memory chips
- Decreasing the weight and thickness of the screens.
- Nanolithography is used for fabrication of chips.
- Reducing the size of transistors used in integrated circuits.

- Improving display screens on electronics devices.
- Reducing power consumption.

5.5 QUANTUM CONFINEMENT

Definition

It is a process of reduction of the size of the solid such that the energy levels inside become discrete.

In this case, small "droplets" of isolated electrons are created. Thus, the energy of a small volume of such materials are quantized just like in an atom. This type of artificial or fake atoms have tunable electrical properties. It is to be noted that only a small percentage of electrons that are free to move during confinement and majority of electrons still tightly bound within inner orbitals.

Usually in order to reduce the dimensions of a given volume, either bottom-up approach or top-down approach is followed.

In bottom-up approach, low-volume structures are built atom by atom. In the top-down approach, material is removed from one or more of three dimensions (length, width, height) of a larger solid.

In both cases, a structure small enough for quantum behavior to manifest can be produced.

5.6 QUANTUM CONFINED STRUCTURES

Definition

When a bulk material is reduced in its size, at least one of its dimension, in the order of few nanometres, then the structure is known as quantum structure.

Explanation

The volume of a box can be reduced by shortening its length, width or, and height. The same is true for the region occupied by the electrons in a solid. There are three dimensions to confine the bulk material.

The quantum confinement needs confining at least one of these dimensions to less than 100 nanometers or even just a few nanometers. The more the dimensions are confined, the more the density of states functions looks like that of an atom. This progressive discretization gives new ways to understand real atoms, behavior of electrons and developing quantum confined electronic devices.

When the electrons are confined inside a region of minimal width, ie., confinement in one dimension "quantum-well" is created. The quantum wells are made from alternating layers of different semiconductors or by deposition of very thin metal films.

By further reducing the depth of the electron's domain, "quantum-wire" is created

Example: nanotube.

Finally, when all three dimensions are minimized, "quantum-dot" is created. The quantum dot is a particle located inside a larger structure or on its surface. It can be used as a space, where electrons can be trapped using electric fields.

As quantum wells and quantum wires each have at least one dimension in which the electrons are free to move, these structures to exhibit "partial confinement". However, quantum dots exhibit "total confinement".

5.7 DENSITY OF STATES IN BULK, QUANTUM WELL, QUANTUM WIRE AND QUANTUM DOT STRUCTURE

5.7.1 Density of States in Bulk Materials OR 3D materials

Density of states

Density of states N (E) dE^{3D} is defined as the number of available energy states present in a metal per unit volume in an energy interval E and E + dE.

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

$$N(E)dE^{3D} = \frac{Z(E)dE}{V}$$

Derivation

- 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
- The number of energy states is equal to the volume of sphere

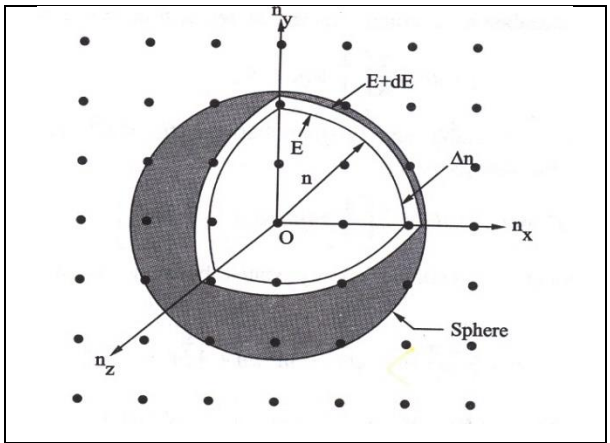


Fig 5.1 Bulk material

The number of energy states within the sphere of radius 'n' is

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

Since n_x, n_y & n_z are positive values, only one octant of the sphere can be considered.

The number of energy states within the sphere of radius 'n' is

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

The number of energy states within the sphere of radius '$n + dn$' is

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

The number of energy states within the sphere of radius 'dn' is

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

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

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

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

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

$$Z(E)\,dE = \frac{\pi}{2}n^2 dn \Rightarrow \frac{\pi}{2}n(n\,dn) \qquad \text{---------- (1)}$$

The energy of the electron in a box

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

$$n^2 = \frac{8ml^2 E}{h^2} \qquad \text{---------- (2)}$$

$$n = \left[\frac{8ml^2 E}{h^2}\right]^{\frac{1}{2}} \qquad \text{---------- (3)}$$

Differentiate (2) on both sides

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

$$n\,dn = \frac{8ml^2}{2h^2}dE \qquad \text{---------- (4)}$$

Sub. (3) & (4) in (1)

