Q.2 a. Explain Ionization Potential, Electron Affinity and Electronegativity. (4+2+2)
Answer:
Ionisation potential

Electrons in the orbital around the nucleus can absorb energy and get promoted to higher energy level .If sufficient energy is given, an electron in outer orbital can break away completely from the atom and become free. The energy required to remove an electron in this manner is known as Ionisation Potential.
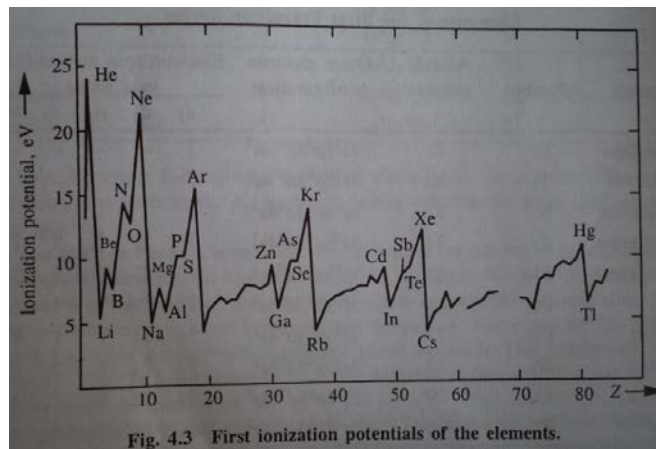

Fig. First ionisation potential of the elements

Fig. gives the first ionisation potential of the elements .The potential is the least for first atom in a row of the periodic table and increases as we go to the right along the row. The alkali metals have alone*s* electron in this outer most orbital, which can be removed with relative case .The inert gases, on the other hand have the full complement of *s*and *p*electrons in their outermost principal orbital. removing an electron from a stable inert gas configure requires a relatively large expenditure of energy .Further, as we go down a column of the periodic table, the outermost electrons are less and less tightly bound to the nucleus .Correspondingly, among the alkali metals, the first ionisation potential is highest for lithium at the top of the column and lowest for cesium at the bottom. Among the inert gases, the potential is highest for helium and lowest foe Xenon.

4

When an electron is removed from the neutral atom, there is a decrease in the mutual repulsion between the orbital electrons .they can approach one another more closely and are therefore attached more strongly to the nucleus, resulting

the shrinking of the all orbitals. As a result, the energy required to remove the second and successive electrons becomes increasingly greater.

Electron Affinity $\boxed{2}$

  Consider a system of neutral atom and an extra electron. The work done by this system, when the extra electron is attached from infinity to the outer orbital of the neutral atom, is known as the electron affinity of the atom.

The stable configuration of the inert gases as no affinity for an extra electron .The halogens, which are just one electron short to achieve the stable inert gas configuration have the largest electron affinity. When an extra electron is added to neutral atom, there is a weakening of the attraction of the electrons to nucleus, resulting in an expansion of the electrons orbitals and an increase in the size of the atom.

Electronegativity $\boxed{2}$

The tendency of an atom to attract electrons to itself during the formation of the bonds with other atoms is measured by the electronegativity of that atom. This is the not the same as the electron affinity, where the tendency of an atom to attract an isolated electron is measured .Consider, for e.g. the bond formation between hydrogen and fluorine by sharing of their outer electrons. Fluorine has a greater tendency to attract the bonding the electrons to itself than hydrogen. Fluorine has thus larger negativity than hydrogen.

    **b. Explain secondary bonding and variation of bonding character and
        properties.**   **(8)**
Answer:
Secondary Bonding

In many molecules, where hydrogen takes part in covalent bonding, the centres of $\boxed{3}$
the positive and negative charges don't coincide .Consider the example of the water molecule. The electronegativity of oxygen is 3.5 and that of hydrogen is 2.1. Therefore the oxygen atom pulls the bonding electrons to itself more strongly than hydrogen does. This result in a net negative charge at the oxygen end and a net positive charge at the hydrogen end of the molecule. Due this imbalance in in electrical charge, the water molecules due to attraction between the positively charge hydrogen and of a molecule and the negatively charged oxygen end of another molecule is called the Hydrogen Bond.
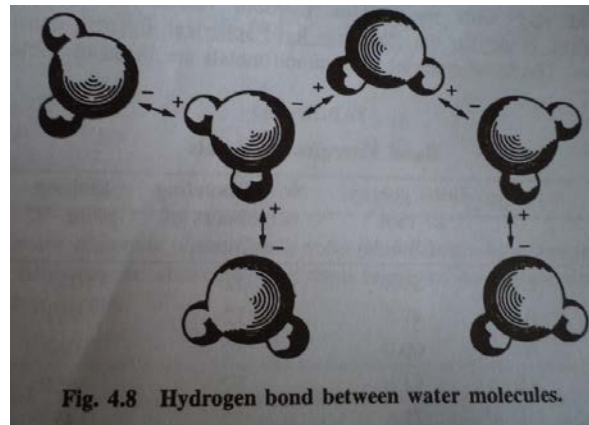
Fig. Hydrogen bond between water molecules

Hydrogen bonds are evidently directional. The bond between water molecules is a strong enough to persist in the liquid state .It is responsible for the unusual properties of ice and water .For e.g. the relatively open network of the hydrogen bonds in ice is shown in fig.

Variation in Bonding Character and Properties   5

We are going to examine some generalisations between the properties and the bonding characters of a material. The solid state can be visualised as atoms vibrating about their mean positions or fixed atomic sites. In the liquid state the atoms have also translational freedom and can slight past one another. The bonds between atoms in the liquid are continuously broken and remade .In the gaseous state the bonds are totally broken. The thermal energy of the atoms must be sufficient to achieve these descriptions in bonding .the higher the bond strength, the more'll thermal energy required to break the bonds.

Correspondingly, strongly bonded materials tends to high melting and boiling temperatures. Among the primary bonds, covalent and the ionic bonds are generally stronger than metallic bonds. Hence, covalent and ionic solids have high melting and boiling points.

The mechanical properties of solids are dependent on the strength of the bonds as well as the directional nature of the bonding. Solids with strong and directional bonds tends to be brittle. For e.g. covalently bonded diamond is very hard and brittle .As metallic bonds are relatively weak and non-directional, metals are soft ,ductile and malleable .They can change their shape permanently without breaking.

Ionic solids fall in between covalent and metallic solids in that they may exhibit a very limited amount of ductility.

In any one row of the periodic table, as we go from left to the right the metallic character of the bond decreases and the covalent character increases .metallic bonds being weaker than covalent bonds, this transition is reflected in increasing bond energy and decreasing bond length from left to right, for the third row of the periodic table. Similarly the transition from the covalent to the metallic character, as we go from top to the bottom of a column is seen in the in the decreasing bond energy.

Element	Na	Mg	Al	Si	P	S	Cl
Bond energy,kJ-mol^{-1}	27	25	54	176	214	243	242
Bond length,Å	3.72	3.18	2.86	2.36	2.20	2.08	1.81
Melting point,°C	98	650	660	1410	44	119	–101
Boiling Point ,°C	892	1107	2450	2680	280	445	–35

Table: Properties of elements of third row

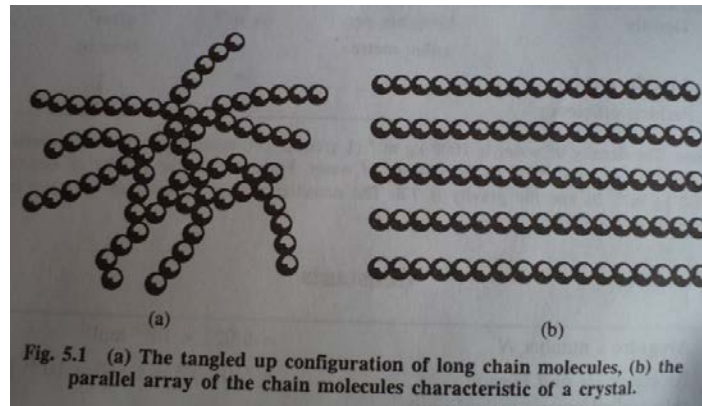**Q.3   a. Explain crystalline and non-crystalline states of solids.**   **(8)**
Answer:
Crystalline and Non-Crystalline solids state

The number and kind of nearest neighbours that an atom or an ion has in a solid, is nearly the same for both the crystalline and non-crystalline forms of the solid. However, the non-crystalline structure doesn't have the long range periodicity characteristics of thecrystalline state .In a crystal, any member of integral lattice translations, would take us from an atom located at a lattice point to another identical atom located at a different lattice point. This is not true for the non-crystalline state. As long as range periodicity is the basis of diffraction defects the non-crystalline solids don't rise to sharp diffraction patterns like crystals.

