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UPPSC – Polytechnic Lecturer

Electrical Engineering

Uttar Pradesh Public Service Commission (UPPSC)

Volume - 7

Material Science & Analog Electronics

SIERRA INNOVATIONS

INDEX

1 — Basics of Engineering Material

CHAPTER

THEORY

1.1 | CHEMICAL BONDS

The binding force between two or more atoms or molecules are known as chemical bonds.

There are two types of chemical bonds.

- Primary
- Secondary

1.1.1 *Primary Bond*

These bond are inter atomic bond.

These bond are having higher bond energy.

Ex. Ionic, covalent and metallic bond.

Ionic Bond : Ionic bond is a bond resulting from the electrostatic interaction of opposite ions by transfer of e^- from one to another.

Ionic solid are formed particularly elements on the left and right hand side of the periodic table.

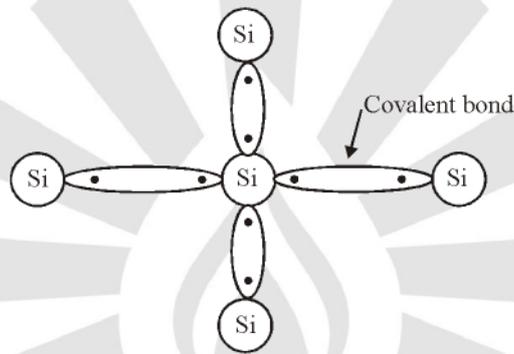*Ex.* Alkali halide (Group I and Group VII elements) Nac*l*, Kc*l* et.)
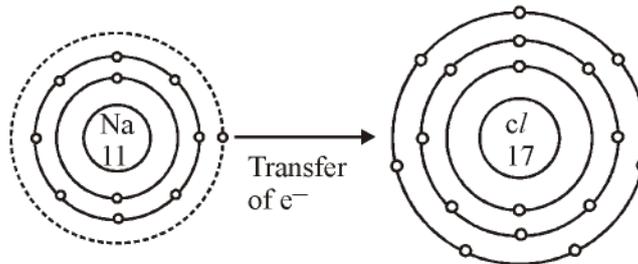
General Characteristic of Ionic Bond

- Moderate to high strength

- Higher hardness

- Brittle (can be break)

- Malleable (can be mould)

- Electrically neutral

- High melting point

Covalent Bond : Covalent bond is formed by sharing of e^- between neighboring atoms.

Ex. Si, Ge, CO_2.

General Characteristic of Covalent Bond

- High strength

- High melting point

- Brittle

- Electrical conductivity depends upon Bond strength

- Tin   :   Conductor (weak covalent bond)

- Si, Ge   :   Semi conductor (moderate)

- Diamond :   Insulator (High)

Metallic Bond : This type of bond is in the element having small number of valence electron, which are loosely held, so that they can be easily released to the common pool.

The Metallic bonding results when each of the atoms of the metal contributes its valence e^- to the formation of an e^- cloud that pervades the solid metal.

General Characteristic of Metallic Bond

- High electrical and thermal conductivity

- Metals are opaque

- They are having surface luster
- Metallic bond are non directional (it means bond strength is equal in all direction)

Ex. Alkali metals (highest metallic bonding)

1.1.2 *Secondary Bond*

These bonds are inter molecular bond.

These bonds are having lesser bond energy as compare to primary bond.

Ex. Vanderwall bond, hydrogen bond.

Vanderwall Bond : Weak or secondary bond known as vander wall force can link molecules that posses a non symmetric distribution of charge.

Dipole interaction between molecules or atoms is due to presence of vanderwall force of attraction.

Ex. HF, H_2O, solid Ar, Solid He, solid hydrogen etc.
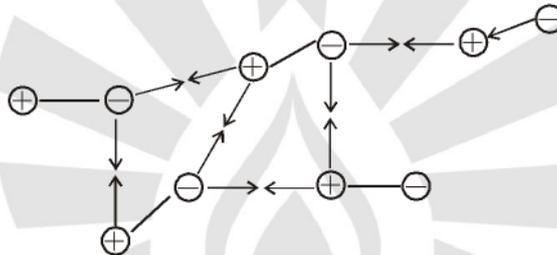
Hydrogen bond is a strong type of vanderwall's bond

1.2 | ATOM ARRANGEMENT IN MATERIALS

Arrangement of atoms in a material has significant effect on properties.