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

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

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

$$Z(E)\,dE = \frac{\pi}{4}\left[\frac{8m}{h^2}\right]^{\frac{3}{2}}l^3E^{\frac{1}{2}}\,dE \qquad \text{---------- (5)}$$

l^3 – Volume of the sphere, i.e., l^3=V

Eqn (5) becomes

$$N(E)\,dE^{3D} = \frac{Z(E)dE}{V} = \frac{\pi}{4}\left[\frac{8m}{h^2}\right]^{\frac{3}{2}}E^{\frac{1}{2}}\,dE \text{ ----- (6)}$$

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

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

$$N(E)\,dE^{3D} = \frac{\pi}{2}\left[\frac{8m}{h^2}\right]^{\frac{3}{2}}E^{\frac{1}{2}}\,dE \quad \textbf{--------(7)}$$

Or $$N(E)\propto\sqrt{E} \text{ ---------- (8)}$$

(7) is the expression for density of states per unit volume in bulk materials. Density of state is directly proportional to square root of E.

5.7.2 Density of States in Quantum well OR 2D materials

Density of states

Density of states N (E) dE^{2D} is defined as the number of available energy states present in a metal per unit area in an energy interval E and E + dE.

Density of energy states = Number of available energy states within energy E and E+dE/ area

$$\text{N (E)}dE^{2D} = \frac{Z(E)dE}{A}$$

Derivation

- Let us assume 2D nano materials like nano well or nano film

- Let n and n+dn are the radius of inner shell and outer shell respectively
- Let E and E+dE are the energy of inner shell and outer shell respectively.
- Let dn be the thickness between ineer and outer shell and dE be the energy on thickness dn.
- O be the origin. The 2D material is cut in to 4 equal pieces.

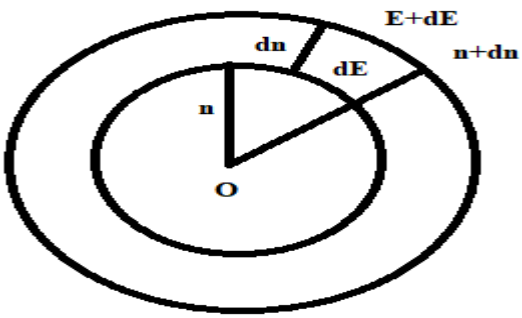


Fig 5.2 2D material or nano well/film

The number of energy states with in the area of circle of radius n in one quadrant is given by

$$= \frac{1}{4}(\pi n^2) \text{ ----------1}$$

The number of energy states with in the area of circle of radius n+dn in one quadrant is given by

$$= \frac{1}{4}(\pi(n+dn)^2) \text{ ----------2}$$

The number of energy states with in the area of circle with in energy interval E and E+dE is given by

$$Z(E)dE = \frac{1}{4}(\pi(n+dn)^2 - \pi n^2) \text{ ----------3}$$

$$= \frac{1}{4}\pi(n^2 + dn^2 + 2ndn - n^2)$$

Simplifying

$$= \frac{1}{4}\pi(dn^2 + 2ndn)$$

Higher term of dn is very small. So dn=0

$$= \frac{1}{4}\pi(2ndn)$$

$$Z(E)dE = \frac{1}{2}\pi(ndn) \text{ ----------4}$$

Energy in a one dimensional potential box of length l is given by,

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

Rearranging we get,

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

Differentiating we get

$$2ndn = \frac{8ml^2}{h^2}dE$$

Or $$ndn = \frac{8ml^2}{2h^2}dE$$ ----------6

Substituting eqn 6 in eqn 4 we get

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

Each energy level occupied by two electrons according to Pauli's exclusion principle. So,

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

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

But $A=l^2$

$$\frac{Z(E)dE}{l^2} = \left[\frac{4\pi m}{h^2}dE\right]$$

$$N(E)dE^{2D} = \frac{Z(E)dE}{l^2} = \left[\frac{4\pi m}{h^2}dE\right]$$----------7

We know, $\hbar = \frac{h}{2\pi}$

Equation 7 can be written as

$$N(E)dE^{2D} = \left[\frac{m}{\pi\hbar^2}dE\right]$$

The mass of the electron is considered as effective mass of an electron m*

$$N(E)^{2D} = \left[\frac{m*}{\pi\hbar^2}\right]$$----------8

Here density of states changes with effective mass of the electron m* and independent to energy.

5.7.3 Density of States in Quantum wire/rod OR 1D materials

Density of states

Density of states N (E) dE^{1D} is defined as the number of available energy states present in a metal per unit length in an energy interval E and E + dE.

