UPPSC-AE | 2020

Uttar Pradesh
Public Service Commission

Combined State Engineering Services Examination

Assistant Engineer

Electrical Engineering

Electrical Engineering Materials

Well Illustrated **Theory** *with*
Solved Examples and **Practice Questions**

MADE EASY
Publications

Electrical Engineering Materials

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1

Introduction to Engineering Materials

1.1 Introduction

Material science concerned with investigating the relationship existing between the structure of materials and their properties.

Engineer is vitally concerned with materials available to him to make any kind of product. While making a choice of material for a particular product an engineer must be aware of basic atomic structure of materials and their properties such as strength, electrical conductivity, thermal conductivity etc.

1.2 Classification of Engineering Materials

From material science point of view, materials are classified as

1. Metals and Alloys

- Metals are familiar objects with characteristic appearance.
- Metals are capable of changing their shape permanently.
- Metals have good thermals and electrical conductivity.
- Alloy is a combination of more than one metal.

2. Ceramics and Glasses

- These are non-metallic inorganic substances.
- These are brittle and have good thermal and electrical insulating properties.

3. Organic Polymers

- These are relatively inert and light.
- Organic polymers have a high degree of plasticity.

Examples of these three groups are given in the above figure and examples of materials which lie between two groups are also shown.
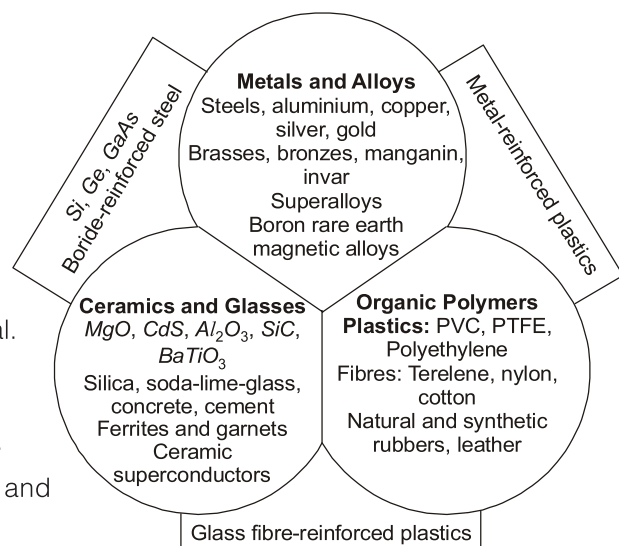

Metals and Alloys
Steels, aluminium, copper, silver, gold
Brasses, bronzes, manganin, invar
Superalloys
Boron rare earth magnetic alloys

Si, Ge, GaAs
Boride-reinforced steel

Metal-reinforced plastics

Ceramics and Glasses
MgO, CdS, Al_2O_3, SiC, $BaTiO_3$
Silica, soda-lime-glass, concrete, cement
Ferrites and garnets
Ceramic superconductors

Organic Polymers
Plastics: PVC, PTFE, Polyethylene
Fibres: Terelene, nylon, cotton
Natural and synthetic rubbers, leather

Glass fibre-reinforced plastics

Fig. 1.1 : *Three major groups of engineering materials*

1.3   Classification of Solids from Electrical Engineering Point of View

From electrical engineering point of view the materials can be classified as:

(i) conductors

(ii) insulators (dielectrics)

(iii) magnetic materials and

(iv) semiconductors

1.3.1   Conductors

Under a difference of electric potential conductors afford continuous passage of an electric current. Due to flow of current in a conductor some heat is developed which is given by **Joule's Law**. Just like electrical conductivity, the heat conduction in conductors is mostly through free electrons. There exists a relationship between the electrical conductivity and thermal conductivity which is called **Wiedemann Franz Law.**

Some of the good conductors of electricity are silver, copper, aluminium etc.

- Low resistivity metals and alloys are used as conductors and for electrical contacts.
- High resistivity alloys are used for resistors and as heating elements.
- A special class of materials called **superconductors** exhibits almost zero resistivity when they operate below certain temperature – **transition temperature or critical temperature.**

1.3.2   Dielectric Materials (Insulating Materials)

- These materials provide electrical insulation between two media which are different potentials.
- These materials can store electrical charges.
- When main function is insulation, these materials are called insulating materials.
- When charge storage is main function, they are termed as dielectrics.

