

Q.2a. Discuss different types of Bravais Lattices.

26 Crystal Geometry and Structure Determination

**TABLE 3.1**  
**The Bravais Lattices**

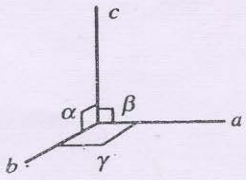
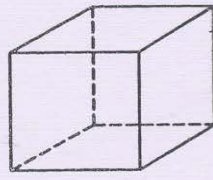
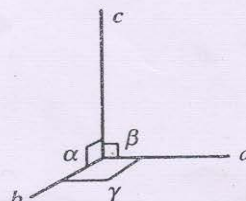
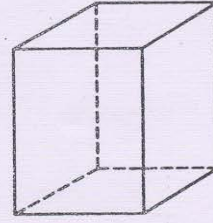
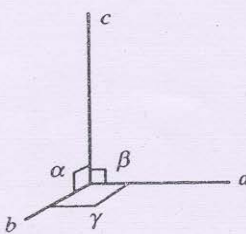
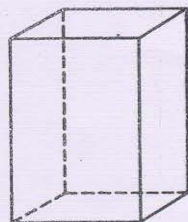
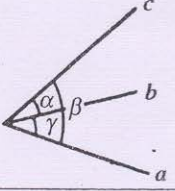
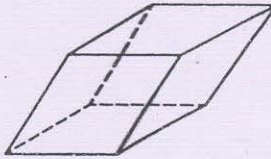
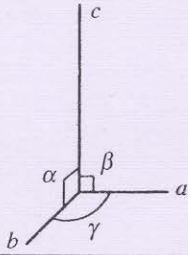
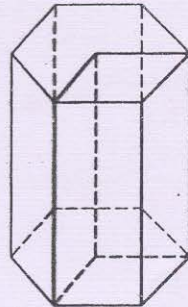
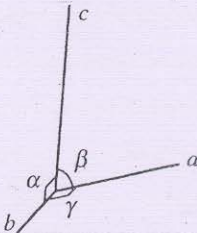
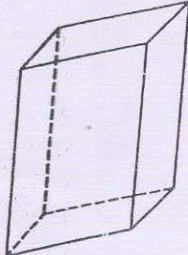
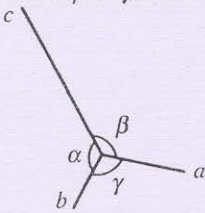
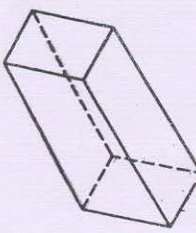
Crystal system	Space lattice	Unit cell
<p>I. Cubic</p> <p><math>a = b = c</math></p> <p><math>\alpha = \beta = \gamma = 90^\circ</math></p> 	<p>(1) Simple (Lattice points at the eight corners of the unit cell)</p> <p>(2) Body centred (Points at the eight corners and at the body centre)</p> <p>(3) Face centred (Points at the eight corners and at the six face centres)</p>	
<p>II. Tetragonal</p> <p><math>a = b \neq c</math></p> <p><math>\alpha = \beta = \gamma = 90^\circ</math></p> 	<p>(4) Simple (Points at the eight corners of the unit cell)</p> <p>(5) Body centred (Points at the eight corners and at the body centre)</p>	
<p>III. Orthorhombic</p> <p><math>a \neq b \neq c</math></p> <p><math>\alpha = \beta = \gamma = 90^\circ</math></p> 	<p>(6) Simple (Points at the eight corners of the unit cell)</p> <p>(7) End centred (Also called side centred or base centred) (Points at the eight corners and at two face centres opposite to each other)</p> <p>(8) Body centred (Points at the eight corners and at the body centre)</p> <p>(9) Face centred (Points at the eight corners and at the six face centres)</p>	

TABLE 3.1 (cont.)  
The Bravais Lattices

Crystal system	Space lattice	Unit cell
IV. Rhombohedral $a = b = c$ $\alpha = \beta = \gamma \neq 90^\circ$ 	(10) Simple (Points at the eight corners of the unit cell)	
V. Hexagonal $a = b \neq c$ $\alpha = \beta = 90^\circ$ $\gamma = 120^\circ$ 	(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]	
VI. Monoclinic $a \neq b \neq c$ $\alpha = \gamma = 90^\circ \neq \beta$ 	(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)	
VII. Triclinic $a \neq b \neq c$ $\alpha \neq \beta \neq \gamma \neq 90^\circ$ 	(14) Simple (Points at the eight corners of the unit cell)	