Density of energy states = Number of available energy states within energy E and E+dE/ length

$$N(E)dE^{1D} = \frac{Z(E)dE}{l}$$

Derivation

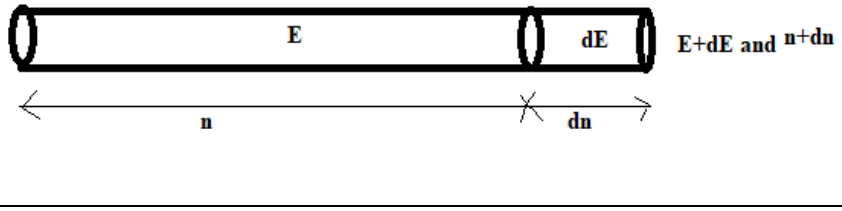


Fig 5.3 1D material or nano wire/rod

- Let us assume one dimensional nano materials such as nano wire or nano rod.
- Let L and L+ dL are the length of inner shell and outer shell
- Let E and E+dE are the energy on inner shell and outer shell
- Let dL and dE are the thickness between two shell and energy on thickness dL.

Number of energy states with in the length between E and E+dE is given by

Z(E)dE=n+dn-n=dn----------1

Energy in a one dimensional potential box of length l is given by,

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

Rearranging we get,

$$n^2 = \frac{8ml^2 E}{h^2} \text{ ----------3}$$

$$n = \left(\frac{8ml^2 E}{h^2}\right)^{\frac{1}{2}} \text{ ----------4}$$

Differentiating eqn 3, we get

$$2ndn = \frac{8ml^2}{h^2} dE$$

Or $$dn = \frac{8ml^2}{2nh^2} dE \text{ ----------5}$$

Subs eqn 4 &5 in eqn 1

$$Z(E)dE = \left(\frac{8ml^2}{2h^2}\right) dE \left(\frac{8ml^2 E}{h^2}\right)^{-\frac{1}{2}}$$

OR $$Z(E)dE = \frac{1}{2}\left(\frac{8m}{h^2}\right)^{\frac{1}{2}} .l..E^{-\frac{1}{2}} dE$$

$$N(E)dE^{1D} = \frac{Z(E)dE}{l} = \frac{1}{2}\left(\frac{8m}{h^2}\right)^{\frac{1}{2}} .E^{-\frac{1}{2}} dE$$

$$N(E)dE^{1D} = \frac{2}{2}\left(\frac{2m}{h^2}\right)^{\frac{1}{2}}.E^{-\frac{1}{2}}dE = \left(\frac{2m}{h^2}\right)^{\frac{1}{2}}.E^{-\frac{1}{2}}dE$$

Each energy level occupied by two electrons according to Pauli's exclusion principle.

$$\text{Or} \quad N(E)^{1D} = 2x\left(\frac{2m}{h^2}\right)^{\frac{1}{2}}.E^{-\frac{1}{2}} \quad \text{----------6}$$

This equation 6 is called as density of states for one dimensional nano materilas.

5.7.3 Density of States in Quantum dot OR 0 D materials

The density of state of a quantum dot in which all the directions are confined and no direction (0D). Here electron movement is free. The density of state of this quantum dot is given by