Depending on the manner of atomic grouping, materials are classified as

1.2.1 *Molecular Structure*

Molecular structure have a distinct number of atoms that are held together by primary bonds, but they have only relatively weak bonds with other similar group of atoms.

Ex. O_2, H_2O, C_2H_4 etc.

1.2.2 *Crystal Structure*

Crystal structure are assumed by solid materials and most minerals.

Atoms are arranged in a regular geometrical array known as space lattice.

1.2.3 *Amorphous Structure*

The atoms have a certain degree of local order but when viewed as an aggregate, have a more disorganized atoms arranged than the crystalline solid.

Ex. Glass

1.3 | ATOMS ARRANGEMENT IN SOLID

1.3.1 *Crystalline Material*

Atoms self-organize in a periodic manner is called crystalline material.

1.3.2 *Single Crystal Material*

Atoms are in a repeating or periodic manner over the entire extent of the material.

These material are anisotropic materials.

Ex. Quartz.

Anisotropic Material : The material in which properties depend on the direction in which they are measured is called anisotropic material.

Ex. Single crystal material

Isotropic Material : The material in which properties are independent of the direction in which they are measured is called isotropic material.
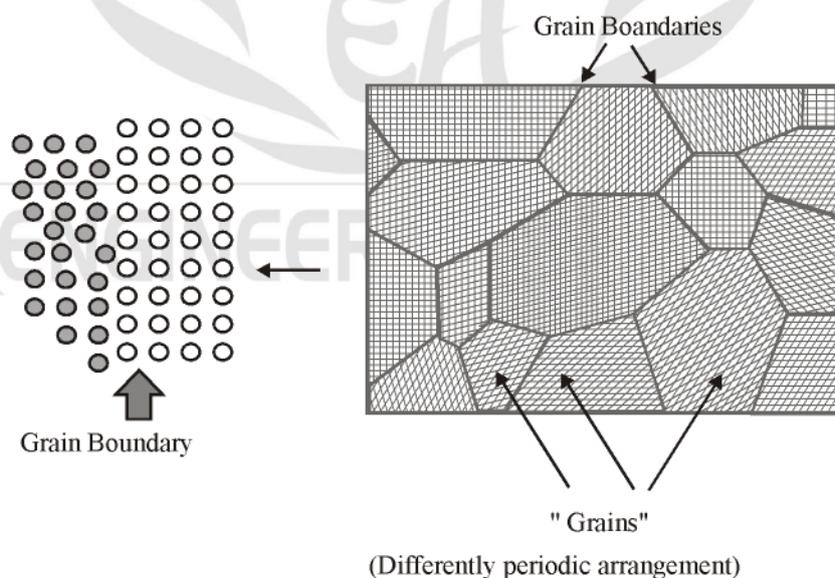
Ex. Polycrystalline material

1.3.3 *Poly Crystalline Material*

These material are divided into no. of small regions. These regions are called grain. within each grain. molecular arrangement is regular or periodic but this arrangement varies from are grain to another.

Ex. Polycrystalline silicon

These materials are isotropic

(Differently periodic arrangement)

1.3.4 Amorphous Material

In amorphous material, atoms upto first nearest neighbour are arranged periodically but atoms which are far away from nearest atoms are found to be arranged randomly.

When atoms or molecules are not given opportunity to arrange in periodic or regular manner, an amorphous materials may be formed.
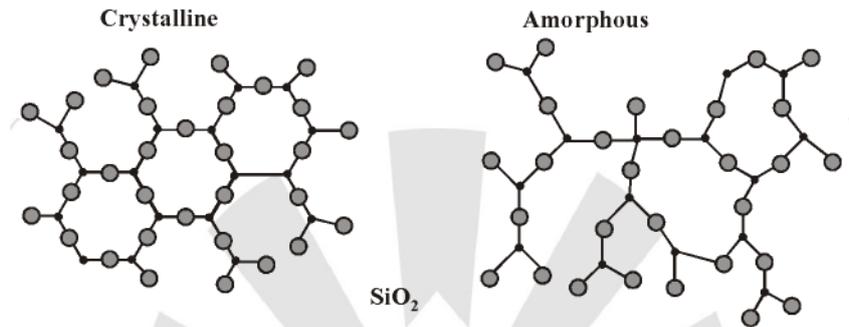
*Ex.* Super cooled state of SiO_2 is called glass (amorphous material)

Note :

- On annealing (heating and cooling) SiO_2 crystallizes into Quartz.
- In some cases molecules may be extremely long and irregular in shape so that periodic or regular arrangement may not be obtained.