Several factors promote the fraction of the non-crystalline structures when primary bonds don't extend in all directions, one dimensional chain molecules or two dimensional sheet molecules are formed. Such units have to be added by structure consisting of long chains molecules. In the molten state, the change persist and are like a bowl of wriggling earthworms.

Fig. 5.1 (a) The tangled up configuration of long chain molecules, (b) the parallel array of the chain molecules characteristic of a crystal.

Fig.(a)The tangled up configuration of long chain molecules,(b) the parallel array of the chain molecules characteristics of a crystal

The free energy of the crystalline state is always lower than that of the non-crystalline state. Only when the free energy difference between the two states is large in magnitude, the tendency to crystallize will be strong. Some materials form a relatively open network structure of atoms, where there is little free energy difference between an orderly array and disorderly array of the units. In such cases, the tendency to crystallize will be weak.

The third factor that promotes the formation of non-crystalline structures is the rate of cooling from the liquid state. Slow cooling rate allow enough time for the crystallization, while fast cooling rates may prevent crystallization altogether. The rate of the cooling which is considered as slow or the fast will vary widely for different materials, depending upon the magnitude of the kinetic barriers.

    b. **Explain point imperfection in elemental crystals.**   (8)
Answer:
Point Imperfection

Point imperfections are also referred to as zero dimensional imperfections. As the name implies, they are imperfect point like regions in the crystal. One or two atomic diameter is the typical size of a point imperfection
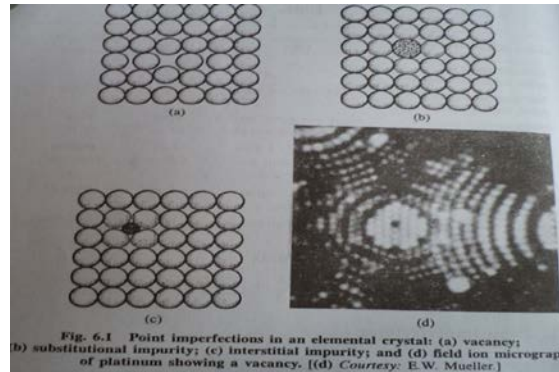
Fig. Point imperfection in elemental crystal

2

A vacancy refers to an atomic site where the atom is missing, as shown in the fig.

A substitutional impurity (or solute) is a point imperfection. It refers to a foreign atom that substitutes for or replaces a parent atom in the crystal.*Al* and *P* doped in the *Si* and substitutional impurities in the crystal.

As interstitial impurity is also a point imperfection. It is a small sized atom occupying the void space in the parent crystals without dislodging any of the parent atoms from their sites. An atom can enter the interstitial void space only when it is substantially smaller than the parent atom.

4

In ionic crystals, the formation of the point imperfection is subject to the requirement that the overall electrically neutrality is maintained. An ion displaced from a regular site to an interstitial site is called a Frenkel imperfection.

As cations are smaller ions, it is possible for them to get displaced into the void space. Anions don't get displaced like this, as the void space is just too small for their size. A Frenkel imperfection doesn't change overall electrical neutrality of the crystal. The Point Imperfections in silver halides and CaF_2 are of the Frenkel type.
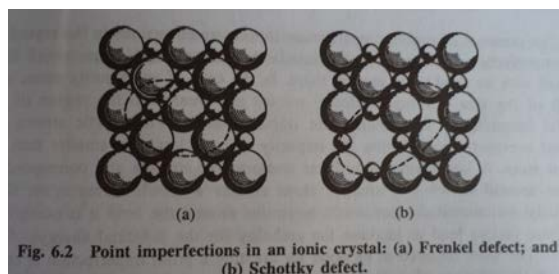

Fig. Frenkel defect and Schottky defect

2

A pair of one cation and one anion can be missing from an ionic crystal. The valency of the missing pair of the ions should be equal to maintain electrical neutrality. Such a pair vacant ion sites is called Schottky imperfection. This type is dominant in alkali halides.

Q.4   a.   Explain Fick's law of Diffusion in solids.   **(6)**
Answer:
Fick's law of diffusion

Diffusion can be defined as the mass flow process by which atoms (or molecules) change their positions relative to their neighbours in a given phase under the influence of thermal energy and a gradient.   **2**

Consider the unidirectional flow matter in a binary system of A and B atoms. The two types of atom will move in opposite directions under the influence of concentration gradient. Let us assume that B is the only moving a species.

Fick's first law states:

$$\frac{dx}{dt} = -DA\frac{dc}{dx}$$ **1**

Where $\frac{dx}{dt}$ is the number of moles of moles of B atoms crossing per unit time a cross-sectional area a perpendicular to the diffusion direction x and $\frac{dc}{dx}$ is the concentration gradient in X-direction. D is called the diffusion coefficient (or **2** diffusivity) and constant characteristics of the system. The diffusion coefficient depends upon the nature of diffusing species, the matrix in which it is diffusing and the temperature at which diffusion occurs. The negative sign indicates that the flow of matter occurs down the concentration gradient. By definition, flux **J** is flow per unit cross section area per unit time so that Fick's first law can also be written as:

$$J = \frac{1}{A}\frac{dx}{dt} = -D\frac{dc}{dx}$$ **1**

b.   Explain Atomic model of diffusion.   **(10)**
Answer:
Atomic Model of Diffusion

Diffusion occurs as a result of repeated jumps of atoms from their sites to other neighbours sites. Even when atoms jump randomly, a net mass flow can

occurs down a concentration gradient, when a large number of such jumps take place. The unit step in the diffusion process in a single jump by the diffusing species.
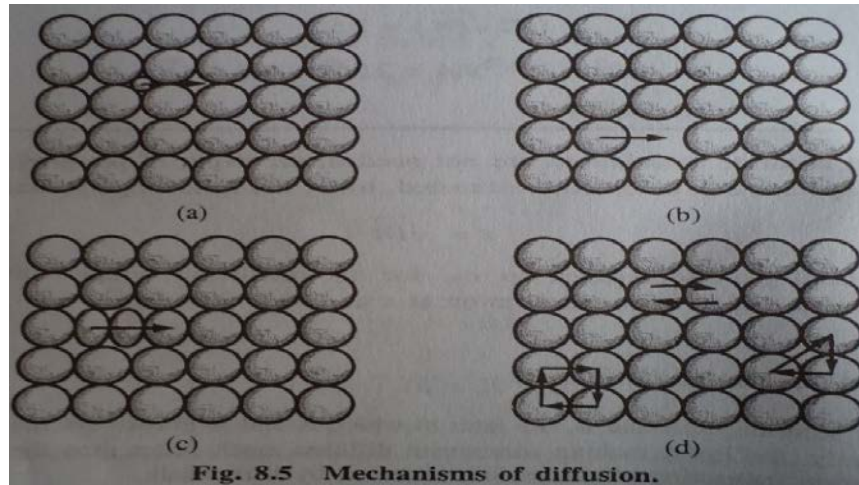
2

Fig. Mechanism of diffusion

2

In interstitial diffusion, solute atoms which are small enough to occupy interstitial sites, diffuse by jumping from one interstitial site to another. In vacancy diffusion, atoms diffuse by interchanging positions with neighbouring vacant sites. In interstitially the mechanism, the mechanism the configuration where two atoms share a common atomic site moves through local distortion is involved during motion. In the ring mechanism, three or four atoms in the form of ring, thereby interchanging their positions.