$$N(E)^{0D} = \delta(E - E_i) \qquad \text{i= 0,1,2,3,……..}$$

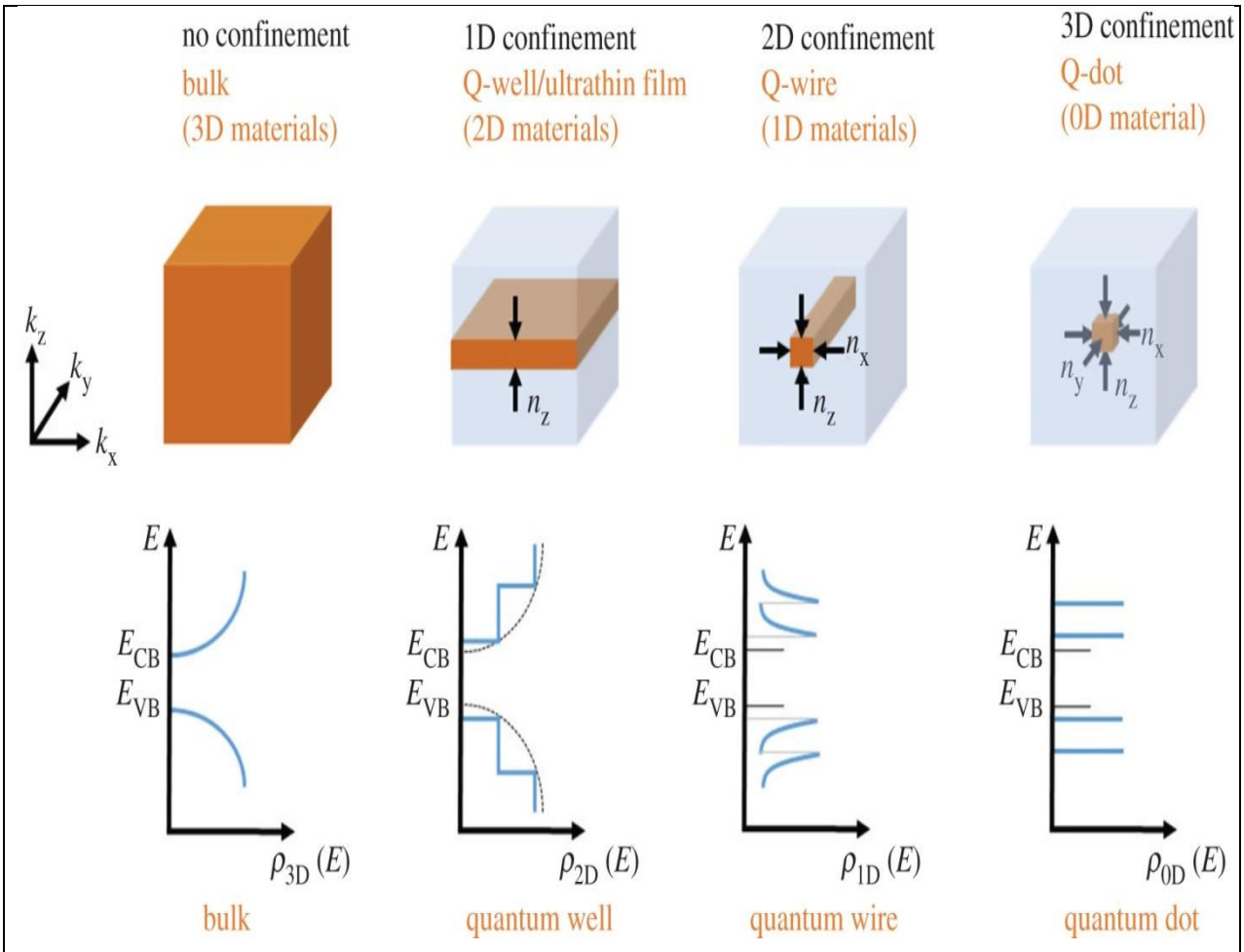


Fig 5.4. Structure of various nano materials & its energy gap

5.8 PREPARATION OF NANO PHASE MATERIALS

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

- Top – down approach
- Bottom – up approach

5.8.1. Top – down approach

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

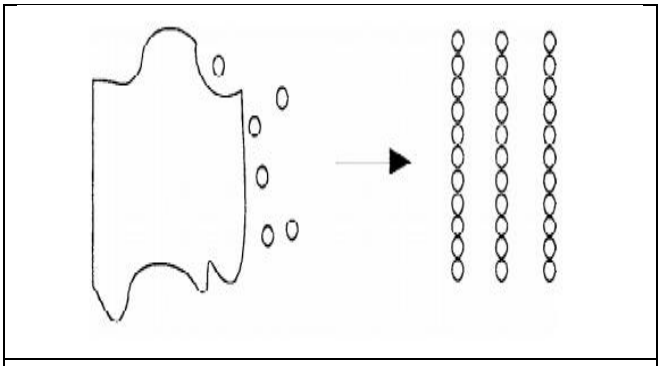


Fig 5.5. Top down approach

Types of Top – down Methods

- Ball Milling
- Lithographic
- Machining

5.8.2 Bottom – up approach

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

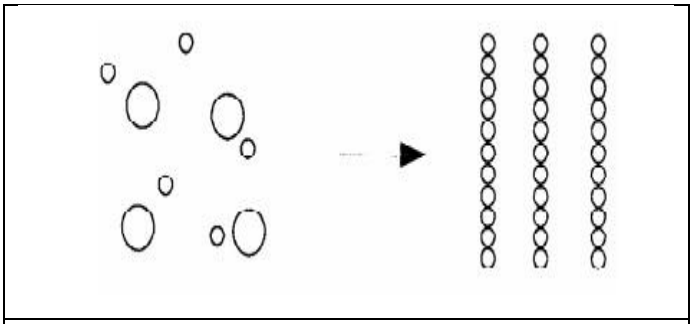


Fig 5.5. Bottom up approach

Types of Bottom up Methods

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

5.9 SYNTHESIS METHODS

5.9.1 PULSED LASER DEPOSITION METHOD

Principle

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

Construction

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

- 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

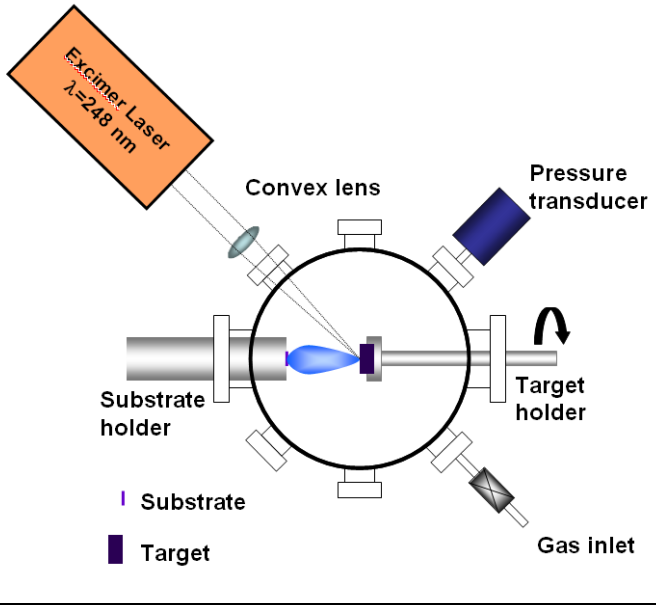


Fig 5.6. Schematics of PLD

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.

5.9.2 PHYSICAL VAPOUR DEPOSITION METHOD

Principle:

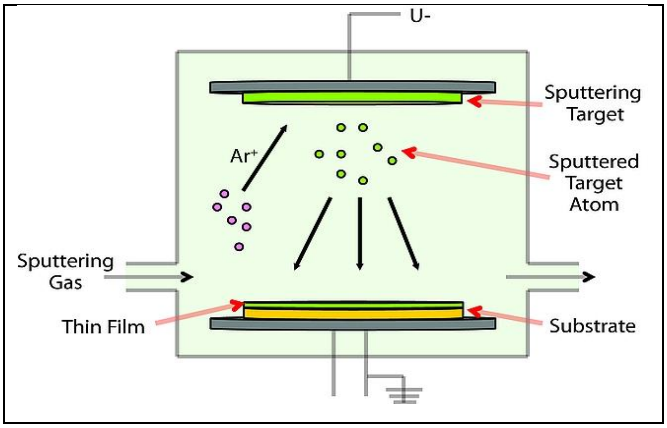


Fig 5.7. Schematics of PVD

Physical vapour deposition (PVD) is fundamentally a vaporisation coating technique, involving transfer of material on an atomic level. The material that is going to be deposited starts out in solid form.

.**Construction & Working**:

PVD processes are carried out under vacuum conditions. The process involved four steps:

- Evaporation
- Transportation
- Reaction
- Deposition

Evaporation

During this stage, a target, consisting of the material to be deposited is bombarded by a high energy source such as a beam of electrons or ions. This dislodges atoms from the surface of the target, 'vaporising' them.

Transport

This process simply consists of the movement of 'vaporised' atoms from the target to the substrate to be coated and will generally be a straight line affair.

Reaction

In some cases coatings will consist of metal oxides, nitrides, carbides and other such materials. In these cases, the target will consist of the metal. The atoms of metal will then react with the appropriate gas during the transport stage. For the above examples, the reactive gases may be oxygen, nitrogen and methane.