- b. Explain the following :
- Production of ions of Opposite Sign
  - Coulomb Attraction

26/11) 66 Atomic Structure and Chemical Bonding

#### 4.5.1 Production of Ions of Opposite Sign

The element sodium has an atomic number  $Z = 11$  and an electronic configuration  $1s^2 2s^2 2p^6 3s^1$ . Being an alkali metal, the first ionization potential for sodium is relatively small,  $496 \text{ kJ mol}^{-1}$  ( $5.1 \text{ eV/atom}$ ). The outermost electron is removed by supplying this much energy:

$$\text{Na} \rightarrow \text{Na}^+ + e^-$$

The released electron is then available to occupy the only vacant state in the chlorine atom to produce a negatively charged ion:

$$\text{Cl} + e^- \rightarrow \text{Cl}^-$$

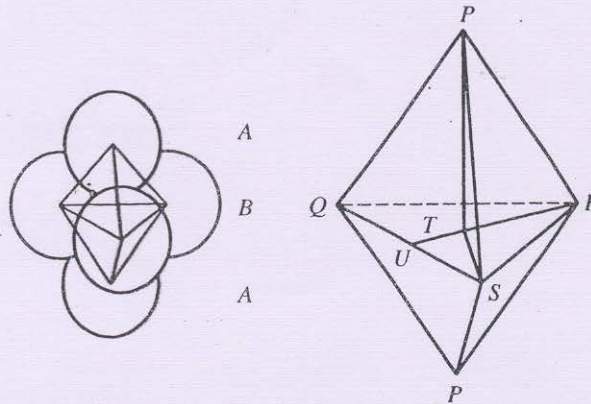
The electron affinity of chlorine is  $369 \text{ kJ mol}^{-1}$  ( $3.8 \text{ eV/atom}$ ). Thus, the electron transfer from sodium to chlorine produces two oppositely charged univalent ions, with a net increase in the potential energy  $\Delta E = 496 - 369 = 127 \text{ kJ mol}^{-1}$  ( $1.3 \text{ eV/pair}$ ). This increase is more than compensated during bonding by the energy decrease due to electrostatic attraction between the two oppositely charged ions.

#### 26/11) 4.5.2 The Coulomb Attraction

The electron transfer results in the inert gas configuration around both the nuclei. This configuration has spherical symmetry of the electron probability cloud. So, the bonding force between the ions is the same in all directions. The ionic bond is said to be *nondirectional*. To start with, the ions can be considered to be point charges. From Coulomb's law of electrostatics, as two opposite charges are brought together, the attractive force between them increases in magnitude inversely as the square of the distance of separation  $r$ . So, the potential energy decreases inversely as the distance. The potential energy is equal to  $-A'z_1z_2e^2/r$ , where  $z_1$  and  $z_2$  are the valency of the two ions,  $e$  is the electronic charge and  $A'$  is a conversion factor.

**Q.3a.** Calculate the  $c/a$  ratio for an ideally closed packed HCP crystal.

**Solution** The ...ABA... type of stacking represents the HCP structure depicted in Fig. 5.9. Joining the centres of the three neighbouring atoms of the



**Fig. 5.9** In the ...ABA... packing, which is HCP, the centres of three atoms  $Q$ ,  $R$  and  $S$  on plane  $B$  are joined to the centres of  $P$  atoms in plane  $A$  above and below.

middle plane to the centres of the atoms of the top and the bottom planes results in two tetrahedra with a common base. The top and the bottom atoms are centred at two lattice points, one above the other on the two hexagonal basal planes of the unit cell. So, the distance between them is the unit distance along the  $c$ -axis. The distance between any two adjacent atoms of a plane is unit distance along the  $a$ -axis. Unit of  $c$  is equal to twice the normal from the apex of a tetrahedron to its base. Unit of  $a$  is equal to the side of the tetrahedron.