2

The unit step in interstitial diffusion is the jump of the diffusing atom from one interstitial site to a neighbouring site.
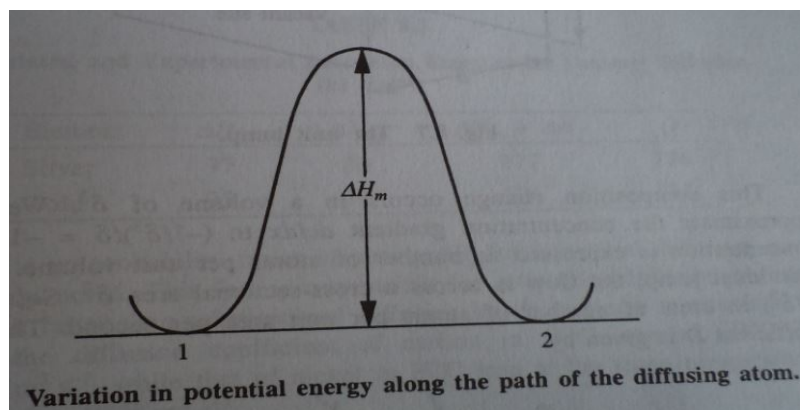

Fig. Variation in potential energy along the path of the diffusing atom

2

The potential energy of the energy of the crystal as a function of the position of the diffusing interstitial is schematically shown in the fig. The energy is a minimum when the interstitial atom is at site 1 or site 2. The energy increases along the path from site 1 to 2 reaching a maximum at the midpoint of the path. The interstitial atom has to push its way through the parent atoms, with its outer electron cloud having a maximum overlap with the parent atoms at the midpoint. The potential energy barrier H_m is called the enthalpy of motion.

2

Q.5 a. Explain phenomenon of polarization in dielectric materials. **(6)**
Answer:
Polarization

The relation between the electric flux density D (charge per unit area in units of $cm^{-2)}$ at a point in a material and the electric field strength E (force per unit charge in units of NC^{-1} or $Vm_{-1)}$ at that point in space is given by

$$D = \varepsilon_r \varepsilon_o E$$

Where ε_o is the dielectric constant or permittivity of free space (vacuum) and ε_r is relative dielectric constant. ε_r is dimensionless and is a property of material related to its atomic structure. Its value is 1 for free space and is greater than 1 for all materials. In S.I units $\varepsilon_o = 8.854 \times 10^{-12}$ farad /m. ε_o has this particular value as a result of conversion C.G.S units to S.I units.

2

$$\varepsilon o = D / \varepsilon_r = Cm^{-2} / Vm^{-1} = Fm^{-1}$$

When an electric field is applied to a solid containing positive and negative charges, the positive charges are displaced in the direction of the field towards negative end, while the negative charges are displayed in the opposite direction. This displacement produces local dipoles throughout the solid. The dipole moment per unit volume of the solid is the sum of all the individual dipole moments within that volume and is called the Polarization P of the solid.

2

As the Polarization measures the additional flux density arising from the pressure of the material as compared to free space, it has the same units as D and is related to as follows:

$$D = \varepsilon_o E + P$$

As may be seen, when a voltage is applied to the capacitor, with the plates separated by vacuum, a charge develops on the plates. The capacitance Cof the capacitor is a measure of this charge and is defined by:

$$C= \varepsilon_o A/d$$

<div style="text-align:right">| 2 |</div>

A= area of parallel plates

d=distance of separation between them.

Polarization occurs due to several atomic mechanism, electronic polarization, ionic polarization, orientation polarization and space charge polarizations are various polarization processes.

   b. **Explain properties of ferroelectric materials using suitable example.**   (10)
**Answer:**
Ferroelectric materials

In many materials known as ferroelectrics, the dielectric constant are some two orders of magnitude larger than those in ordinary dielectrics. Barium Titanate is a ferroelectric with a relative dielectric constant of 2000,compared to less than 10 for ordinary dielectrics .The difference in the magnetic susceptibility between ferromagnetic and paramagnetic materials bears a direct analogy to this difference in the values of the dielectric constants are called ferroelectrics. As in the ferromagnetic phenomenon, the electric dipoles in a ferroelectric solid are all aligned in the same direction, even in the absence of an electric field.

<div style="text-align:right">| 2 |</div>

The ferroelectric phenomenon is discussed here with the reference to the classical e.g. of barium Titanate, $BaTiO_3$ .The cubic Titanate crystal is shown in the fig.
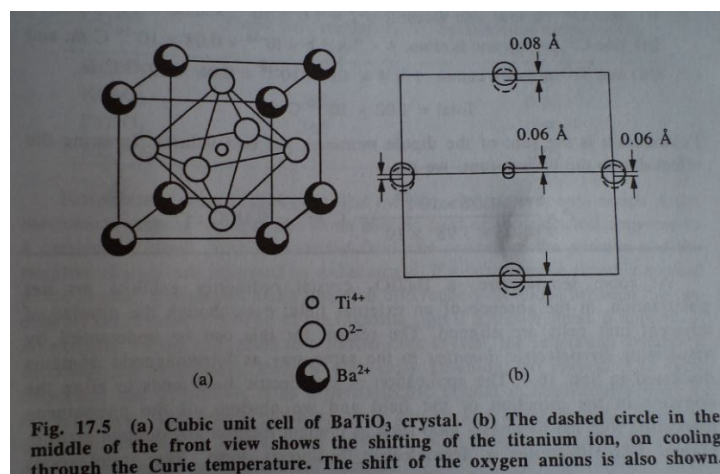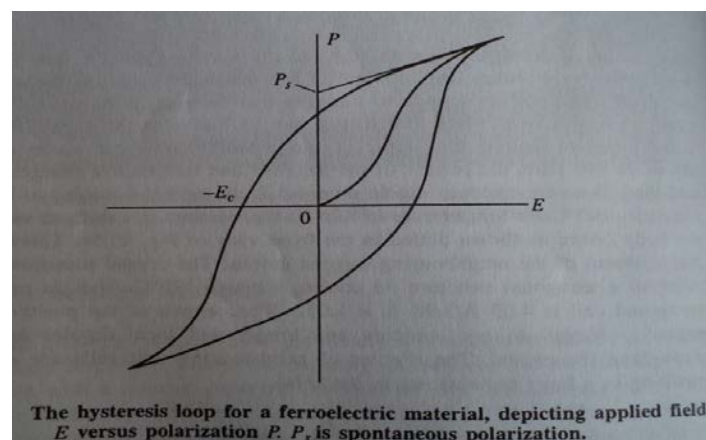

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Fig. 17.5 (a) Cubic unit cell of $BaTiO_3$ crystal. (b) The dashed circle in the middle of the front view shows the shifting of the titanium ion, on cooling through the Curie temperature. The shift of the oxygen anions is also shown.

Fig.Cubic unit cell of $BaTiO_3$

Barium Ions are at the body corners, the oxygen are at the face centres and the titanium is in the octahedral void at the body centre. Only one out of fouroctahedral voids in the unit cell is occupied and this corresponds to the chemical formula, with one titanium for the four species of the other kinds: one barium plus three oxygen. Above 120°C, barium Titanate is a cubic crystal with the ions located as described above. In this state, the centres of the negative and the positive charges coincide and there is no spontaneous dipole moment. If the crystal is cooled to below the body centre as shown dotted in the front view of fig. There is also a displacement of the neighbouring oxygen anions .the crystal transforms from a cubic to a tetragonal structure on cooling through 120°C. The c/a ratio of the tetragonal cell is 4.03 Å/3.98 Å=1.012. The centres of the positive and negative charges don't coincide any longer and local dipoles are created throughout the crystal. The dipoles of neighbour'sunit cells are all aligned resulting in a large polarization in the solid.

2

At room temperature, a $BaTiO_3$crystal ordinarily do net polarization, in the absence of an external field, even though the dipoles of adjacent unit cells are aligned. The application of the electric field tends to align the domains in the direction of the field and we observe all the phenomena associated with the hysteresis loop such as domain rotation and domain growth.

2

The hysteresis loop for a ferroelectric material, depicting applied field E versus polarization P. P_s is spontaneous polarization.

Fig. The hysteresis loop for a ferromagnetic material, depicting applied field **E** versus polarization **P.P$_s$** is spontaneous polarization.