In instances where the coating consists of the target material alone, this step would not be part of the process.

Deposition

This is the process of coating build up on the substrate surface.

Depeding on the actual process, some reactions between target materials and the reactive gases may also take place at the substrate surface simultaneously with the deposition process.

Advantages of the Physical Vapour Deposition Process

- Materials can be deposited with improved properties compared to the substrate material
- Almost any type of inorganic material can be used as well as some kinds of organic materials

- The process is more environmentally friendly than processes such as electroplating

Disadvantages of the Physical Vapour Deposition Process

- It is a line of sight technique meaning that it is extremely difficult to coat undercuts and similar surface features
- High capital cost
- Some processes operate at high vacuums and temperatures requiring skilled operators
- Processes requiring large amounts of heat require appropriate cooling systems
- The rate of coating deposition is usually quite slow

Applications

As mentioned previously, PVD coatings are generally used to improve hardness, wear resistance and oxidation resistance. Thus, such coatings use in a wide range of applications such as:

- Aerospace
- Automotive
- Surgical/Medical
- Dies and moulds for all manner of material processing
- Cutting tools
- Fire arms

5.9.3 CHEMICAL VAPOUR DEPOSITION METHOD

Principle

The deposition of nano films from gaseous phase by chemical reaction on high temperature is known as Chemical Vapour Deposition (CVD).

In this method, initially the material is heated to form a gas and then it is deposited on a solid surface under vacuum condition to form nano powder by chemical reaction on the solid surface.

Construction

- The Chemical vapour Deposition System consists of a substrate.
- The substrate is kept on a susceptor.
- This system is connected with the resistance heater.
- This system contains two openings, i.e. inlet & outlet.
- The gas with diffused reactants is passed through the inlet.
- The byproducts are removed through the outlet.