Ex. Polymers

1.3.5 Epitaxial Material

The process of growth of a layer of silicon over a substrate is called epitaxial and the material through layer is made is called epitaxial material.
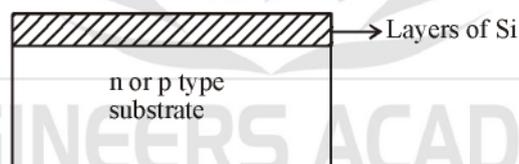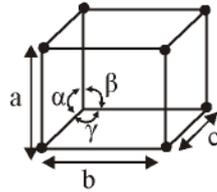

1.4 UNIT CELL

It is defined as the minimum area cell in 2-dimension or minimum volume cell in 3 dimension by repetittion of which a crystal may be formed.

Parameters of unit cell :

- Unit cell dimension
- Angle between axis

- Number of atoms per unit cell

- Co-ordination number

- Atomic packing factor (APF)

Ex. $\angle \alpha : a, c$

$\angle \beta : b, a$

$\angle \gamma : c, b$

Co-ordination Number : The no. of atoms which are in physical contact with a particular atoms in a crystal structure is called co-ordination number.

Atomic packing factor (APF) : APF or packing efficiency indicates how closely atoms are packed in unit cell.

$$APF = \frac{\text{No. of atoms per unit cell} \times \text{Atomic volume}}{\text{Volume of unit cell.}}$$

Lattice : Periodically or orderly arrangement of unit cell is called lattice.

1.5 | CUBIC CRYSTAL STRUCTURE

1.5.1 *Simple Cubic*

In a simple cubic there are 8 atoms at eight corner of a cube.

Atoms are in physical contact along edge of the cube.

$a = 2r$

No. of atoms per unit cell $= 8 \times \dfrac{1}{8} = 1$

$$APF = \frac{1 \times \frac{4}{3}\pi r^3}{a^3} = \frac{\frac{4}{3}\pi\left(\frac{a}{2}\right)^3}{a^3} = 0.52$$
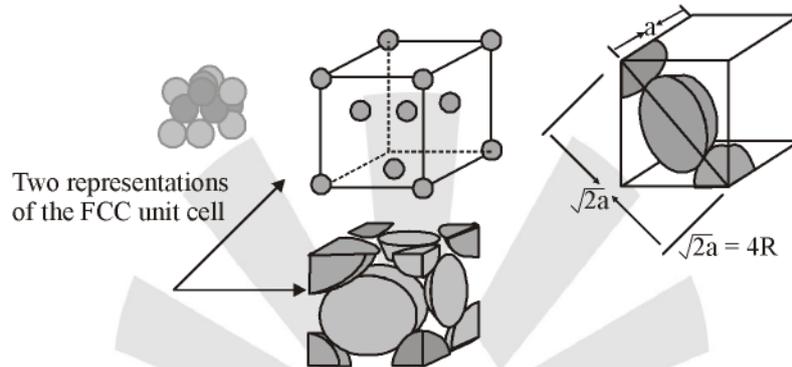
Co-ordination no. = 6.

Ex. Mn, Polonium, Flourspar etc

1.5.2 Face Centered Cubic (FCC)

In FCC, there are 8 atoms at 8 corner of the cube and 6 atom at the centre of 6 faces of the cube.

No. of atoms per unit cell = $8 \times \dfrac{1}{8} + 6 \times \dfrac{1}{2} = 4$

Atoms are in physical contact along face diagonal

Two representations of the FCC unit cell

Cube length edge $a = \dfrac{4r}{\sqrt{2}} = 2\sqrt{2}r$

$$APF = \dfrac{4 \times \dfrac{4}{3}\pi r^3}{a^3} = 0.74.$$

Co-ordination number = 12

Corner and face atoms in the unit cell are equivalent

FCC crystal structure has APF of 0.74, the maximum packing for a system (FCC has closed pack structure).

Ex. Gold (Au), Ag, pt, Cu, Ni, Pb, Pt, Fe (γ-type), Al etc.

1.5.3 Body Centered Cubic (BCC)

In BCC, 8 atoms are at 8 corners of cube and one atoms is located at the center of unit cell.