Ferroelectric crystals always exhibit the piezoelectric property, which is mechanical response of a crystal to an electric field or the electric response to a

mechanical stress. With no external field, the centres of the positive and negative charges are separated by a distance D. If a compressive stress is applied to the crystal, D decrease and a potential difference V develops the two ends of the crystal. V will be of the opposite sign if a tensile stress is applied. If an external voltage is applied to a ferroelectric crystal, the separation distance D increases (or decreases), thereby elastically straining the crystal. The most important use of $BaTiO_3$ is as a piezoelectric crystal in applications such as microphones, phonograph pickups, strain gauges and SONAR devices. The high dielectric constant of ferroelectric crystals is also useful a for storing energy in small- sized capacitors in electrical circuits.
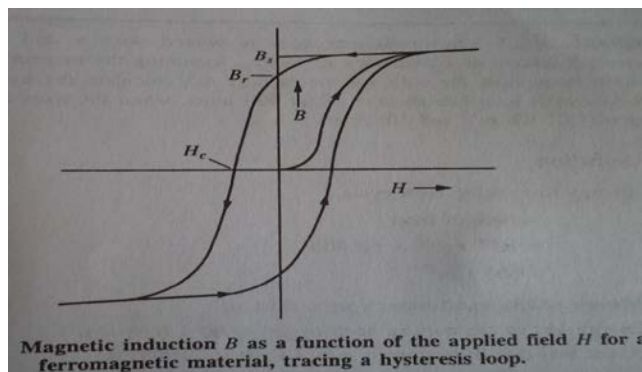
> **2**

Q.6   a. Explain hysteresis in magnetic materials.   (8)
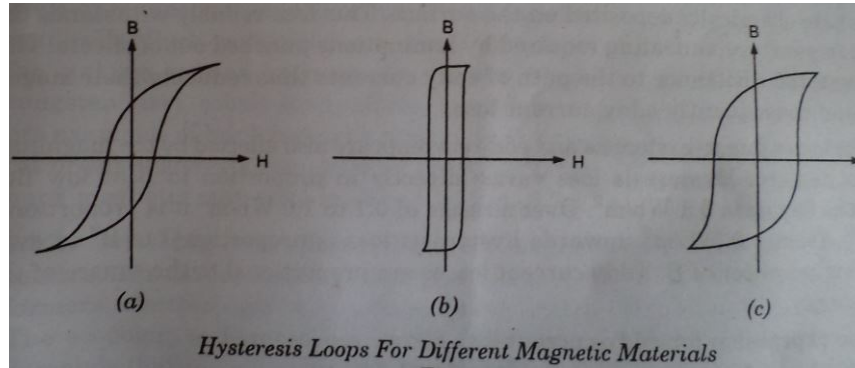**Answer:**
Hysteresis of magnetic materials

Fig. Magnetic induction **B** as a function of the applied field **H** for a ferromagnetic material, tracing a hysteresis loop

> **2**

The B-H curve for a typical ferromagnetic material is shown in fig. As the applied field **H**is increased, the magnetic induction **B**increases slowly at first then more rapidly. The rate of magnetic induction slows down again, eventually attaining a saturation value B_s. With further increase in the magnetic field, there is no increase in the induction. If the field is reversed, the induction decreases slowly at first and reaches aresidual value B_r at zero field.$B_r$represents the amount of residual induction left in the specimen after the removal of the field. If the application of the field is continued in the opposite direction, the domains tend to reverse their alignment, so that remaining induction is lost at a certain value of the reverse field called the coercive field H_c. The process of reversal of domains continues to give a net magnetization in the opposite direction. After saturation occurs in this direction, restoring the original field direction completes the hysteresis loop.

> **4**

Fig. Hysteresis loop for different magnetic materials

2

   b. Explain soft and hard magnetic materials.   **(8)**
Answer:
Soft magnetic materials

Soft magnetic materials are used for the construction of cores for electric machines,transformers,electromagnets,reactors,relays   etc.   The   economic construction of such equipment demands that the magnetic flux should be produced in the minimum space and with minimum loss. We already know that: Flux= Flux density x cross sectional area i.e. ø = B x A. To obtain a given value of flux density in order to keep to minimum the cross sectional area means less quantity of material.
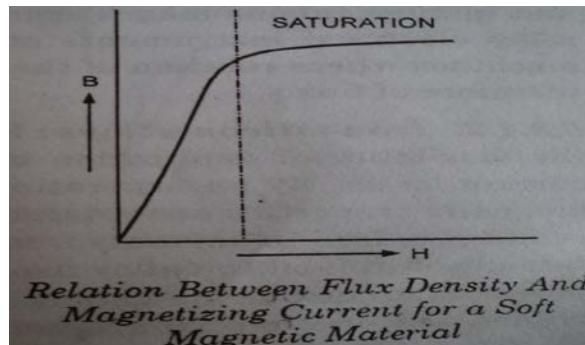
Fig. Relation between Flux density and magnetizing current for a soft magnetic material

4

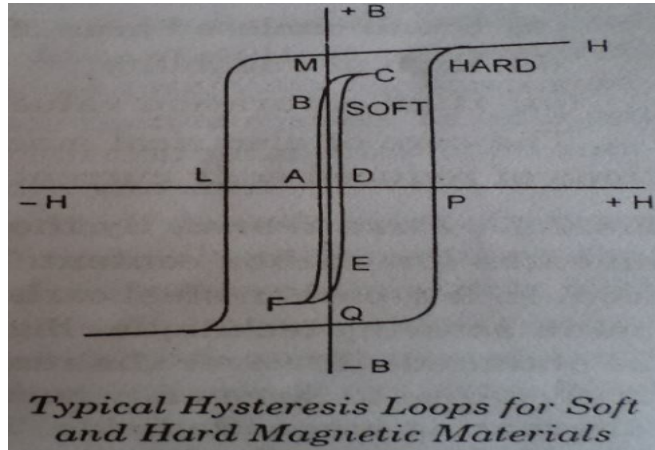| Properties of Soft Magnetic Materials				
Material	Initial relative permeability	Electrical resistivity, ohm m	Hysteresis loss, $J\ m^{-3}$	Saturation induction, $Wb\ m^{-2}$
Commercial iron	250	0.1×10^{-6}	500	2.2
Fe–4% Si	500	0.6×10^{-6}	100	2.0
Fe–Si oriented	1500	0.6×10^{-6}	90	2.0
Permalloy (45% Ni)	2700	0.55×10^{-6}	120	1.6
Supermalloy (79% Ni, 5% Mo)	100,000	0.65×10^{-6}	21	0.8
Ni–Zn ferrite	200–1000	$\sim 10^{6}$	35	0.4
Mn–Zn ferrite	2000	$\sim 10^{6}$	40	0.3

Table:-Properties of soft magnetic materials

Soft magnetic materials are Pure Iron, Iron- Silicon alloys, Grain oriented sheet steel. Nickel Iron alloys, soft ferrites etc.

Hard Magnetic Materials

Hard magnetic materials are used for making permanent magnets. The desired properties of material required of making permanent magnet are high saturation values, high- residual magnetism. In a hard magnetic material, it is difficult to orient the domains as compared to the soft magnetic materials. Thus it is difficult to magnetise a hard magnetic material. The coercive force is large and hence the material is magnetically hard. In a very hard material, the domain wall may be absolutely immobile.

a) Soft magnetic material such as silicon steel;
b) Soft magnetic material such asperm alloy;
c) Hard magnetic material.