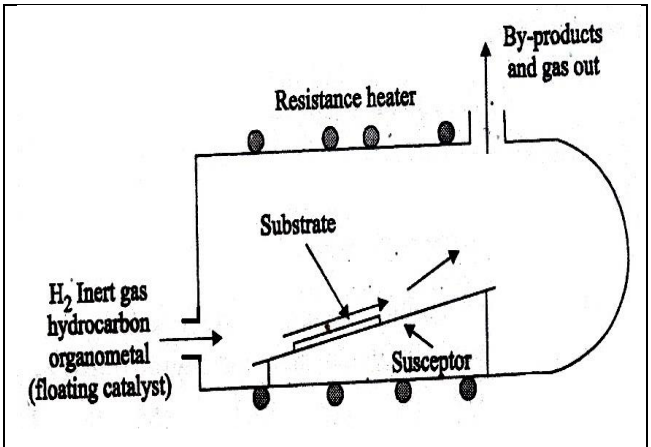


Fig 5.8. Schematics of CVD

Working

- The gas with diffused reactants is passed through the inlet.
- Switch on the resistance heater.
- The surface of the substrate is heated.
- Since the surface of the substrate is very hot, the heat energy increases the chemical reactions of the reactants.
- The reactants form the film during and after the reactions.
- The thin film is deposited on the substrate.
- Byproducts of the chemical reactions are removed through the outlet.

Advantages

- This method is used to produce defect free nano particles.
- High purity (more than 99%) nano materials are produced.
- This is a low cost technique.
- Temperature of the deposition is low compared to other methods.

5.9.4 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.

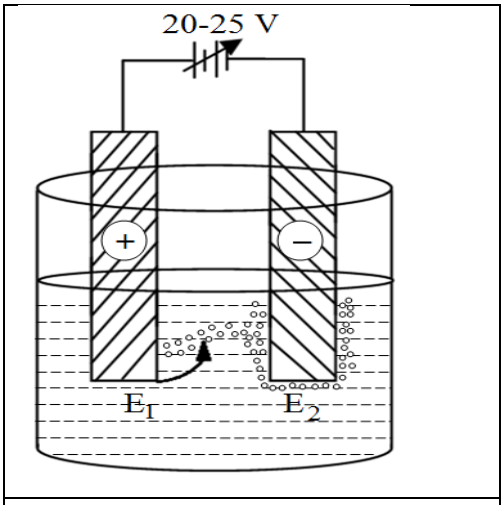


Fig 5.9. Schematics of Electro deposition

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.

5.10 CARBON NANOTUBES (CNT)

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

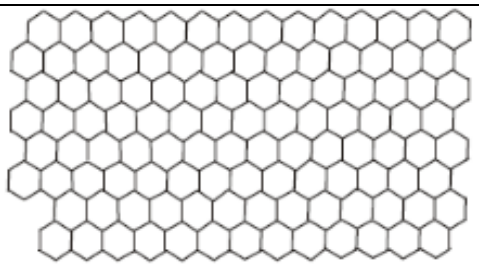


Fig 5.10. Graphene sheet

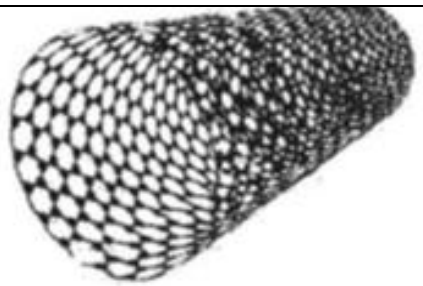


Fig 5.11. Rolled Graphene sheet

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

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

Structures of CNT

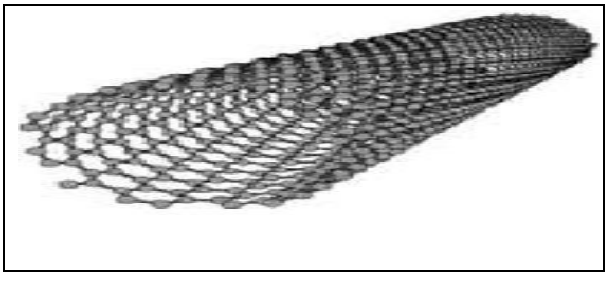
The CNTs have many structures on the basis of their length, type of spiral and number of layers. Their electrical properties depend on their structure and they act as both metal and semiconductor.

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

5.11 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

Fig 5.12. SWCNT

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.

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.