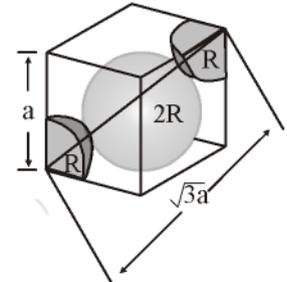Atoms are in physical contact along body diagonal or in cubic diagonal.
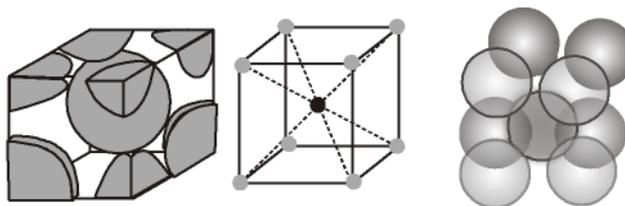
Cube edge length, $\quad\quad\quad a = \dfrac{4R}{\sqrt{3}}$

Co-ordination number = 8

No. of atoms per unit cell = $8 \times \dfrac{1}{8} + 1 = 2$

$$APF = \dfrac{2 \times \dfrac{4}{3}\pi R^3}{a^3} = 0.68$$

Body and corner atoms of unit cell are equivalent

Ex. Li, Na, K, Cr, Mn, Cb, W, Ti, Fe (α – iron, δ–iron) etc.

1.5.4 *Diamond Cubic*

Diamond cubic unit cell is having contribution of 18 atoms, out of 18 atoms

(i)   8 atoms are corner atoms

(ii)   6 atoms are face centered atoms

(iii) Remaining 4 atoms are completely inside

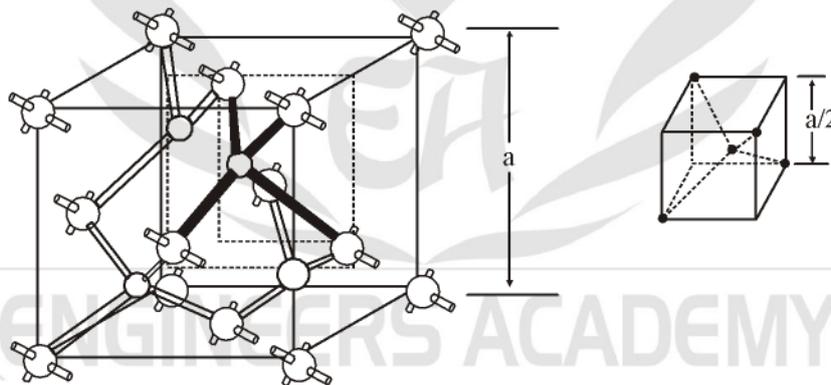No. of atoms per unit cell = $8 \times \dfrac{1}{8} + 6 \times \dfrac{1}{2} + 4 = 8$

Fig. : Tetrahedral Structure of Closest Neighbor in Diamond Lattice

Length of cube $\quad\quad\quad a = 8r/\sqrt{3}\ or\ r = a\sqrt{3}/8$

$$APF = \dfrac{8 \times \dfrac{4}{3}\pi r^3}{a^3} = 0.34$$

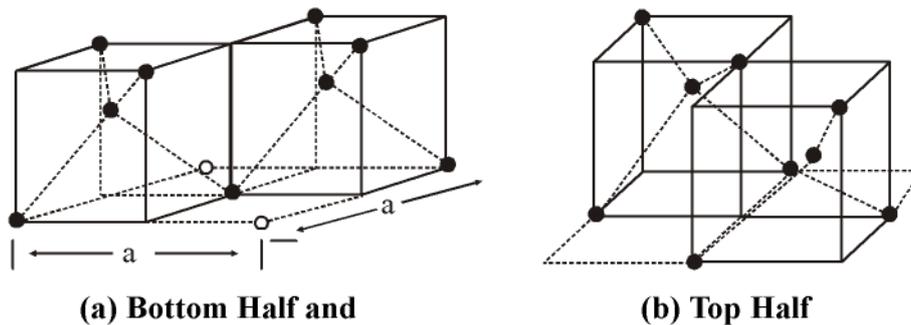**(a) Bottom Half and**   **(b) Top Half**