In Fig. 5.9,

$$c/a = \frac{2PT}{RS}$$

$$RU = \sqrt{RS^2 - SU^2} = \sqrt{a^2 - a^2/4} = \sqrt{3} a/2$$

$$RT = \frac{2}{3} RU = a/\sqrt{3}$$

$$PT = \sqrt{PR^2 - RT^2} = \sqrt{a^2 - a^2/3} = a\sqrt{2/3}$$

$$c/a = 2(a\sqrt{2/3})/a = 1.633.$$

b. The surface of a copper crystal is of the [111] type. Calculate the surface energy of copper.



**3b** **Example 6.5** The surface of a copper crystal is of the {111} type. Calculate the surface energy (enthalpy) of copper.

**Solution**

The bond energy per atom of copper  
 = bond energy per bond  $\times$  no. of bonds per atom  $\times$  1/2 **(4)**  
 =  $(56.4 \times 1000 \times 12) / (6.023 \times 10^{23} \times 2)$   
 =  $5.62 \times 10^{-19}$  J

Three out of twelve bonds are broken at the surface.

Energy of broken bonds per atom =  $5.62 \times 10^{-19} \times 1/4$  **(2)**

No. of atoms on {111} planes in copper (see Problem 3.11)  
 =  $1.77 \times 10^{19} \text{ m}^{-2}$

Surface enthalpy of copper  
 =  $5.62 \times 10^{-19} \times \frac{1}{4} \times 1.77 \times 10^{19}$   
 =  $2.49 \text{ J/m}^2$  **(2)**

Q.4 a. Discuss carburization of steel based on the Fick's second law solution.

**4a** **8.3.3 Carburization of Steel**

Surface hardening of steel objects such as gears is frequently done by carburizing or nitriding. The process consists of diffusing carbon (or nitrogen) into the surface layers of the steel object. In pack carburizing, the object is packed in solid carbon powder. In gas carburizing, an atmosphere of methane gas that is rich in carbon surrounds the object to be carburized. Here, the following reaction takes place at the steel surface:

$$\text{CH}_4 (\text{g}) \rightarrow 2\text{H}_2 (\text{g}) + \text{C} (\text{steel})$$

When the steel object is annealed at an elevated temperature in the carburizing medium, carbon diffuses into the steel from the surface under a concentration

gradient. Surface hardening improves the wear resistance of components such as gears, without impairing the bulk mechanical properties such as toughness.

If the carbon content of the carburizing atmosphere remains constant, it would give rise to a constant carbon concentration  $c_s$  at the surface of the steel, Fig. 8.4a.

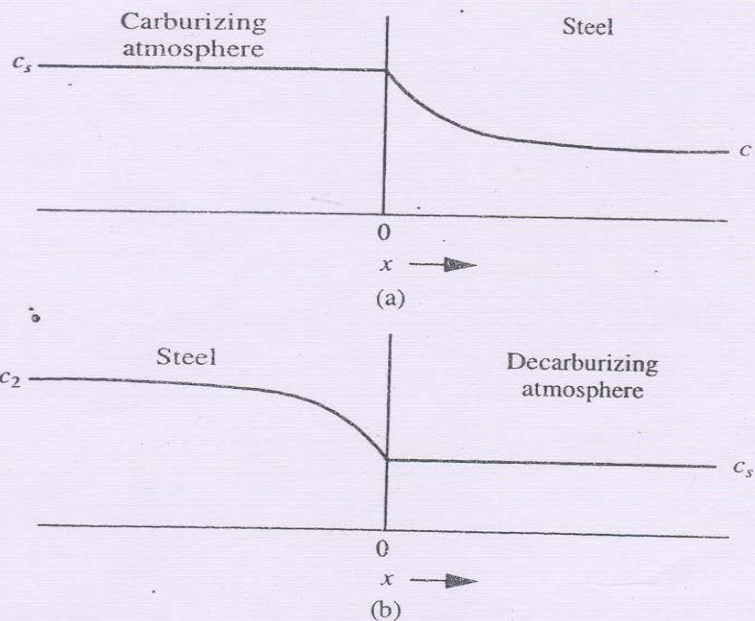


Fig. 8.4 Concentration-distance profiles for (a) carburization, and (b) decarburization.