1.3.3   Magnetic Materials

- Magnetic materials are the materials which can become magnets or can be attracted by magnets.
- Magnetic materials generate electric power, energize electric motors, reproduce sound and visual images and store information in computers etc.
- Of the pure element, only iron, cobalt, nickel and gadolinium are known to be magnetic in the sense at ordinary temperature.
- The desired properties in magnetic materials can be obtained by a combination of these metals with other elements to form alloys which generally have to be subjected to certain heat treatment to bring about the desired result.

1.3.4   Semiconductors

- Semiconductors are a class of materials whose electrical conductivity is intermediate between that of a conductor and an insulator.
- Semiconductors have resistivities that are highly sensitive to temperature and impurity content.
- Silicon and Germanium are the best known semiconductor materials, have structures which are almost perfect.
- Some other semiconducting materials are selenium, gray tin, tellurium, etc.
- Some examples of magnetic semiconductors are NiO, $LaMnO_3$, $Cd\ Cr_2Se_4$, etc.

1.4   The Atomic and Electronic Structure

Recall that every atom consists of a central nucleus surrounded by one or more orbital electrons. Nucleus is composed of protons and neutrons (collectivity known as nucleons). The number of positive charges on the nucleus of an atom always equals the number of orbital electrons, and is called the **atomic number** of the element. **Atomic weight (M)** of the atoms are related to the sum of number of protons and neutrons. But this number physically corresponds to the actual weight of an atom.

Here in this set writer assumes that readers are well known with the atomic and electronic structure, so much importance is not given to the concerned topic.

1.5   Quantized Energies

Recall that a basic law of quantum theory reveals that the energies of particles and waves can assume only certain fixed or quantized values.

For photons, the energy (E) is given by,

$$E = h\nu = \frac{hc}{\lambda}$$

...(1.1)

where, h = Planck's constant = 6.62×10^{-34} Js

c = Speed of light = 2.998×10^8 m/s

λ = Wavelength

$\Rightarrow$ Energy levels (E_n) are given by the Bohr's theory as,

$$E_n = -\frac{13.6}{n^2} \text{ eV}$$

...(1.2)

where, n = states = 1, 2, 3, 4,...........

The closer they are to the nucleus, the lower the energies of the electrons.

1.6   Bonding in Solids

Atoms are rarely found as free and independent units, but usually are linked or bonded to other atoms in some manner as a result of interatomic forces. These binding forces between the atoms are called chemical bonds. According to the strength, chemical bonds are grouped into **Primary** and **Secondary bonds.** The primary bonds are interatomic bonds, where as the secondary bonds are inter molecular bonds. The primary bonds are stronger than the secondary bonds.

There are basically four classes into which the bonds can conveniently be divided, although the boundaries between them are not always distinct:

(i)   ionic bonding

(ii)   covalent bonding

(iii) metallic or unsaturated covalent bonding, and
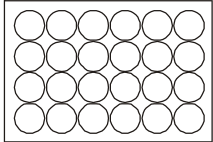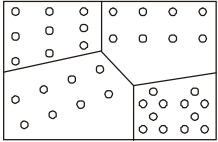
(iv) Vander Waal's bonding.

The first three are primary bonds, whereas the fourth one is a secondary bond.

1.7 Atom Arrangement in Materials

Properties of materials are highly influenced by arrangement of atoms. Depending upon the manner of atomic grouping, materials are classified as having **molecular structures, crystal structures and amorphous structures.** Typical examples of molecules include O_2, H_2O and C_2H_4. Glass is an example of amorphous structure.

1.7.1 Crystalline Structure of Metals

Generally metals are crystalline and non-metals (Plastic, Ceramics, Rubber etc.) are non-crystalline. But this is not a rule. In crystalline solids the atoms are arranged in a regular geometrical array known as **space lattice.** These lattices are described by a unit building block which is essentially repeated throughout space in a periodic manner. Such blocks are known as unit cells. A crystalline solid can be either a single crystal, where the entire solid consists of only one crystal, or an aggregate of many crystals separated by well-defined boundaries. In the latter form, the solid is said to be **polycrystalline.**

1. **Crystallinity :** Crystallinity is the property of a solid in which atoms or molecules are arranged in orderly or periodic manner.

2. **Single Crystal:** A single crystal material atoms or molecules are arranged in regular or periodic manner. These materials are anisotropic for e.g. Quartz.

3. **Polycrystalline :** These materials consist of grain within which atomic arrangement is regular but it shows irregularities from one grain to another, because of random distribution of grain these materials are isotropic. e.g. Polycrystalline silicon.