Fig. : Portions of the Diamond Lattice

Diamond cubic structure is similar to zinc blende structure
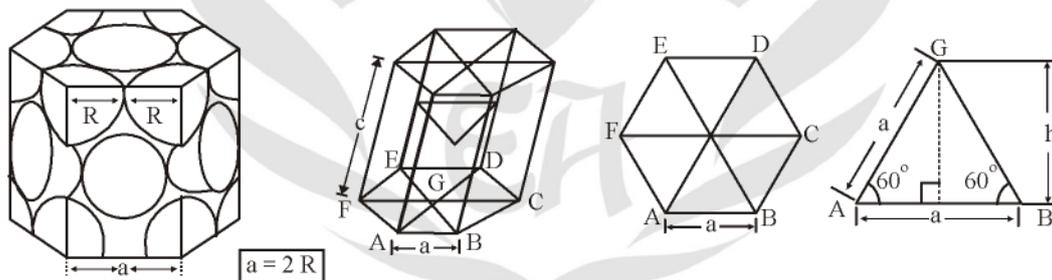
Group (III-V) compounds are having zinc blende structure

Ex.   Diamond, C, Si, Ge, group II-V compounds

1.5.5 *Hexagonal Close Packing (HCP)*

HCP unit cell is having

(i)   12 corner atoms

(ii)   2 face centre atoms in top and bottom hexagon

(iii)   3 atoms are inside

No. of atoms per unit cell $= 3 + 2 \times \dfrac{1}{2} + \dfrac{1}{6} \times 12 = 6$

$$\frac{c}{a} = \frac{max^m \ dimension}{min^m \ dimension} = 1.63$$

$$\text{Unit Cell Volume} = \left(6 \times \frac{1}{2} \times a \times h\right) \times c$$

$$= (3 \times a \times a \sin 60^o) \times C$$

$$= 3a^2 c \ \sin 60^o$$

The face-centered atom and the three mid-layer atoms from a tetrahedron MNOP which has sides equal to a (as atoms at vertices touch each other) and height of c/2. Using this tetrahedron it can be shown that for an ideal hexagonal crystal c/a ratio = 1.633.
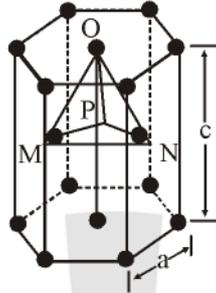
$$APF = \frac{6 \times \frac{4}{3}\pi R^3}{3a^2 c \sin 60^o} = \frac{8\pi a^3}{3 \times 8 \times 1.414 a^3} = 0.74$$
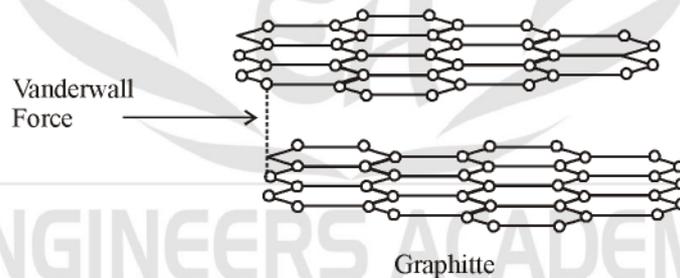
Co-ordination number of HCP unit cell is 12.

Ex. Be, Cd, Mg, Zn, Zr, etc.

Note :

- HCP ad FCC are also called closed pack structure as their packing efficiency is highest i.e., 74%

1.6 | GRAPHITE

Graphitte

Structure of graphite is hexagonal but it is not HCP as there is no centre atom in top and bottom hexagon.

Each carbon atom has 4 valence e^-, 3 of these valence e^- are used in forming covalent bond with adjacent atom in the same layer. The 4th e^- is free to move over the surface of the layer making graphite electrical conductor.

Weak bonding forces between layers are called vanderwall's force because this force is weak, the layers can slide on each other.

The sliding property of layers gives graphite its softness for writing and lubricating properties.

Comparison Between Diamond and Graphite		
	Diamond	Graphite
Hardness	Extremely hard	Soft
Transparency	Transparent	Opaque
Electrical properties	Insulator	Conductor
Thermal properties	Conductor	Insulator
Structure	Tetrahedral	Hexagonal (not HCP)

1.7 | MILLER INDICES

Miller indices are used to determine the direction and planes in the unit cell and crystals.
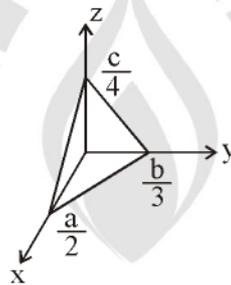
Where a, b, c, are unit cell dimension along x, y, and z respectively.