Fig. Typical hysteresis loops for Soft and Hard magnetic materials

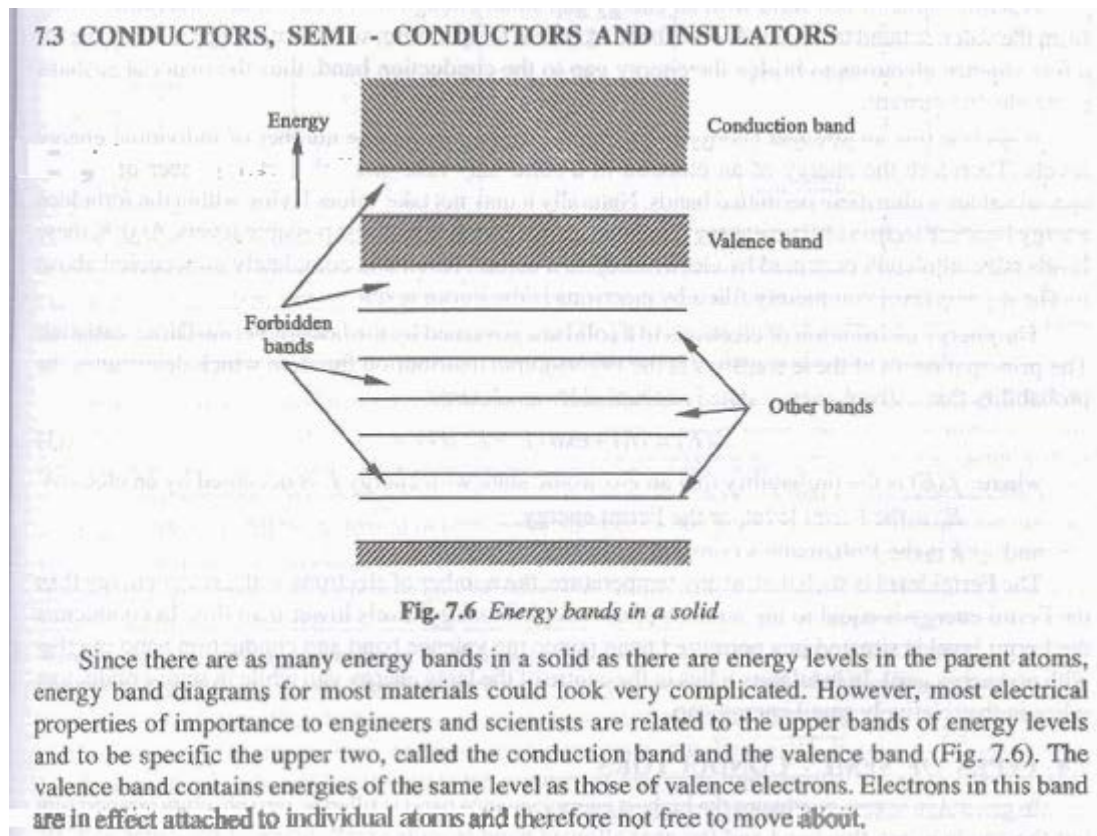| Properties of Hard Magnetic Materials			
Material	B_r, Wb m^{-2}	H_c, kA m^{-1}	$B_r H_c$, kJ m^{-3}
High carbon steel (martensitic)	0.90	3.98	3.58
Tungsten steel (5% W)	1.05	5.57	5.85
Chromium steel (4% Cr)	0.95	5.17	4.91
Cobalt steel (36% Co)	0.95	18.31	17.40
Al–Ni–Co alloys	0.8–1.2	60–120	48–144
Barium ferrite	0.21	140	29.4
Cobalt rare-earths Co_5 (Sm, Pr)	1.0	200	200

Table:-Properties of hard magnetic materials

Hard magnetic material are carbon steel, tungsten steel, cobalt steel, alnico, hard ferrites. These are used for making Permanent Magnets.

 Q.7   **a. Compare conductors, semiconductors and insulators based on energy band diagrams.**   **(6)**
Answer:

7.3 CONDUCTORS, SEMI - CONDUCTORS AND INSULATORS

Fig. 7.6 *Energy bands in a solid*

Since there are as many energy bands in a solid as there are energy levels in the parent atoms, energy band diagrams for most materials could look very complicated. However, most electrical properties of importance to engineers and scientists are related to the upper bands of energy levels and to be specific the upper two, called the conduction band and the valence band (Fig. 7.6). The valence band contains energies of the same level as those of valence electrons. Electrons in this band are in effect attached to individual atoms and therefore not free to move about.

                     16

The conduction band energies are high enough so that electrons attaining these levels of energy are loosely attached to individual atoms or practically free such that they could easily move under the influence of an electric field. Electrons in the valence band can leave their band to join the conduction band if given sufficient energy to jump the forbidden energy band (energy gap, E_g). The size of E_g is a prime factor in determining whether a solid is a conductor, an insulator or a semiconductor.

With reference to different band structures shown in Fig. 7.7 we can not broadly divide solids into conductors, semiconductors and insulators. Conductors contain a large number of electrons in the conduction band at room temperature. No energy gaps exist and the valence and conduction bands overlap. An insulator is a material in which the energy gap is so large that practically no electron can be given enough energy to jump this gap. These materials might conduct little electricity if their temperatures are raised to very high values enabling a number of electrons to join the conduction band:
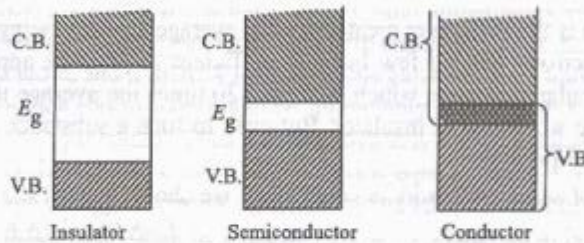

Fig. 7.7 Types of band structure

A semiconductor is a solid wild an energy gap small enough for electrons to cross rather easily from the valence band to the conduction band. At room temperature, sufficient energy is available for a few valence electrons to bridge the energy gap to the conduction band, thus the material sustains some electric current.

It is clear that an allowed energy band in a solid contains a large number of individual energy levels. Therefore the energy of an electron in a solid may take one value of a number of closely spaced values within these permitted bands. Naturally it may not take values laying within the forbidden energy bands. Electrons fill up energy positions starting from the lowest possible levels. At 0°K these levels are completely occupied by electrons up to a certain level, and completely unoccupied above it. The highest level completely filled by electrons is the Fermi level.

The energy distribution of electrons in a solid are governed by the laws of Fermi-Dirac statistics. The principal result of these statistics is the Fermi-Dirac distribution function which determines the probability that a given energy state is occupied by an electron.

$$f(E) = 1/[1 + \exp(E - E_F)/kT)] \qquad \qquad ...(1)$$

where $f(E)$ is the probability that an electronic state with energy E is occupied by an electron.

E_F is the Fermi level, or the Fermi energy,

and k is the Boltzmann's constant.

The Fermi level is such that, at any temperature, the number of electrons with greater energy than the Fermi energy is equal to the number of unoccupied energy levels lower than this. In conductors the Fermi level is situated in a permitted band (since the valence band and conduction band overlap with no energy gap). In insulators it lies in the centre of the large energy gap while in semi-conductors it lies in the relatively small energy gap.

b. **What is Hall effect? Derive expression for Hall Voltage and Hall Coefficient.(2+4+4)**

Answer:

7.10 HALL EFFECT

Consider a slab of material in which there is a current density J resulting from an applied electric field E_x in the x-direction. The electrons will drift with an average velocity $\bar{v}_x$ in the x-direction. When a magnetic field of flux density B_z (Wb/m²) is superposed on the applied electric field in the Z direction of electrons will experience a Lorentz force perpendicular to $\bar{v}_x$ and to B_z; the magnitude of

this force will be given by $B_z (u_z) e$. Thus the electrons are driven towards one face in the sample resulting in an excess of electrons near one face and a deficiency of electrons near the other face. These charges will in turn create a counteracting electric field E_y in the y-direction. E_y would build up until it is of sufficient magnitude to compensate the Lorentz force exerted on the electrons due to the magnetic field. We may, therefore, write
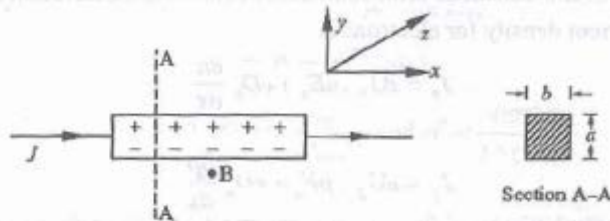
$$eE_y = B_z e(\overline{v_x})$$

Fig. 7.15

In the steady state, a Hall voltage, V_H, is thereby established in the y-direction given by

$$V_H = E_y \cdot a = B_z(\overline{v_x}) \cdot a$$

The current density in the sample is given by

$$J_x = N.e.(\overline{v_x})$$

where N = no. of conduction electrons/m³.

The current density can be calculated from the total current and the cross section $(a \times b)$ of the sample.

Thus,

$$J_x = I/a \times b = Ne(\overline{v_x})$$

or

$$I = Ne(\overline{v_x}) a \times b \qquad \qquad ...(9)$$

and

$$V_H = B_z \overline{v_x} \cdot a \qquad \qquad ...(10)$$

Eliminating $\overline{v_x}$ from equation (9) and (10), we have

$$V_H = \frac{I}{N.e.b.}$$

$$= (1/Ne) \cdot \frac{(B_z \cdot I)}{b}$$

Thus the ratio $\pm I/Ne = E_y /(I_x \cdot B_z)$ must be constant.