4. **Anisotropic and Isotropic Material:**

   (a) **Anisotropic Material:** If the properties of material depends on the direction in which they are measured then materials are called anisotropic, e.g. Quartz.

   (b) **Isotropic Material:** If the properties of material does not depend on the direction in which they are measured then materials are called isotropic material, e.g. Polycrystalline silicon.

✏️ **Example - 1.1**   Materials in which the atomic order extends uninterrupted over the entirely of the specimen; under some circumstances, they may have flat faces and regular geometric shapes, are called

(a) Anisotropy   (b) Crystallography
(c) Single crystals   (d) Crystal system

Answer: (c)

1.8 Amorphous

In amorphous structure atoms up to first nearest neighbours are arranged periodically but the atom which are away from nearest atom are found to be arranged randomly.

When the atoms are not arranged in a regular manner an amorphous material may be formed. e.g. Supercooled state of SiO_2 corresponds to glass.

In other cases, the molecule may be extremely long and irregular in shape so that orderly arrangement may not be obtained, e.g. Polymer.

1.9 Space Lattice

A space lattice is defined as an infinite array of points in three-dimensional space in which each point is identically located with respect to the other. Concept of space lattice is helpful in understanding the crystal structure of existing materials, and also those materials which are likely to be developed in future.

If we locate ourselves at any point in the array and look out in a particular direction that lies on the plane of the paper, the scenery is the same, irrespective of where we are.
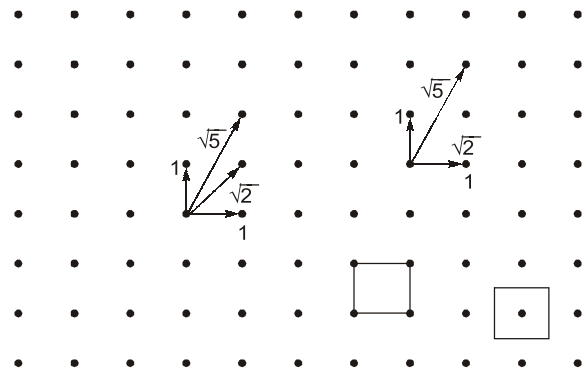
A two dimensional square array of points gives a square lattice. Two ways of choosing a unit cell are illustrated
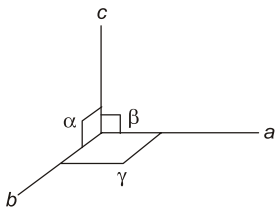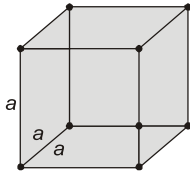
Fig. 1.2
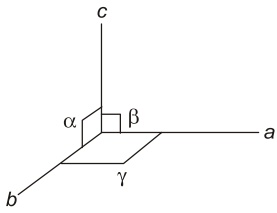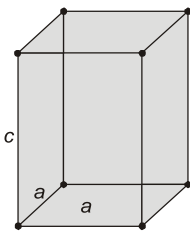
1.10 Basis
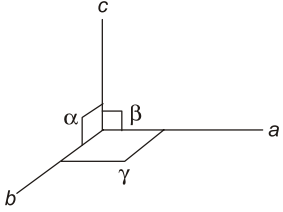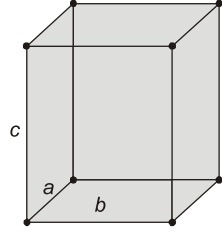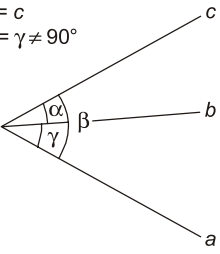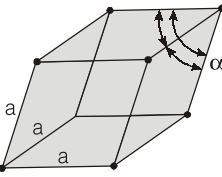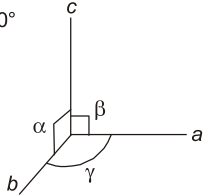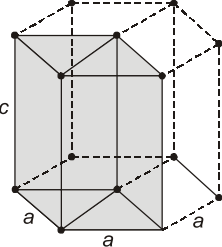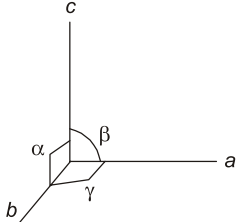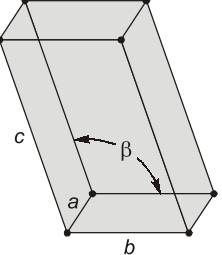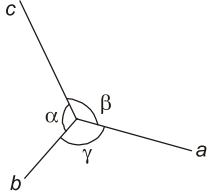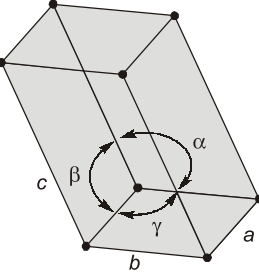
The way of filling-up of points in a space lattice by the atoms is known as **Basis.** Each point may be occupied by one, two or many atoms in different solids. The space lattice when combines with the basis generates a unit cell. Thus, | Space lattice + Basis = Unit cell |.