The initial carbon content of the steel is  $c_1$ . We can then write

$$c(x, 0) = c_1, \quad x > 0$$

$$c(0, t) = c_s$$

So, from Eq. (8.8),

$$A = c_s, \quad B = c_s - c_1$$

With  $D$ ,  $c_s$  and  $c_1$  known, the amount and depth of carbon penetration as a function of time can be computed.

**b. Explain the factors affecting the Resistivity of Electrical materials.**

Ans Refer Pg No. 68 para 2.2 of Text book II. Introduction to Electrical Engineering Materials by CS Indulkar



**Q.5 a. Derive expression for dielectric constant of monoatomic gasses.**

**4.4. The dielectric constant of monoatomic gases**

In a gas the average distance between the atoms or molecules is large enough so that one can neglect interaction between them and the individual atoms can be studied independently. Consider a single atom consisting of a positive nucleus of charge  $Ze$  with  $Z$  electrons moving around the nucleus. Let us assume that the total negative charge  $-Ze$  is distributed homogeneously throughout a sphere of radius  $a$ .

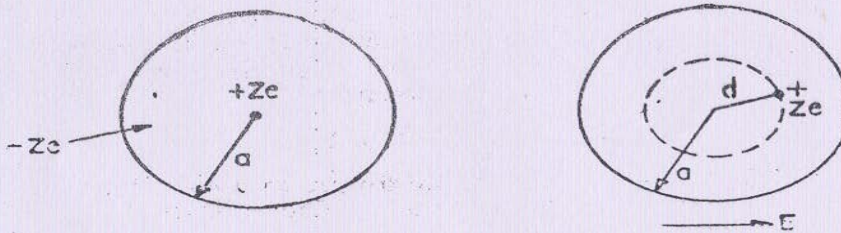


Fig. 4.3.

When this atomic model is placed in a field  $E$  as shown in Fig. 4.3 there is no translational force on the atoms as a whole, since it is electrically neutral. But the nucleus and the electron cloud will evidently try to move in opposite directions because of the opposite signs of their charges. However, as they are pulled apart, a force will develop between them tending to bring the nucleus back to the centre of the sphere. Consequently, an equilibrium condition will be obtained in which the nucleus is displaced relative to the centre of the electron cloud in the direction of  $E$ . The displacement of the nucleus may be calculated as follows: assume that the nucleus is shifted by an amount  $d$  as shown in the figure. The force on the nucleus in the direction of the field equals  $ZeE$ . The electron cloud can be divided into two regions—one inside an imaginary sphere of radius  $d$  and the other between the two spherical surfaces of radii  $d$  and  $a$ . From Gauss's theorem the charge in the latter region does not exert any force on the nucleus. The only force exerted on the nucleus is the one produced by the negative charge which is distributed inside the smaller sphere of radius  $d$ . The charge inside this sphere equals  $-Ze \times \frac{\text{Volume of sphere with radius } d}{\text{Volume of sphere with radius } a}$ .

$$= \frac{-Zed^2}{a^3}$$

The force exerted on the nucleus by this charge assuming it to be concentrated at the centre of the sphere is given by Coulomb's law. In the equilibrium condition, one obtains

$$ZeE = \frac{1}{4\pi\epsilon_0} \frac{(Ze)(Zed^3/a^3)}{d^2}$$

Hence, the displacement of the nucleus relative to the centre of the sphere is given by

$$d = 4\pi \frac{\epsilon_0 a^3}{Ze} \cdot E$$

This shows that the displacement is proportional to the field strength—a situation akin to the one in which a mechanical force is exerted on a particle bound with an elastic force to a certain equilibrium position.

On the application of an electric field the atom still remains neutral but has non-zero dipole moment due to the displacement of the nucleus relative to the centre of the electron cloud. The magnitude of the dipole moment is given by