It is called the **Hall coefficient** and is denoted by R_H. R_H varies from metal to metal. The + and − signs refer to the positive and negative charge carriers respectively. Thus the measurement of Hall coefficient reveals the sign of the charge carriers, thus giving the type of conductivity besides the concentration of the charge carriers. The measurement of electrical conductivity, on the other hand, does not reveal the type of conductivity (n - or p-type) because electrical conductivity depends upon the square of the charge.

The Hall coefficient is negative for free electrons. A positive Hall coefficient implies that current is carried by positive charges or holes and the occurrence of the positive values of the Hall coefficient was the first experimental evidence for the existence of holes.

A full analysis of the effect using Fermi-Dirac distribution confirms the result $\left(R_H = \pm \frac{1}{Ne} \right)$ derived on the simple analysis above though the classical theory using a Maxwell-Boltzmann energy distribution leads to an expression for R_H which is larger by a factor $3\pi/8$.

The above remarks apply to the impurity semi-conductor in which there is only one type of charge carrier (*i.e.*, pure electron or pure hole conduction). In the general case of n-type $(n_e > n_h)$ or p-type $(n_h > n_e)$ conduction, a more exact treatment of charge carriers leads to a slight modification of the expression for R_H and we have

$$R_H = \pm 1/e \left[\frac{N_e u_e^2 - N_h u_h^2}{(N_e u_e + N_h u_h)^2} \right]$$

When the behaviour of an *n*-type semi-conductor becomes intrinsic with the raising of temperature, R_H falls continuously, whereas for the transition from *p*-type to intrinsic, the sign of R_H changes at the transition, becoming zero when $N_e (u_e/u_h)^2 = N_h$.

Another variable which is often used to describe the Hall effect is the ratio of the currents J_y to J_x. This is called the hall angle and is denoted by θ.

$$\theta = \frac{J_y}{J_x} = \frac{\sigma E_y}{J_x} = \sigma R_H B_z = \mu_H B_z$$

where μ_H is called the Hall mobility. The hall angle is equal to the average number of radians (usually fractional) traversed by a particle between collisions.

The Hall voltage is measured by attaching voltage probes at the two faces of the sample. This gives a method for *obtaining* R_H from measurement and thus calculating the number of charge carriers per m^3 and checking against the chemical evidence from Avogadro's number in the case of metals. This also provides a fairly reasonable check on the validity of the electron gas model.

The observed and calculated values of the Hall coefficient are given in Table 7.7.

Table 7.7 Observed and calculated value of R_H

Metal	Observed	R($cm^3 \times 10^{-5}$/coulomb) Calculated assuming q electrons per atom
InAs	as	
InSB	Id	
Li	− 17	− 13.1 (q = 1)
Na	− 25	− 24.4 (q = 1)
Cu	− 55	− 7.4 (q = 1)
Ag	− 8.4	− 10.4 (q = 1)
Zn	+ 4.1	− 4.6 (q = 2)
Cd	+ 6.0	− 6.5 (q = 2)
Si	~ − 10^{+3}	
Ge	~ − 10^{+4}	

The expression $R_H = \pm 1/Ne$ has been derived by ignoring the random velocities of the electrons. Even then the experimental and the calculated values of R_H agree fairly well (around 20%).

For copper $N = 8.44 \times 10^{28}/m^3$

$$e = 1.6 \times 10^{-19} C$$
$$R_H = 7.4 \times 10^{-11} m^3/C$$

which is a very small quantity. Since 1 Wb/m² is about the largest flux density that can be obtained conveniently, the thickness (b) of the Hall plate should be as small as possible in order to obtain a measurable Hall voltage (cf. $V_H = R_H(B_z I/b)$). Assume $b = 0.1$ mm $= 10^{-4}$ m. Through a thin piece of material such as this, about 100 A can be passed without much difficulty.

$$\therefore V_H \text{ for copper} = 7.3 \times 10^{-11} \times \frac{1 \times 100}{10^{-4}} \text{ V}$$

$$= 74 \, \mu V$$

Thus the Hall voltage has a value of a few microvolts for fields and currents easily accessible in an ordinary laboratory. It can be measured directly with a sensitive galvanometer or a d.c. potentiometer.

Semi-conductors possess a measurable Hall effect because N is much smaller, and the existence of Hall effect is accepted as proof that a given substance is a semi-conductor.

The difference between the calculated (74 μV) and measured (55 μV) values of Hall voltage for copper may be explained as follows :

In the preceding treatment of the Hall effect we have ignored the thermal velocities of the electrons and have assumed that *the* number of electrons is equal to the number of atoms. Both of these assumptions may not be true.

The sign of the current carriers may also be determined by the direction of the thermo-*e.m.f.* developed in a conductor when its ends are maintained at different temperatures. At the hot end there are more free charges and their heat energy is higher than at the cold end. The charges therefore travel to the cold end. Experiments show that in certain semi-conductors the cold end becomes negatively charged while in others it becomes positively charged. Thus a semi-conductor is capable of sustaining the movement of free negative electrons and also of positive charges or holes. The positive charges cannot be positrons (of nuclear physics) because to liberate the latter an energy as high as 1 million *e*V or more would be required. Positrons obviously do not participate in current conduction.

Q.8   **Write short notes on the following:**   **(4x4)**
         (i) Varactor diode
         (ii) Avalanche breakdown
         (iii) Ferrite Core Inductor
         (iv) Ferreed Relay

Answer:

(ii) *Varactor diodes* also called the variable capacitance diodes are distinguished by their small physical size and a junction capacity which is a rapidly varying function of the applied voltage. The small size is necessary for high frequency performance since the total capacitance must be minimized for high frequency use and the capacitance is directly proportional to the junction area. The principal uses of such diodes are in parametric amplifiers and subharmonic generators.

The small signal equivalent circuit of a *p-n* junction diode is shown in Fig. 8.10.

This shows the series body resistance, the leakage resistance, the diode conductance, and the depletion-layer capacitance. The desired varactor diode equivalent circuit is shown in Fig. 8.15.

$$\dashv\vdash$$
$$C(v)$$
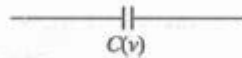
Fig. 8.15 *Small-signal equivalent circuit for a varactor diode*

Thus a properly designed varactor diode would have a small series body resistance and a large leakage resistance. Furthermore, it should be biased such that the diode conductance is negligible with respect to the admittance of the depletion-layer capacitance. The varactor diode is often used at frequencies of kilomegacycles. The cut-off frequency of such a diode is a measure of the highest frequency at which the diode can be represented as a capacitance. The cut-off frequency is the frequency at which *the* series body resistance is equal to the depletion-layer capacitive reactance :

$$f_{cut-off} = \frac{1}{2\pi rC}$$

At frequencies higher than this the diode appears resistive. The capacitance C is a function of the d.c. bias voltage, so this voltage should be specified, when the cut-off frequency is specified.

Avalanche breakdown: In wider junctions it is found that breakdown occurs at a much lower voltage than can be explained by the Zener breakdown theory. If a large field is applied to the barrier layer and if the mean free path of the electrons is large, the electrons gain more energy between collisions than they lose to the lattice during a collision. The electron would be accelerated by the applied field until it acquires sufficient energy to excite an electron from the filled band into the conduction band(Fig. 8.13) thus creating an electron-hole pair. The original electron and the new electron-hole pair then continue to create new electron-hole pairs thus creating a continuous discharge through the material The effect is that of ionisation by collision

of carriers as in a gas discharge. This is known as the *avalanche effect*. At higher temperatures the mean free paths of electrons and holes are shorter. Therefore a larger field is needed to cause ionisation and a higher breakdown voltage is observed. The critical field strength in germanium at room temperature is about 2×10^7 volts/m for "avalanche breakdown". If the critical field strength is denoted by E_{crit}; the avalanche breakdown will occur when $E_{max} \leq E_{crit}$
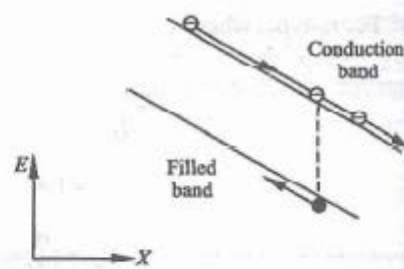

Fig. 8.13

or
$$\frac{2eN_d N_a (V_0 + V)}{\epsilon_r \epsilon_0 (N_a + N_d)} \geq (E_{crit})^2$$

or
$$(V_0 + V) \geq \frac{\epsilon_r \epsilon_0}{2e}\left(\frac{1}{N_d} + \frac{1}{N_a}\right)(E_{crit})^2$$

$$= \frac{\epsilon_r \epsilon_0}{2}\left(\frac{U_n}{\sigma_n} + \frac{U_p}{\sigma_p}\right)(E_{crit})^2$$

assuming that all donors and acceptors are ionised and the conductivities in the p and n-regions become $\sigma_p = N_0 e U_p$ and $\sigma_n = N_d e U_n$ respectively. For voltages greater than the critical voltage given by the above equation, the resistance of the barrier layer is extremely small and the current increases extremely rapidly with voltage. It is possible to obtain diodes with avalanche breakdown occurring at specified voltage by a proper choice of the conductivities σ_p and σ_n.