1.11 Bravais Lattices

A three-dimensional space lattice is generated by repeated translation of three non-coplanar vectors, $\vec{a}$, $\vec{b}$ and $\vec{c}$.

Table-1.1

Crystal System	Space Lattice	Unit cell
1. Cubic $a = b = c$ $\alpha = \beta = \gamma = 90°$	1. Simple (Lattice points at the eight corners of the unit cell). 2. Body centred (Points at the eight corners and at the body centre). 3. Face centred (Points at the eight corners and at the six face centres).	
2. Tetragonal $a = b \neq c$ $\alpha = \beta = \gamma = 90°$	4. Simple (Points at the eight corners of the unit cell). 5. Body centred (Points at the eight corners and at the body centre).	

3. Orthorhombic $a \neq b \neq c$ $\alpha = \beta = \gamma = 90°$	6. Simple (Points at the eight corners of the unit cell). 7. End centred (Also called side centred or base centred) (Points at the eight corners and at two face centre opposite to each other) 8. Body centred (Points at the eight corners and at the body centre). 9. Face centred (Points at the eight corners and at the six face centres).	
4. Rhombohedral or Trigonal $a = b = c$ $\alpha = \beta = \gamma \neq 90°$	10. Simple (Points at the eight corners of the unit cell).	

5. Hexagonal
$a = b \neq c$
$\alpha = \beta = 90°$
$\gamma = 120°$
	11. Simple
	   [(i) Points at the eight corners of the unit cell outlined by thick lines
	         or
	   (ii) Points at the twelve corners of the hexagonal prism and at the centres of the two hexagonal faces].	

6. Monoclinic $a \neq b \neq c$ $\alpha = \gamma = 90° \neq \beta$	12. Simple (Points at the eight corners of the unit cell). 13. End centred (Points at the eight corners and at two face centres opposite to each other)	
7. Triclinic $a \neq b \neq c$ $\alpha \neq \beta \neq \gamma \neq 90°$	14. Simple (Points at the eight corners of the unit cell).	

Example - 1.2   Lattice constants and angles of Triclinic crystal are

(a) $a = b = c$, $\alpha = \beta = \gamma \neq 90°$.
(b) $a = b \neq c$, $\alpha = \beta = 90°$, $\gamma = 120°$.
(c) $a \neq b \neq c$, $\alpha = \gamma = 90° \neq \beta$.
(d) $a \neq b \neq c$, $\alpha \neq \beta \neq \gamma \neq 90°$.

Answer: (d)

Example - 1.3   The unit cell of a certain type of crystal is defined by three vectors $\overline{a}$, $\overline{b}$ and $\overline{c}$. The vectors are mutually perpendicular, but $a \neq b \neq c$. The crystal structure is

(a) Triclinic
(b) Tetragonal
(c) Orthorhombic
(d) Monoclinic
(c) x
(d) x

Solution: (c)
Here: $a \neq b \neq c$ and $\alpha = \beta = \gamma = 90°$ (perpendicular vector)
So crystal structure is orthorhombic.

Example - 1.4   Which crystal system requires six lattice parameters to fully specify its unit cell?

(a) Triclinic
(b) Monoclinic
(c) Cubic
(d) Hexagonal

Solution: (a)
For triclinic crystal system
$$\alpha \neq \beta \neq \gamma \neq 90°$$
$$a \neq b \neq c$$
Therefore, all 6 lattice parameters (a, b, c, α, β, γ) are required to fully specify unit cell.

1.12 Unit Cell

A unit cell is defined as the basic structure part in the composition of materials.

It is analogous to a brick used in the building construction.

The unit cell will be called monatomic if only one atom occupies a lattice point. When two atoms occupy a lattice point, it will make a dia-atomic unit cell. Similarly the unit cell will be known as multi-atomic when too many atoms occupy a lattice point.

In 3-Dimensional point of view there are four types of possible unit cells.