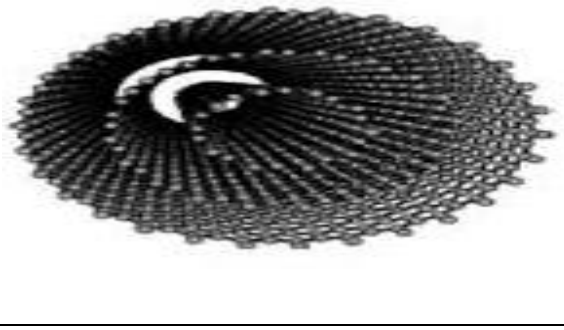


Fig 5.13. MWCNT

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.

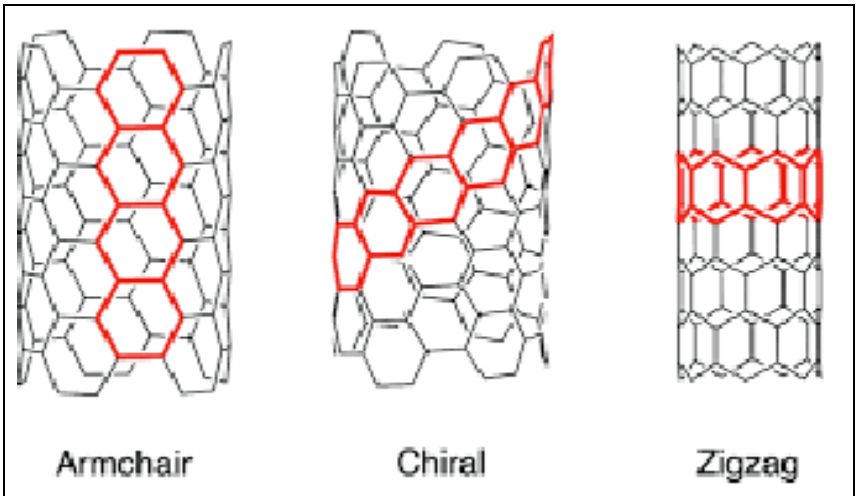


Fig 5.14.

5.12 PROPERTIES OF CNTs

(a) Electrical Properties

- Carbon nanotubes are metallic or semiconducting depending on the diameter and chirality (ie., how the tubes are rolled).
- The energy gap of semiconducting chiral carbon nanotubes is inversely proportional to the diameter of the tube as shown in fig 5.13. The energy bandgap decreases with increase of diameter of the CNTs.

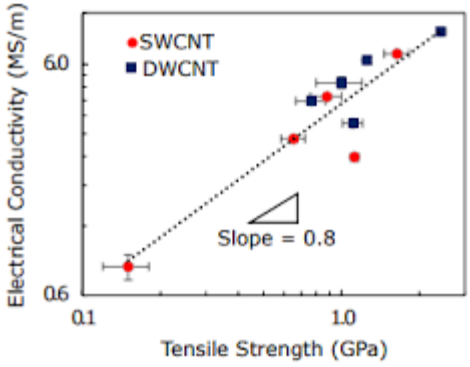


Fig 5.14. Electrical property

- The energy gap also varies along the tube axis and reaches a minimum value at the tube ends. This is due to the presence of localized defects at the ends due to the extra energy states.
- In SWNTs, conduction occurs through discrete electronic states that are coherent between the electrical contacts (hundreds of nanometers). This means that nanotubes can be treated as quantum wires atleast at very low temperatures.

(b) Mechanical Properties

- The strength of the carbon-carbon bond is very high therefore any structure based on aligned carbon-carbon bonds will ultimately have high strength.
- Young's modulus of CNT is about 1.8 TPa (1012 Pa about 10 times larger than that of steel). Nanotubes have therefore high ultimate tensile-strength
- One of the important properties of nanotubes is their ability to withstand extreme strain.
- The carbon nano tubes can recover from severe structural distortions. This is due to the ability of

carbon atoms to rehybridize.

(c) Physical Properties

- Nanotubes have a high strength-to-weight ratio (density of 1.8 g/cm^3 for MWNTs and 0.8 g/cm^3 for SWNTs). This is indeed useful for lightweight applications. This value is about 100 times that of steel and over twice that of conventional carbon fibres.
- The surface area of nanotubes is of the order of 10 - 20 m^2/g which is higher than that of graphite.

(d) Chemical properties

Nanotubes are highly resistant to any chemical reaction. It is difficult to oxidize them and the onset of oxidation in nanotubes is 100□C higher than that of carbon fibres.As a result, temperature is not a limitation in practical application of nanotubes.

(e) Thermal properties

Nanotubes have a high thermal conductivity and the value increases with decrease in diameter.

