UPPSC-AE | 2021

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

Contents

○○○○

CHAPTER 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.
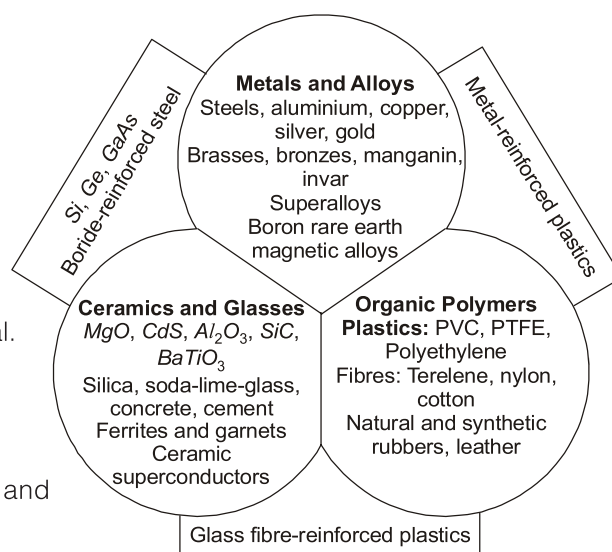- Alloy is a combination of more than one metal.

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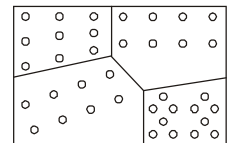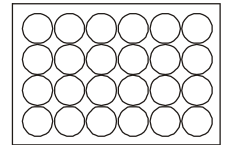
Example - 1.1　Materials in which the atomic order extends uninterrupted over the entirely of the specimen; under some circumstances, they may have flat faces and regular geometric shapes, are called

(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.
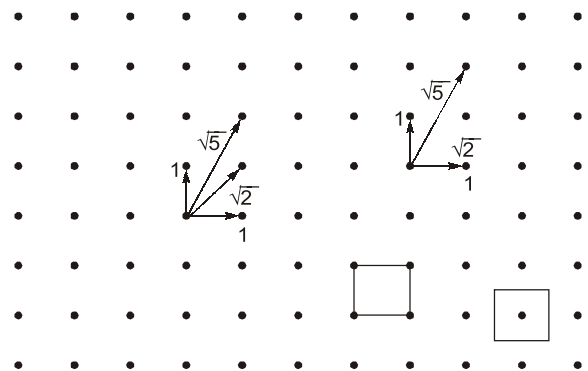
A two dimensional square array of points gives a square lattice. Two ways of choosing a unit cell are illustrated

Fig. 1.2
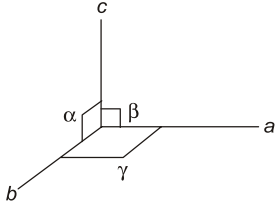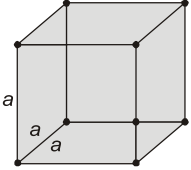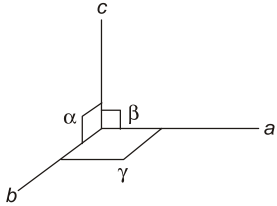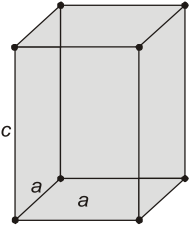
1.10 Basis
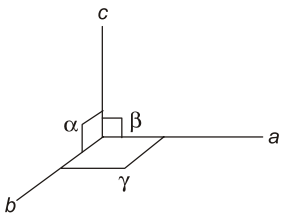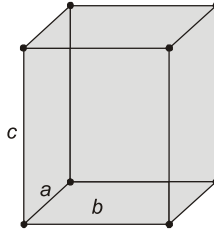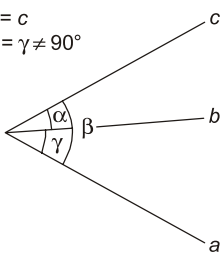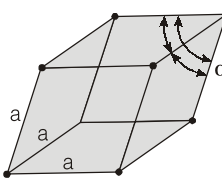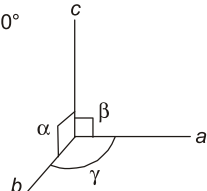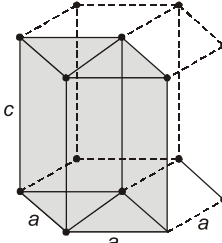
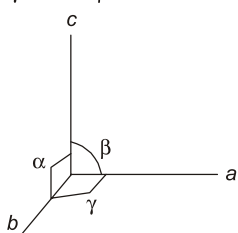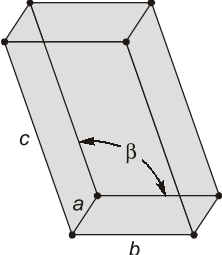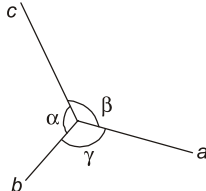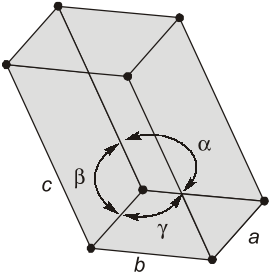The way of filling-up of points in a space lattice by the atoms is known as **Basis.** Each point may be occupied by one, two or many atoms in different solids. The space lattice when combines with the basis generates a unit cell. Thus, | Space lattice + Basis = Unit cell |.