Atom

Unit cell
Fig. 1.3

1. **Primitive (p-type) or Simple Cubic :** It has lattice point only at corners and each corner is common in eight cells. So each cell represents a single lattice point as shown in figure (a)

∴ $8 \times \dfrac{1}{8}$ = 1 lattice point/unit cell.

2. **Body centered cell (I-type or Incentre type):** It has lattice points at corners as well as at centre of each cell. So each cell has two lattice points per unit cell as shown in figure (b)

i.e. $8 \times \dfrac{1}{8} + 1$ = **2 lattice points/unit cell**, as shown in figure (b).

3. **Face centred cell (F-type):** It has lattice points at corners as well as at centre of each face of the cell, as shown in figure (c).

i.e. $8 \times \dfrac{1}{8} + 6 \times \dfrac{1}{2} = 1 + 3 =$ **4 lattice points/unit cell.**

4. **Base centred (C-type):** It has lattice points at corners as well as at centre of top and bottom face of cell.
It has two lattice points per unit cell as shown in figure (d).

i.e. $8 \times \dfrac{1}{8} + 2 \times \dfrac{1}{2} = 1 + 1 =$ **2 lattice points/unit cell.**
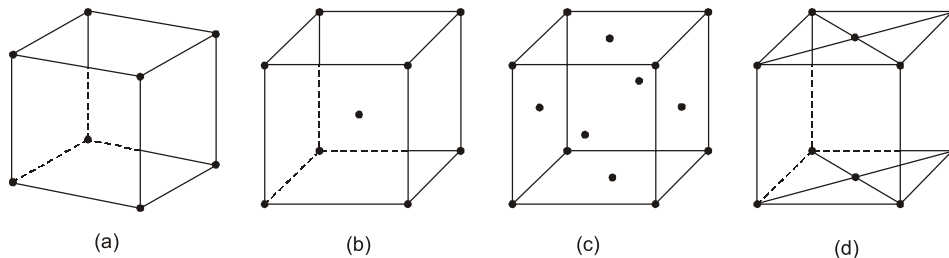

(a)   (b)   (c)   (d)

Fig. 1.4

1.13 Cubic Crystal Structures

There are three cubic crystal structures:

1.13.1 Simple Cubic Crystal Structure (SCC)

In a simple cubic structure, there is one lattice point at each of the eight corners of the unit cell. If we take an atom at one corner as the centre, it is observed that this atom is surrounded by six equidistant nearest neighbours and hence the **co-ordination number of a simple cubic lattice is six.**

In this structure, each corner atom is shared by **eight unit cells.**

Fig. 1.5 : Simple cubic structure

1. **Atomic Radius**

Atomic radius is defined as, **"half the distance between nearest neighbours in a crystal of pure element."**

Figure shows the unit cell of a simple cubic structure.

Let r be the radius of atom.

In simple cubic (SCC) lattice

$$a = 2r$$

$$\therefore \quad \boxed{r = \dfrac{a}{2}} \qquad ...(1.3)$$

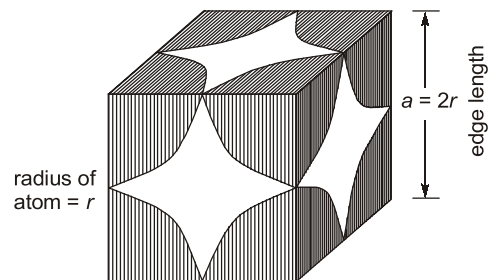***Fig. 1.6***

2. **Atomic Packing Factor**

The packing of atoms in a unit cell of the crystal structure of a material is known as atomic packing factor (APF).

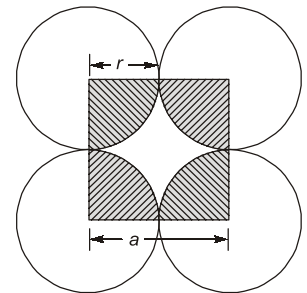i.e. $\boxed{APF = \dfrac{\text{Total volume of the atoms per unit cell}}{\text{Volume of the unit cell}}} \qquad ...(1.4)$

It is also known as **packing efficiency (η).**

For simple cubic structure,

$$APF = \frac{N \times \text{volume of each sphere}}{\text{Total volume of each cell}}$$

Where, N = total number of atoms in each unit cell.