$$m = Ze \cdot d = 4\pi\epsilon_0 a^3 E$$

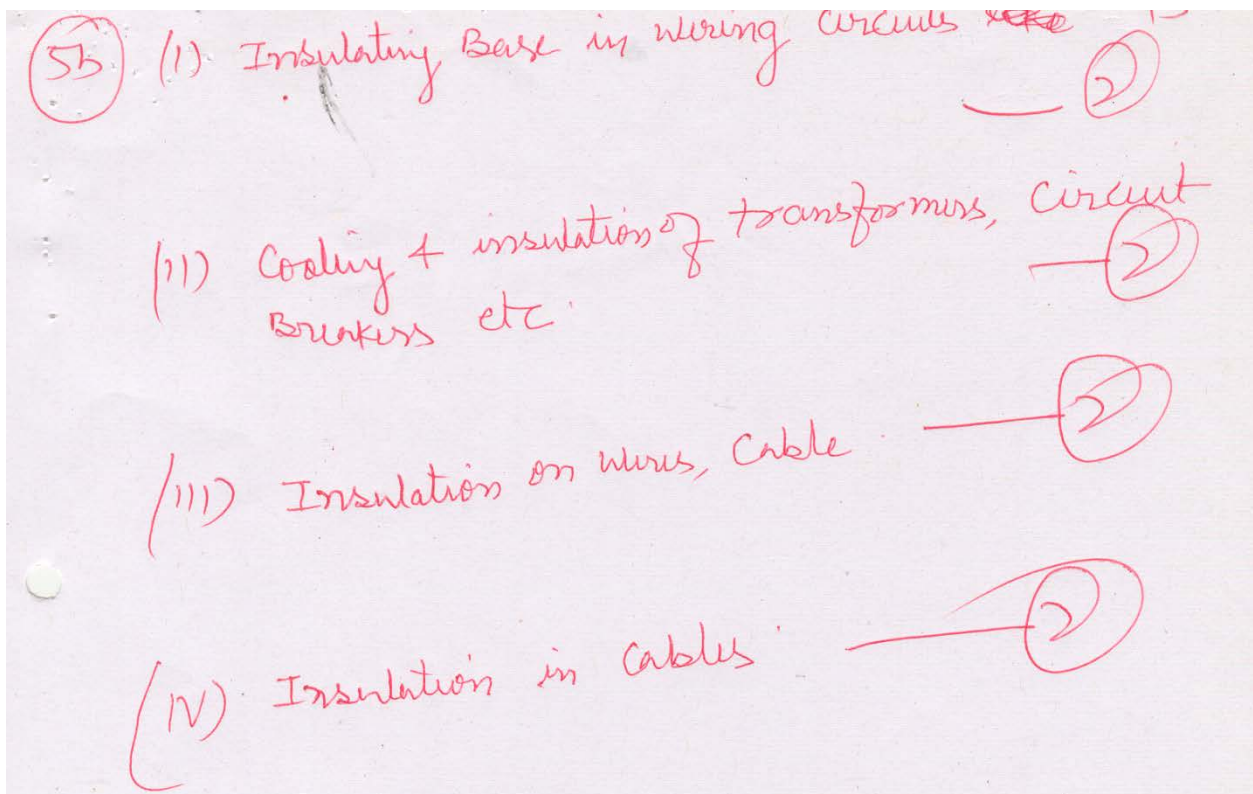
This expression shows that the dipole moment is proportional to the volume of the electron cloud. The polarisability  $\alpha$  is thus equal to  $4\pi\epsilon_0 a^3$ . ... (5)

Finally using equation (2) the dielectric constant of a mono-atomic gas may be expressed as

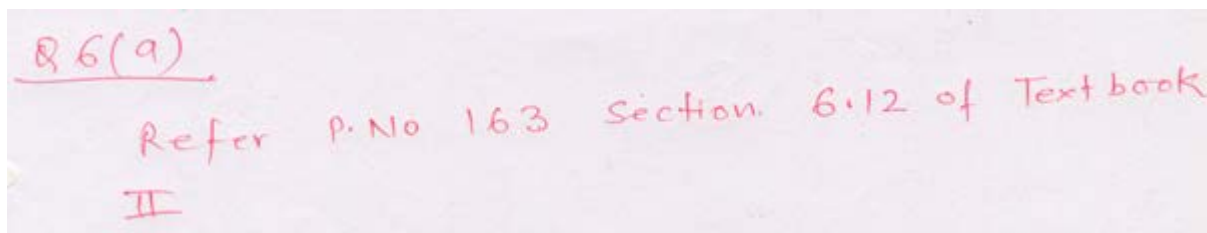
**b. Write specific applications of the following :**