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).	

Student's Assignment

Q.1 The Miller indices are same for
(a) perpendicular planes
(b) crystal planes
(c) parallel planes
(d) three crystallographic axes

Q.2 When *BCC* iron is heated, it changes to *FCC* iron resulting in
(a) increase in volume of unit cell
(b) contraction in volume of unit cell
(c) no change in volume of unit cell
(d) cracks in the material

Q.3 A crystal lattice, the vacancies created by the absence of certain atoms are known as
(a) Hurtz defect   (b) Pauli's defect
(c) Frankel defect   (d) Schottky defect

Q.4 Which one of the following statements is correct? Ionic crystals are
(a) hard and brittle   (b) soft and elastic
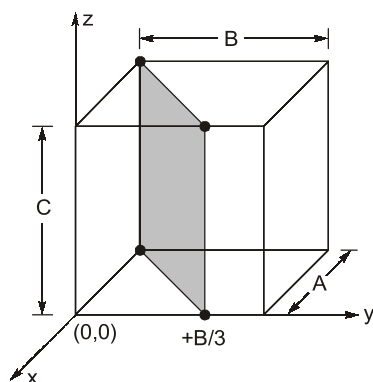(c) hard and corrosive (d) soft and inflammable

Q.5 The atomic packing factor for body centric cubic is
(a) 0.52   (b) 0.62
(c) 0.68   (d) 0.74

Q.6 In ionic crystals, electrical conductivity is
(a) Very high
(b) Depends on material
(c) Depends on temperature
(d) Practically zero

**Q.7** Miller indices of the shaded figure in structure given below is

Q.8 The unit cell of a certain type of crystal is defined by 3 vectors $\vec{a}, \vec{b}$ and $\vec{c}$. The vectors are mutually perpendicular but $a = b \neq c$. The crystalline structure is
(a) Triclinic   (b) Tetragonal
(c) Monoclinic   (d) Orthorhombic

Q.9 In a silicon crystal, the arrangement of atoms repeats periodically. This type of material is classified as
(a) Amorphous and non-crystalline
(b) Non-crystalline and epitaxial
(c) Epitaxial and single crystal
(d) Amorphous and single crystal

Q.10 Each side of the cube shown below is of length a. What are the Miller indices of the shaded surface?
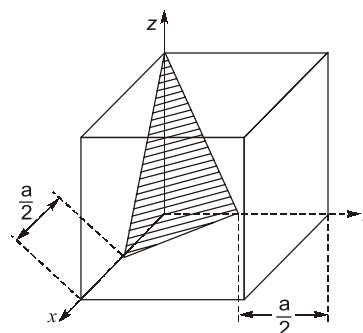
(a) (100)   (b) (123)