For simple cubic, **N = 1**

Radius of each sphere = $r = \dfrac{a}{2}$

Volume of each sphere = $\dfrac{4\pi}{3} r^3 = \dfrac{4\pi}{3} \times \left(\dfrac{a^3}{8} \right) = \dfrac{\pi}{6} a^3$

$\because$ $\qquad\qquad\qquad$ $APF = \dfrac{1 \times (\pi/6)\, a^3}{a^3} = \dfrac{\pi}{6} = 0.52$

% APF = 52.4% filled

1.13.2 Body Centred Cubic Structure (BCC)

In BCC structure, in a unit cell, there are eight atoms at the eight corners and another atom at the body centre. The corner atoms do not touch each other, but each corner atom touches the body centre atom along the body diagonal as shown in figure.

Hence the co-ordination number of BCC structure is eight.
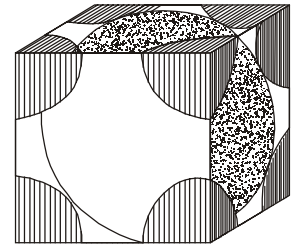
***Fig. 1.7 :** Body centered cubic structure*

1. **Atomic Radius of BCC**

From figure, $\qquad\qquad AG = r + 2r + r = 4r$

In ΔDCG, $\qquad\qquad DG^2 = DC^2 + CG^2$

$$DG = \sqrt{a^2 + a^2}$$

Diagonal of face = $a\sqrt{2}$

$\therefore$ In ΔDGA, $\qquad AG^2 = a^2 + (a\sqrt{2})^2$

$$AG = a\sqrt{3} = \text{diagonal of cube}$$

Also, $\qquad\qquad\qquad 4r = a\sqrt{3}$

$$\boxed{r = \dfrac{a\sqrt{3}}{4}}$$ $\qquad\qquad\qquad$ ...(1.5)

2. **Atomic Packing Factor**

For BCC, N = 2 and $r = \dfrac{a\sqrt{3}}{4}$

Volume of each sphere = $\dfrac{4\pi}{3} r^3 = \dfrac{4\pi}{3} \left(\dfrac{a\sqrt{3}}{4} \right)^3 = \dfrac{\pi\sqrt{3}}{16} a^3$

$$APF = \frac{N \times \text{Volume of each sphere}}{\text{Total volume of each cell}} = \frac{\dfrac{2 \times \pi\sqrt{3}}{16} a^3}{a^3} = \frac{\pi\sqrt{3}}{8} = 0.68$$

% APF = 68% filled

1.13.3 Face Centered Cubic Structure (FCC)

- In FCC structure, one atom lies at each corner of the cube in addition to one atom at the centre of each face.
- For any corner atom, there are four atoms at each corner that surround it.
- Each face centre has an atom. There are four atoms nearest to the atom on four atomic planes below it and four above it in the atomic plane.

Fig. 1.8 : Face centred cubic structure

- The **co-ordination number** of **face centred cubic structure is thus 4 + 4 + 4 = 12.**

  Note : The co-ordination number is defined as the number of nearest and equidistant atoms with respect to any other atom in a unit cell.

1. Atomic Radius of FCC

From figure, $AC^2 = AB^2 + BC^2$

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

$16\, r^2 = 2a^2$

$$\boxed{r = \frac{a\sqrt{2}}{4}}$$ ...(1.6)

Fig. 1.9

2. Atomic Packing Factor

For FCC, **N = 4** and $r = \dfrac{a\sqrt{2}}{4}$

Volume of each sphere $= \dfrac{4\pi}{3}r^3 = \dfrac{4\pi}{3}\left(\dfrac{a\sqrt{2}}{4}\right)^3 = \dfrac{\sqrt{2}\,\pi}{24}a^3$

$\therefore$ $\text{APF} = \dfrac{4 \times \dfrac{\sqrt{2}\pi\, a^3}{24}}{a^3} = \dfrac{\sqrt{2}\,\pi}{6} = \dfrac{\pi}{3\sqrt{2}} = 0.74$

% APF = 74% filled

✎ **Example - 1.5**   Titanium has a face centered cubic structure with an atomic radius of 1.47 Å. Then the lattice parameter for FCC titanium is

(a) 1.47 Å   (b) 2.94 Å

(c) 3.74 Å   (d) 4.16 Å

Solution: (d)

In FCC structure, radius of the atom, $r = \dfrac{a}{2\sqrt{2}}$

$\therefore$ Lattice parameter, $a = 2\sqrt{2}\,r = 2\sqrt{2} \times 1.47\,\text{Å} = 4.16\,\text{Å}$