- (i) Wood
- (ii) Transformer Oil
- (iii) PVC
- (iv) Polythene



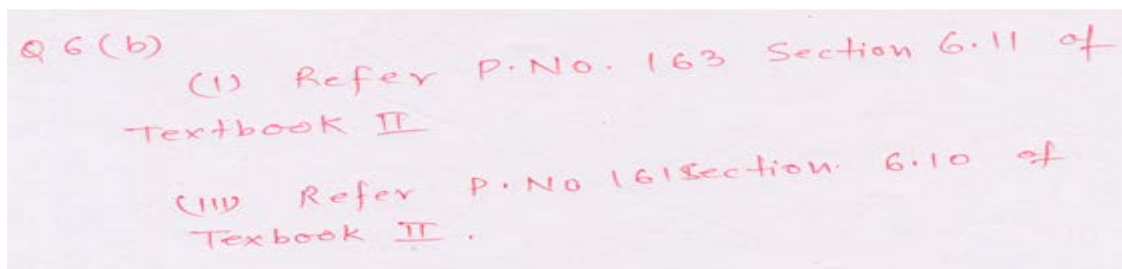


Q.6 a. Discuss the factors affecting permeability of Hysterisis Loss.



b. Define the following:

- (i) Magnetostriction
- (ii) Magnetic Resonance
- (iii) Hysterisis Loop



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MAGNETIC PROPERTIES OF MATERIALS

223

6.16. Magnetic resonance.

A rotating body will produce a kinetic moment along the axis of rotation. This kinetic moment is proportional to the speed of rotation. The rate of change of the kinetic moment with time is equal to the couple of the applied force.

An electron having a mass and spin will give rise to both magnetic moment and kinetic moment. If  $M$  is the magnetic moment and  $P$  is the kinetic moment then the gyromagnetic ratio is given by

$$\gamma = M/P$$

The electron will rotate in a fixed direction along the axis  $OC$  (Fig. 6.22), when an external field is applied. If an external field  $H$  is applied along the  $OZ$  axis : this magnetic field exerts a couple

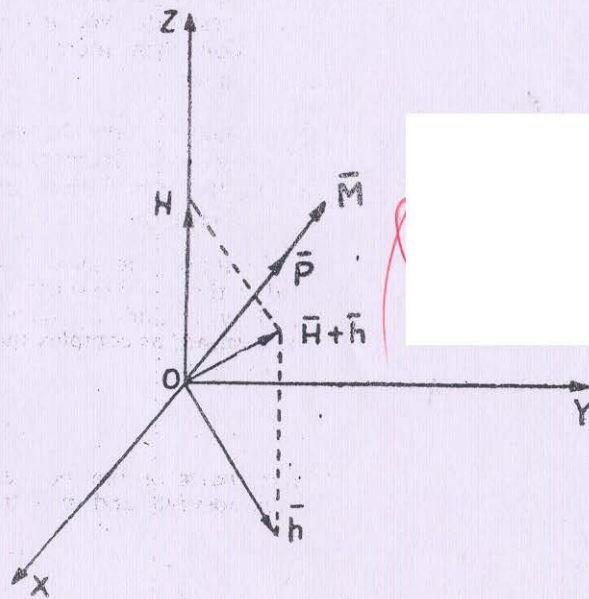


Fig.

on moment  $M$ , that is

$$C = dP/dt = \vec{M} \times \vec{H}$$

Also  $dP/dt = -\frac{1}{\gamma} \frac{d\vec{M}}{dt}$

Therefore  $-\frac{1}{\gamma} \frac{d\vec{M}}{dt} = \vec{M} \times \vec{H}$

**Q.7 a. What do you mean by energy band diagram? Classify different types of materials on the basis of energy band diagram.**

Ans Refer pg no. 177 of Section 7.3 of Text Book II



b. What is Hall effect? Derive expression for Hall coefficient.

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

Fig. 7-15

electrons will drift with an average velocity  $\bar{v}_x$  in the  $x$ -direction. When a magnetic field of flux density  $B_z$  ( $\text{Wb}/\text{m}^2$ ) is superposed on the applied electric field in the  $Z$  direction the electrons will experience a Lorentz force perpendicular to  $\bar{v}_x$  and to  $B_z$ ; the magnitude of this force will be given by  $B_z (u_x) e$ . 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

$$eE_y = B_z \bar{v}_x$$

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

$$V_H = E_y \cdot a = B_z (\bar{v}_x) \cdot a.$$

The current density in the sample is given by

$$J_x = N \cdot e \cdot (\bar{v}_x)$$

where  $N$  = no. of conduction electrons/ $m^3$ .