(iii) Cored Coils

In high frequency ranges, coil formers may be of a ceramic material and have no core, but receiver coils in the lower region of high frequency band use cores of a high permeability material classed as ferrite. A ferrite is a hard non-porous material which has the insulting ability of a ceramic but a magnetic permeability similar to a ferromagnetic material. Forms for coils in this range may be using a plastic known as polyesterene.

Types of Cores

In order to minimise losses while maintaining high flux density, the core can be made of laminated sheets insulated from each other or insulated powdered iron granules and ferrite materials can be used.

Laminated Core

Each laminated section is insulated by a very thin coating of iron oxide and varnish. This insulating borders increase the resistance in the cross-section of core of reduce the eddy currents but allow a low reluctance path for high flux density around the core. Transformers for audio frequencies are generally made with a laminated iron core. Fig. 12.18 shows a shell type core formed with a group of individual laminations.
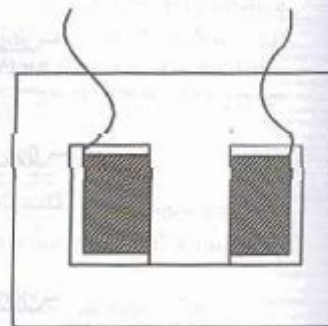

Fig. 12.18 Shell-type core.

Powdered Iron Core

To reduce eddy currents in the iron core of an inductance for radio frequencies, powdered iron is generally used, It consists of individual insulated granules pressed into one solid ....

Ferrite core

The ferrites are ceramic materials that provide high values of magnetic flux density but with the advantage of being an insulator. Therefore, a ferrite core can be used in inductance for high frequencies with minimum eddy current losses.

(xviii) The Ferreed. Fig. 12.21 shows the basic arrangement of Ferreed relay. Here current pulses are applied to two series aiding coils, causing contacts to close. Release is obtained when, a reverse pulse is obtained to a single coil. No maintaining current is necessary because attraction between reeds depends on core magnetisation. Automatic latching action is also obtained. The operating current pulse may be of the order of microsecond.
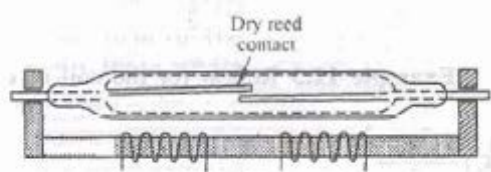
Fig. 12.21 *Ferreed*

Q.9　　　**Explain the following:**　　　　　　　　　　　　　　　　　　**(2x8)**
　　　　　　　(i) Fabrication of Junction Transistor
　　　　　　　(ii) Operation of JFET with high drain voltage

Answer:

14.6 FABRICATION OF JUNCTION TRANSISTORS

Transistors have been made using all the basic junction forming techniques, namely,

Grown junction

Alloyed junction

Diffused junction, and

Epitaxial diffused junction;

and by various combinations of these processes.

Grown transistors (Fig. 14.5) which are produced by compensation doping of the melt from which the semiconductor ingot is pulled with alternate amounts of opposite polarity impurities, have historical significance. The process has little practical importance today because of difficulties of

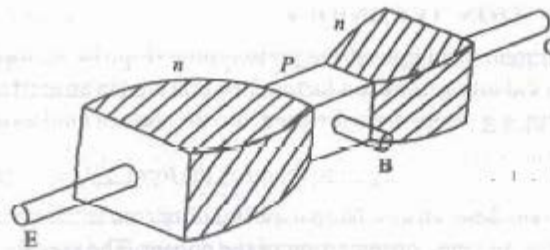locating the junction and of attaching leads to the narrow grown base region.

Fig. 14.5 *Grown junction.*

Alloyed junction (Fig. 14.6) is used extensively to make general purpose, *low frequency transistors*. A thin wafer of say *n*-type material has small dots of pure *p*-type impurity e.g., In, or another metal heavily doped with *p*-type impurities, alloyed to either side of it. The alloyed sections have the two fold purpose of providing both the correctly doped collector and emitter regions and making ohmic contacts to them. Transistors made using this technique usually have a *poor high frequency performance* because *of high junction* capacitances and because of the difficulty of controlling the process sufficiently to produce very thin base regions.
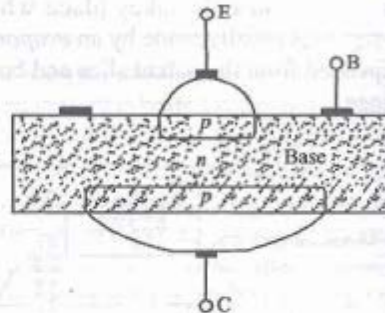
Fig. 14.6 *Alloyed junction*

The transistor shown in Fig. 14.7 is fabricated by an alternative process which produces a reduced base thickness thus extending the transistor's *h.f.* operation range to above 100 MHz. The base region is formed by etching away the parent semiconductor using jets of etching solution, which is subsequently employed as the electrolyte used to electroplate alloying contacts on to either side of the base.
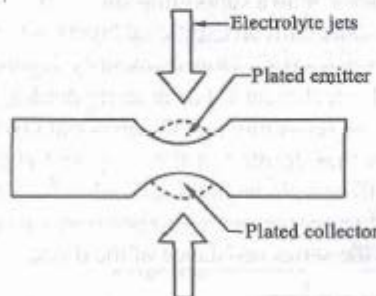

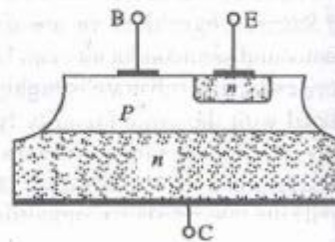**Fig. 14.7** *Surface Barrier alloyed junction transistor*

Fig. 14.8 *Diffused mesa*

The diffusion process for fabricating transistors has many advantages and is now most prevalent. A *p*-type impurity to form the *base* is diffused into the top face of an *n*-type semiconductor slice, followed by a shallower, more highly concentrated *n*-type diffusion which forms the emitter and delineates the narrow base region. Ohmic contacts are made to various regions by evaporation of metallic conductors. In the MESA version (Fig. 14.8), the area of the collector junction is formed by an etching process which leaves the active positions of the transistor isolated on a tapered plateau or mesa.

In the planar diffused version (Fig. 14.9), the geometry of the C, B and E and ohmic contacts is determined by an *oxide masking* technique before each successive stage of manufacture similar to that described for the planar diode.

A disadvantage of the diffusion process is that the lightly doped collector region provides a high resistance path in series with the collector circuit.