Method to determine the Miller indices

(i) Determine intercept made by plane among x,y and z axis respectively.

$$\frac{a}{2}, \frac{b}{3}, \frac{c}{4}$$

(ii) Express intercept as multiples of unit cell dimension

$$\frac{1}{2}, \frac{1}{3}, \frac{1}{4}$$

(iii) Get reciprocal of multiples

2, 3, 4

(v) Reduce reciprocals to smallest set of integers

[2, 3, 4]

1.8 | INTERPLANAR SEPARATION

The distance between two adjacent parallel planer in a crystal structure is known as inter planar separation.

For a cubic crystal structure

Interplanar separation

$$d = \frac{a}{\sqrt{l^2 + m^2 + n^2}}$$

Where

a = edge length of cube

[l, m, n] → Miller indices of given plane.

1.9 | BRAVAIS LATTICE

The unit vectors a, b and c are called lattice parameters. Based on their length equality or inequality and their orientation (the angles between them α, β and γ) a total of 7 crystal systems can be defined. With the centering (face, base and body centering) added to these, 14 kinds of 3D lattices, known as Bravais Lattices, can be generated.

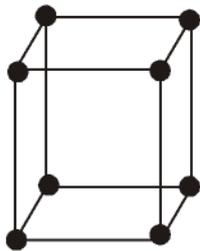| S.No.	Crystal Structure	Unit Cell Dimension	Angle Between Axis	Bravais Lattice
1.	Orthorhombic	$a = b \neq c$	$\alpha = \beta = \gamma = 90°$	P, I, C, F
2.	Monoclinic	$a = b \neq c$	$\alpha = \beta = 90° \neq \gamma$	P, C
3.	Triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma \neq 90°$	P
4.	Hexagonal	$a = b \neq c$	$\alpha = \beta = 90°,$ $\gamma = 120°$	P
5.	Tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90°$	P, I
6.	Rhombohedral/Trigonal	$a = b = c$	$\alpha = \beta = \gamma \neq 90°$	P
7.	Cubic	$a = b = c$	$\alpha = \beta = \gamma = 90°$	P, I, F

P : Simple cubic

I : Body centered cubic
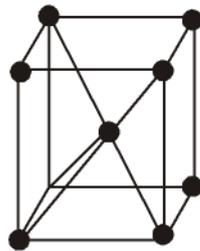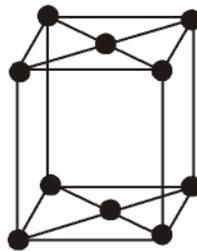
C : Base centered

f : Face centered

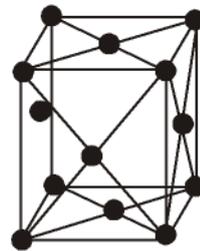Orthorhombic : $a \neq b \neq c$, $\alpha = \beta = \gamma = 90°$
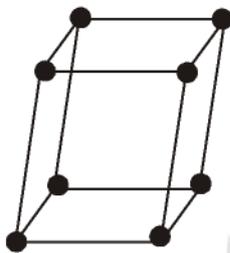

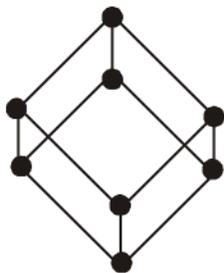Simple   Body-centered   Base-centered   Face centered

Monoclinic : $a \neq b \neq c$, $\alpha = \gamma = 90° \neq \beta$
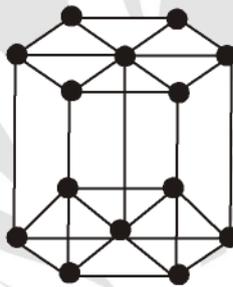

Simple Monoclinic   Base-centered Monoclinic
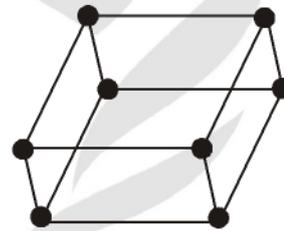

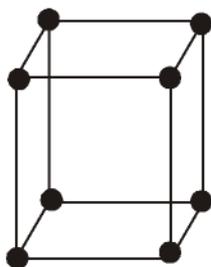Rhombohedral
$a = b = c$
$\alpha = \beta = \gamma \neq 90°$

Hexagonal
$a = b \neq c$
$\alpha = \beta = 90°$ $\gamma = 120°$
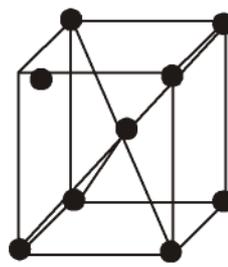
Triclinic
$a \neq b \neq c$
$\alpha \neq \beta \neq \gamma \neq 90°$