(c) (221)   (d) $\left(\frac{1}{2}\frac{1}{2}1\right)$

Q.11 Molybdenum has a Body-Centered Cubic (BCC) structure with an atomic radius of 1.36 Å. Then the lattice parameter for BCC molybdenum is
(a) 2.77 Å   (b) 3.14 Å
(c) 5.12 Å   (d) 6.28 Å

(a) $+A, \dfrac{B}{3}, C$ (b) $-1, \dfrac{1}{3}, \infty$

(c) $-A, \dfrac{B}{3}, \infty$ (d) $-1, 3, 0$

Q.12 Which one of the following helps experimental confirmation of the Crystalline state of matter?
(a) Shock compression
(b) Photo emission
(c) Conductivity measurements
(d)   X-ray diffraction

Q.13 The crystal structure of some Ceramic materials may be thought of being composed of electrically charged Cations and Anions, instead of Atoms, and as such:
(a) The Cations are negatively charged, because they have given up their valence electrons to Anions which are positively charged.
(b) The Cations are positively charged, because they have given up their valence electrons to Anions which are negatively charged.
(c) The Cations are positively charged, because they have added one electron to their valence electrons borrowing from Anions which are negatively charged.
(d) The Cations are negatively charged, as they are non-metallic whereas Anions are positively charged being metallic.

Q.14 The crystal in which atoms are chemically highly inactive and they do not form compounds with other atoms is
(a) Ionic crystal   (b) Metal
(c) Valence crystal   (d) Van der Walls crystal

Q.15 Which one of the following exhibits the most well defined X-ray diffraction pattern?
(a) A polycrystalline aggregate
(b) An amorphous material
(c) A single crystalline material
(d) A plastically deformed crystal

Q.16 The difference between the number of atoms in a unit cell of a BCC crystal and an FCC crystal is
(a) 1   (b) 2
(c) 4   (d) 6

Q.17 Crystals like diamond and silicon are brittle, because
(a) they contain no dislocations.
(b) they are non crystalline.
(c) the stress to move a dislocation is high.
(d) they contains very few dislocation.

Q.18 Packing factor for FCC structure is
(a) 0.73   (b) 0.68
(c) 0.52   (d) None of these

Q.19 Fill in the blanks. Iron (Fe) is an example of _____ material.
(a) Allotropic   (b) Anisotropic
(c) Ceramic   (d) Both (a) and (b)

Q.20 The co-ordination number of Cl and Cs atoms in simple cubic structure of CsCl (Cesium chloride) is
(a) 4   (b) 6
(c) 8   (d) 12

> **ANSWER KEY** // **STUDENT'S ASSIGNMENT**

1. (c)	**2.** (b)	**3.** (d)	**4.** (a)	**5.** (c)
6. (d)	**7.** (d)	**8.** (b)	**9.** (c)	**10.** (c)
11. (b)	**12.** (d)	**13.** (b)	**14.** (d)	**15.** (c)
16. (b)	**17.** (c)	**18.** (a)	**19.** (d)	**20.** (c)

> **HINTS & SOLUTIONS** // **STUDENT'S ASSIGNMENT**

2. **(b)**

APF of *BCC* = 0.68
APF of *FCC* = 0.74

and $APF \propto \dfrac{1}{\text{Volume of unit cell}}$

4. **(a)**

Ionic crystals are hard and brittle because of strong ionic bonding.

7. **(d)**

Intercepts made by plane on 3 axis

$$\Rightarrow -A, \frac{B}{3}, \infty$$

$\therefore$ Miller indices
$\Rightarrow -1, 3, 0$

9. **(c)**

A crystal has periodicity of atoms.

11. **(b)**

For BCC structure,

$$a = \frac{4r}{\sqrt{3}} = \frac{4 \times 1.36}{\sqrt{3}}\,\overset{\circ}{A} = 3.14\,\overset{\circ}{A}$$