The current density can be calculated from the total current and the cross section ( $axb$ ) of the sample.

Thus,  $J_x = I/axb = Ne(\bar{v}_x)$  ... (9)

or

$$I = Ne(\bar{v}_x)axb$$

and

$$V_H = B_z \bar{v}_x \cdot a$$
 ... (10)

Eliminating  $\bar{v}_x$  from equations (9) and (10), we have

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

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

Thus the ratio  $\pm I/Ne = E_y/(J_x \cdot B_z)$  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.

**Q.8 a. Explain breakdown of depletion layer in semiconductors.**



stitution in the relevant formulae.

#### 8.4. Breakdown phenomena in the barrier layer

If the voltage applied across the barrier layer is too large electric breakdown may occur. This may be due to the following two causes :

- (i) Zener breakdown.
- (ii) Avalanche breakdown.

(i) *Zener breakdown.* When a sufficiently large field is applied the band picture becomes as shown in Fig. 8.12 and an electron in the filled band has a probability of passing through the forbidden band into the conduction band. In the case of very narrow junctions Zener breakdown seems to occur, and in the case of wider junctions avalanche breakdown is evident. It is possible to distinguish between the two forms of breakdown because in Zener breakdown, the breakdown voltage decreases as the temperature increases and in avalanche breakdown the breakdown voltage increases as the temperature increases. Zener effect is sometimes described as internal field emission. What this means is that in a very thin junction where the field may become large with only small applied reverse bias voltage, the bands in the transition region are steeply tilted. The effect is tunnelling. Tunnelling is a purely quantum-mechanical effect which has no analogue in classical physics. The wavelike properties ascribed to the electron may

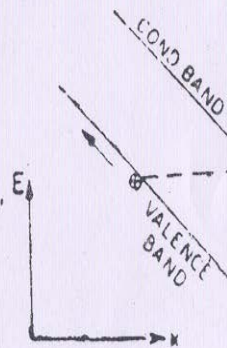


Fig. 8.12.

be used to explain tunnelling. The electron which impinges on the very thin barrier in the transition region has some probability of penetrating it. The result of such mechanism is that an appreciable number of electrons may pass right through the potential barrier formed by the forbidden band when high fields are applied. An increase in the temperature causes the forbidden band to become somewhat narrower, and thus the probability of Zener emission increases and Zener breakdown occurs at the lower voltage.

(ii) *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.

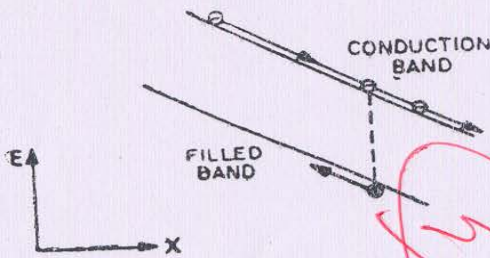


Fig. 8.13.

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  $2 \times 10^7$  volts/m for "avalanche breakdown". If the critical field strength is denoted by  $E_{crit}$ ; the avalanche breakdown will occur when  $E_{max} \geq E_{crit}$

or

$$\frac{2eN_dN_a(V_o+V)}{\epsilon_r\epsilon_o(N_a+N_d)} \geq (E_{crit})^2$$

or

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

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

assuming that all donors and acceptors are ionised and the conductivities in the *p* and *n*-regions become  $\sigma_p = N_o eU_p$  and  $\sigma_n = N_d eU_n$  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  $\sigma_p$  and  $\sigma_n$ .

**b. Write applications of the following:-**

- (i) Carbon resistor
- (ii) Paper capacitor
- (iii) Air cored inductor
- (iv) Thermal Relay



8b (i) High power dissipation resistors used in large current circuits — (2)

(ii) used in high voltage circuits — (2)

(iii) Low frequency applications — (2)

(iv) Protection of motors — (2)

MODERATION

**Q.9 a. Explain linear operation of JFET.**

100

14.9.1. Linear operation of JFET

Consider first that  $V_d$  is small enough for the conduction channel to be substantially uniform.