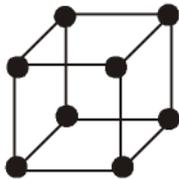Tetragonal : $a = b \neq c$, $\alpha = \beta = \gamma = 90°$

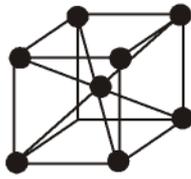Simple Tetragonal   Body-centered Tetragonal (BCT)

Cubic : $a = b = c, \alpha = \beta = \gamma = 90°$

Simple Cubic   Body-centered cubic (BCC)   Face-centered cubic (FCC)

| Crystal system	Example
Triclinic	$K_2S_2O_8$, $K_2Cr_2O_7$
Monoclinic	As_4S_4, KNO_2 $CaSO_4.2H_2O$ β-S
Rhombohedral	Hg, Sb, As, Bi, $CaCO_3$
Orthorhombic	Ga, Ge_3C, α-S
Tetragonal	In, TiO_2, β-Sn
Cubic	Au, Si, Al, Cu, Ag, Fe, NaCl

1.10 | CRYSTAL DEFECTS

In a real crystal, the lattice is not perfect, but contains imperfections or defects.

Such imperfections tend to alter the electrical properties of a material. In some cases, electrical parameters can be dominated by these defect.

Imperfections in crystalline solids

1. Point defect

2. Line defect

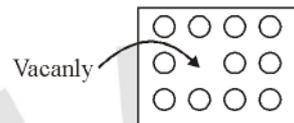3. Surface or plane defect

4. Volume defect
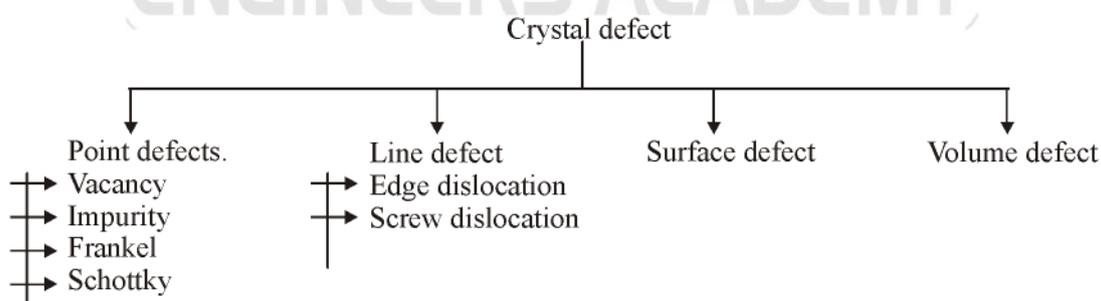
1.10.1 *Point Defects*

Point defects are where an atoms is missing or is in irregular place in the lattice structure.

Point defect is of three types

(i)   Vacancy

(ii)   Impurity

(iii) Frankel

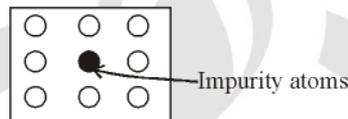**(i)   Vacancy Defect :** In this type of defect an atoms or molecule is absent in the crystal.

Vacanly

In a ionic crystal, if there is missing pair of +ve and −ve ion with in a crystal structure then it is called schottkey defect.

(ii) Impurity Defect : Impurity defect arises when an impurity atoms is introduced in crystal structure either as an 'interstitial' or 'substitutional'

It is of two types.

(a) Substitutional Type Impurity Defect : In this type impurity atoms replaces parent atoms of crystal.

Impurity atoms

(b) Interstitial Type Impurity Defect : In this type impurity atoms occupies free space or void space in the crystal structure.

Impurity atoms
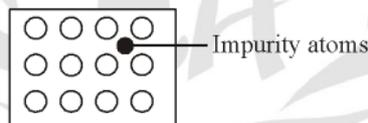
(iii) Frankel Defect : Combination of a vacancy and interstitial is called a frankel imperfection.

1.10.2 *Line Defect*

Line defect are commonly known as dislocation.

Any deviation from perfectly periodic arrangement of atoms along a line is called the line imperfection.

Dislocations are generated and more when a stress is applied.

There are two types of dislocation

1.   Edge dislocations

2.   Screw dislocations.

❑❑❑

2 CHAPTER
Dielectric Properties of Material

Non-conducting material are divided into two category.

(i) Insulator : If the main function of the non conducting material is to provide electrical insulation, material is called insulator.