This difficulty is overcome in the epitaxial planar process (Fig. 14.10). A highly doped, low resistance substrate has a higher resistivity epitaxial layer grown from the vapour phase onto it to form a composite collector. The base and emitter layers are diffused in the usual way into the high resistivity epitaxial layer. The substrate provides the required low resistance path to the collector terminals. Such transistors have the additional advantage of *reduced collector capacitance and higher breakdown voltages.*

In all type of transistors made by the diffusion process, any grading of the impurity in the base layer to produce a drift field in it is readily obtained by controlling the diffusion conditions so as to form a *predetermined impurity profile.*
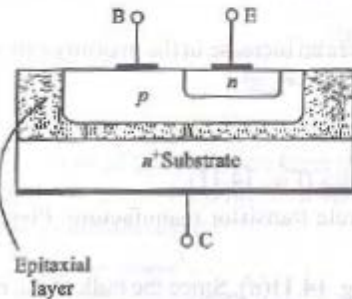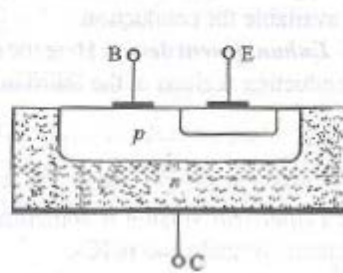

Fig. 14.10 *Epitaxial planar diffused.*   Fig. 14.9 *Planar diffused*

14.9.3 Operation of JFET with high drain voltages

Assume gate junctions can be treated as equipotentials because of relatively high-gate conductivity. If gate voltage is V_g, then the total reverse bias the at the element is $V_x + V_g$. The equation, $I_d = V_d \cdot G$, is still applicable provided

$$l \to \delta x$$

$$V_d \to \frac{dV_x}{dx} \delta x$$

$$V_g \to V_x + V_g$$

$$\therefore \quad I_d = \frac{e\,N_d\,\mu_e\,2\omega a}{\delta x} \left[1 - \left(\frac{V_g + V_x}{V_0} \right)^{1/2} \right] \frac{dV_x}{dx} \cdot \delta x \qquad \qquad ...(14.12)$$

Assume that contact voltage V_0 is negligible. Then,

$$\frac{I_d}{2e\,N_d\mu_e\omega a}\int_0^l dx = \int_0^{V_d}\left[1-\left(\frac{V_x+V_g}{V_p}\right)^{1/2}\right]dV_x \qquad \dots(14.13)$$

$$\therefore \quad I_d = G_0\left[V_d - \frac{2}{3}\frac{(V_d-V_g)^{3/2}}{V_p^{1/2}} + \frac{2}{3}\frac{(V_g)^{3/2}}{V_p^{1/2}}\right] \qquad \dots(14.14)$$

and in terms of drain gate voltage $V_{dg} = V_d + V_g$,

$$I_d G_0\left[V_{dg}\left\{1-\frac{2}{3}\left(\frac{V_d}{V_p}\right)^{1/2}\right\} - V_g\left\{1-\frac{2}{3}\left(\frac{V_g}{V_p}\right)^{1/2}\right\}\right] \qquad \dots(14.15)$$

These equations are only valid for $V_{dg} = (V_d + V_g) < V_p$, otherwise when $V_{dg} = V_p$, the channel has zero thickness and becomes pinched-off.

Detailed analysis of the behaviour of the device above pinch-off is complex but the following qualitative analysis might be useful. As V_{dg} is made bigger than V_p, most of the excess voltage appears across the depletion layers at the drain end of the channel, causing a *relatively strong axial electric field* to exist there. Electrons which reach this pinched-off depletion region are therefore rapidly removed into the drain. The effect of further increasing V_{dg} or V_d is to move the position where pinch-off occurs nearer to the source as shown in Fig. 9.14 (b). However since large drain voltage changes cause only slight movement of the pinch-off position, there is a tendency for the drain current to saturate and increases in drain voltage above pinch-off cause only small increases in drain current.

$I_d - V_d$ curves assuming that current saturation occurs after pinch-off are then as shown in Fig. 14.15.
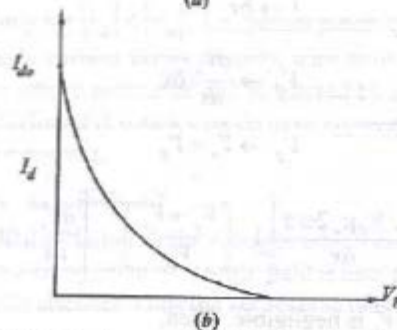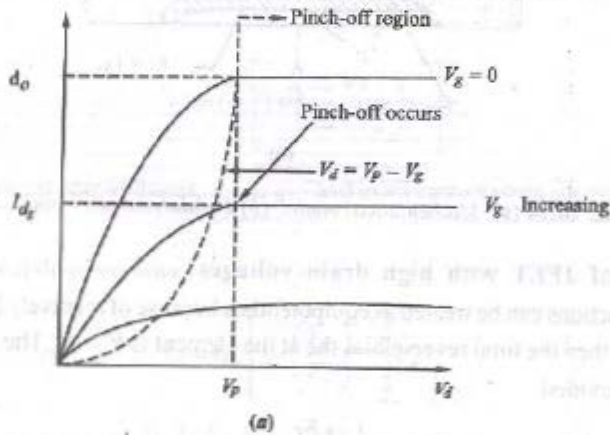

Fig. 14.15 (a) Drain characteristic, (b) Transfer characteristic of JFET

The current in the saturation region I_{ds} for a particular gate voltage can be obtained by letting $V_{dg} = V_p$. Thus

$$I_{ds} = G_0 \left[\frac{V_p}{3} - V_g \left\{ 1 - \frac{2}{3} \left(\frac{V_g}{V_p} \right)^{1/2} \right\} \right] \qquad \ldots(14.16)$$

and for zero gate voltage, the saturation current

$$I_{d0} = \frac{G_0 V_p}{3} \qquad \ldots(14.7)$$

Also

$$I_{ds} = I_{d0} \left[1 - \frac{3V_g}{V_p} + 2 \left(\frac{V_g}{V_p} \right)^{3/2} \right] \qquad \ldots(14.18)$$

The transfer characteristic of the device, in the pinch-off region, can be predicted from the equation:

g_m (mutual conductance) beyond pinch-off is given by

$$g_m = \frac{\partial I_{ds}}{\partial V_g} V_d = \frac{\partial}{\partial V_g} \left[I_{d0} \left\{ 1 - \frac{3V_q}{V_g + V_d} + \frac{2V_g}{V_g + V_d} \right\}^{1/2} \right]$$

$$\approx -I_{d0} \frac{3V_d}{V_p^2} \left[1 - \left(\frac{V_g}{V_p} \right)^{1/2} \right] \qquad \ldots(14.19)$$

Max, g_m occurs at $V_g = 0$ and is

$$g_{m0} = \frac{-3I_{d0}}{V_p} = -G_0$$

$$= \text{Conductance of channel with zero gate voltage}$$

$$g_m = g_{m0} \left[1 - \left(\frac{V_g}{V_p} \right)^{1/2} \right] \text{ at any other gate voltage} \qquad \ldots(14.21)$$

MARKING SCHEME

AE106 MATERIALS

2. a. Ionization potential – 3 marks

Electron affinity - 3 marks

   Electronegativity - 2 marks

  b. Secondary bonding – 4 marks

Bonding characteristics and properties – 4 marks

3. **a.** crystalline Solid - 4 marks

Non-crystalline Solid -4 marks

b. point imperfection

   Definition – 2 marks, explanation -3 marks, diagram -3 marks.

4. **a.** Fick's law of Diffusion

Definition – 2 marks, explanation -3 marks, equation -3 marks

b. Atomic model of Diffusion

   Explanation – 4 marks, diagram – 4 marks

5. **a.** Phenomena of superconductivity in materials

   Explanation – 4 marks, diagram – 4 marks

 b. Hysteresisof magnetic materials

   Explanation – 4 marks, diagram – 4 marks

6. **a.** Soft materials – 4 marks

   Hard materials - 4 marks

b. polarization

   Explanation – 4 marks, formula – 4 marks

7. **a.** Electric breakdown

   Application-2 marks, Explanation – 6 marks

b. ferroelectric material

Explanation – 5 marks, Diagram -3 marks.

8. **a.** Diodes

Explanation-5 marks, Diagram-3 marks.

b. Resistors

Classification – 3 marks, Explanation – 5 marks.

	b.	
Q.6	a.	
	b.	
Q.7	a.	2 marks for each 2×3 = 6
	b.	Hall effect — 2 " voltage — 4 " coefficient — 4
Q.8	a.	a, b, c, d → four marks each
	b.	
Q.9	a.	
	b.	

MODERATION-I

TEXT BOOK

I.   Materials Science and Engineering – A First Course by V. Raghavan, Fifth Edition, Thirty-Fourth Print, April 2007 Edition, Prentice-Hall Of India Pvt Ltd

II. Introduction to Electrical Engineering Materials by C.S. Indulkar and S. Thiruvengadam, 4th Edition, Reprint 2006, S. Chand and Company Ltd