5.13 APPLICATIONS OF CARBON NANOTUBES

The unusual properties of carbonnano tubes have many applications such as battery electrodes, electronic devices and reinforcing fibers for stronger composites etc.,

Electrical and Electronics applications

1. When a small electrical field is applied parallel to the axis of a nanotube, the electrons are emitted at a very high rate from the ends of the tube. This is called field emission and it is used in development of flat panel displays.
2. Vacuum tube lamps that are as bright as conventional light bulbs with long life time and more efficient can be produced using CNT.
3. Semiconducting carbon nanotubes connecting two gold electrodes form field effect transistors (FET) device as shown in fig. 5.14. The switching time of these devices is very fast. They exhibit clock speeds of a terahertz which is 104 times faster than present processors. Further, small size allows a large number of component in a chip.

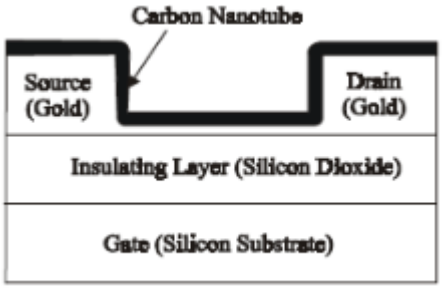


Fig 5.14. FET made by CNT

4. Carbon nanotubes with diameters of 2 nm have extremely low resistance and thus they can carry large currents without getting heated. So, they can be used as interconnects in chip.

Computer applications

Carbon nanotubes can be used to make a computer switching device as shown in fig. 5.15.

Nano-RAM is a proprietary computer memory technology from the company Nantero. It is a type of nonvolatile random-access memory based on the position of carbon nanotubes deposited on a chip-like substrate. In theory, the small size of the nanotubes allows for very high density memories. Nantero also refers to it as NRAM.

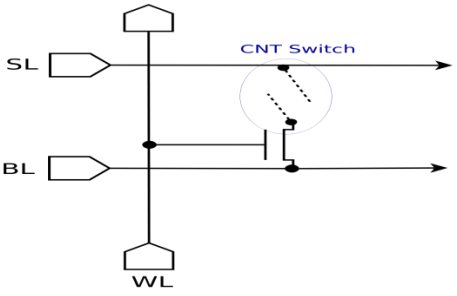


Fig 5.15. Switch made by CNT

Battery technology

- Carbon nanotubes have many applications in battery technology. Lithium which is a charge carrier in some batteries, can be stored inside nanotube.
- Carbon nano tube can be used for storing the hydrogenwhich is used in the development of fuel cells.

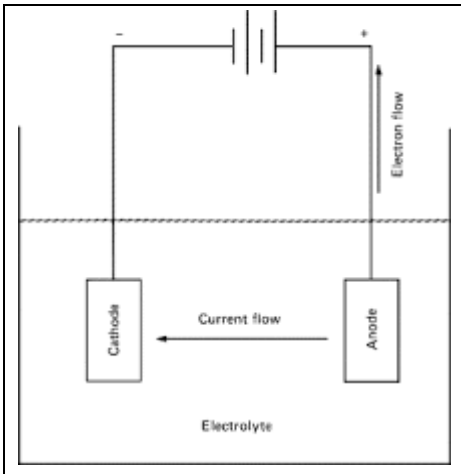


Fig 5.16. Electrochemical cell made by CNT

The cell consists of an electrolytic solution of KOH with a negative electrode consisting of carbon nanotube (CNT) paper (fig.5.16).

Mechanical Applications

- Nanotubes can be used to increase the tensile strength of steel.
- A plastic composite of carbon nanotubes provides light weight shielding material for electromagnetic radiation.

Chemical applications

- A field-effect transistor made of chiral semiconducting carbon nanotubes is used as sensitive detector of various gases (gas sensors). Fig. 5.17 shows the voltage-current characteristics before and after exposure to NO_2.
- Nanotubes act as catalysts for some chemical reactions.

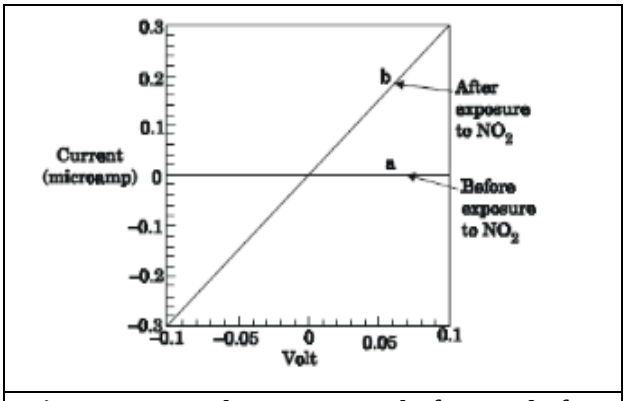


Fig 5.17. V-I characteristics before and after exposure to NO_2