(ii) Di-electric : If the main function of non conducting material is storage of charge, material is called di-electric.

Dielectric are non conducting material which can be polarized by application of electric field.

2.1 | DIELECTRIC PARAMETER

2.1.1 Dielectric Constant

If is defined as the ratio of electric flux density to electric field intensity.

$$\in = \frac{D}{E}$$

Where   E = Electric field intensity (V/m)

D = electric flux density (C/m^2)
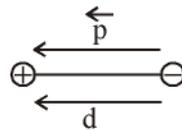
$$\in = \in_0 \in_r$$

$\in_0$ = Permittivity of free space = 8.85×10^{-12} F/m.

$\in_r$ = Relative permittivity

$\in_r$ (relative dielectric) is determined by atomic structure of the material.

2.1.2 Dipole Moment

Two charges of equal magnitude but of opposite polarity kept 'd' distance apart, constitute a dipole.

Dipole moment (p) is defined as the product of charge and distance of separation.

$$\vec{p} = q \times d$$

Dipole moment is a vector quantity pointing from the negative charge to the positive charge.

unit of dipole moment is C-m and debye.

$$1 \text{ debye} = 3.33 \times 10^{-30} \text{ C} - \text{m}$$

2.1.3 Polarization

The phenomenon in which two opposite surfaces of dielectric becomes opposite charged is known as polarization.

Mathematically polarization is defined as dipole moment per unit volume.

P = no. of dipoles per unit volume × Dipole moment

$$P = N \times p$$

unit $\rightarrow$ C/m^2

Total Flux Density : The total flux density inside dielectric material under the influence of electric field depends on two factors.

(a) applied electric field

(b) polarization induced inside material

Total flux density is given by

$$D = \epsilon_0 \, E + P \qquad \qquad \ldots(1)$$

Where P$\rightarrow$ flux density due to induced polarization.

$$D = \epsilon E$$

$$D = \epsilon_0 \epsilon_r \, E \qquad \qquad \ldots(2)$$

Equate equation (1) and (2)

$$\epsilon_0 \epsilon_r \, E = \epsilon_0 \, E + P$$

$$P = \epsilon_0 \, (\epsilon_r - 1)E$$

$$P = \epsilon_0 \, \chi_e E$$

Where $\chi_e = \epsilon_r - 1$ is a dimensionless parameter known as electrical susceptibility.

2.1.4 *Polarizability*

The application of an electric field to a dielectric material causes a displacement of electric charges giving rise to the creation or re-orientation of the dipoles in the material.

The average dipole moment p of an elementary particle may be assumed to be proportional to electric field strength 'E' that acts on the particle

$$p = \alpha E$$
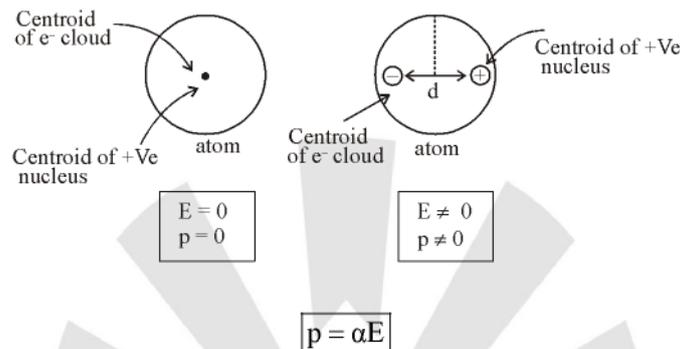
Where proportionality factor α is called polarizability

→ Unit of α is $F–m^2$.

2.2 | MECHANISMS OF POLARIZATION

There are basically four basic type of polarization mechanisms :

2.2.1 *Electronic Polarization*

A simple model of an atom having a positive nucleus of charge Ze (Z is the atomic number of the atom, and e is the charge of an electron), surrounded by a spherical negative cloud of charge having a magnitude – Ze. It is assumed that the charge cloud is of uniform density and of radius R.

With no external field, the nucleus is at the centre of this sphere. Under the influence of the field E, the nucleus and the electron cloud shift with respect to one another by a distance x (the e⁻ cloud is assumed to remain spherical).

It is also known as atomic polarization.

Materials having single type of atoms are having only electronic polarization.

Ex. Diamond, Sulphur, inert gases etc.

α_e is the measure of a relative shifting between centroids of nucleus and e⁻ cloud. It is given by

$$\alpha_e = 4\pi \in_0 R^3$$