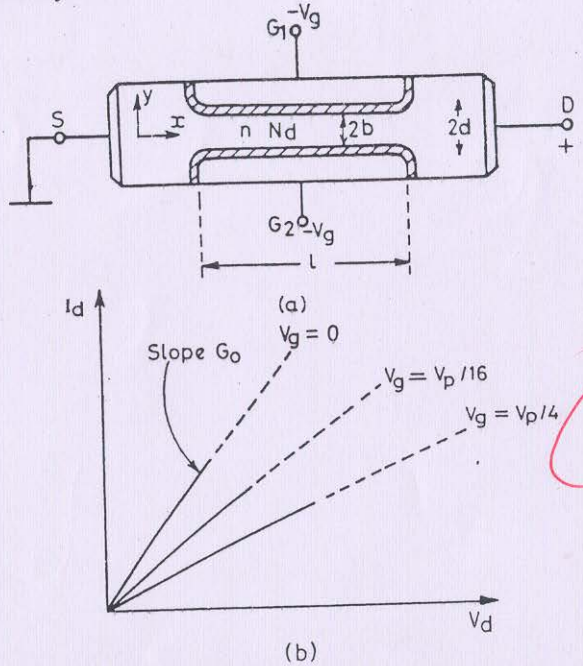


Fig. 14.13. Operation of JFET with low-drain voltage. (a) Mathematical model. (b) Linear drain characteristics.

Assume that the channel is relatively lightly doped compared with the gates i.e.  $N_a \gg N_d$  so that nearly all depletion layer thickness occurs in the  $n$ -region.

The thickness of space-charge layer

$$d_n = a - b \approx \left[ \frac{2\epsilon (V_0 + V_g)}{e N_d} \right]^{1/2} \quad \dots(14.1)$$

where  $V_0$  is the contact potential between  $n$  and  $p$ -regions. Rearranging, the channel half-thickness,

$$b = a - \left[ \frac{2\epsilon (V_0 + V_g)}{e N_d} \right]^{1/2} \quad \dots$$

Note that  $b$  decreases as  $V_g$  increases.



Pinch-off occurs when the gate voltage is just sufficient to make the conduction channel width zero or  $b = 0$ , when  $V_g = V_p$ , the pinch-off voltage. Then

$$a^2 = \frac{2\epsilon(V_0 + V_p)}{eN_d} \quad \dots(14.3)$$

or

$$V_p = \frac{eN_d a^2}{2\epsilon} - V_0 \quad \dots(14.4)$$

$b$  can be expressed in terms of pinch-off voltage as

$$b = a \left[ 1 - \left( \frac{V_0 + V_g}{V_0 + V_p} \right)^{1/2} \right] \quad \dots(14.5)$$

Conductance  $G$  of the conducting channel is

$$G = \frac{\sigma_n 2b \omega}{l} = eN_d \mu_e \frac{2b\omega}{l} \quad \dots(14.6)$$

$\omega$  = gate width

Therefore, for small drain voltage,  $V_d$ , the drain current is

$$i_d = V_d G = eN_d \mu_e \frac{2b\omega}{l} V_d$$

$$= \frac{eN_d \mu_e}{l} 2\omega a \left[ 1 - \left( \frac{V_0 + V_g}{V_0 + V_p} \right)^{1/2} \right] V_d \quad \dots(14.7)$$

It is convenient to write the drain current in terms of the channel conductance when zero gate-bias voltage is applied,  $G_0$  where

$$G_0 = \frac{\sigma_n 2a\omega}{l} = \frac{eN_d \mu_e 2a\omega}{l} \quad (14.8)$$

$$\therefore i_d = G_0 \left[ 1 - \left( \frac{V_0 + V_g}{V_0 + V_p} \right)^{1/2} \right] V_d \quad \dots(14.9)$$

At all but the lowest gate voltages,  $V_g \gg V_0$ , and in all cases except for very thin, high resistivity channels,  $V_p \gg V_0$ .

The drain-current then becomes

$$I_d = G_0 \left[ 1 - \left( \frac{V_g}{V_p} \right)^{1/2} \right] V_d \quad \dots(14.10)$$

- b. Discuss fabrication technology used in the making of semiconductor devices.

25

### 14.1. Fabrication Technology

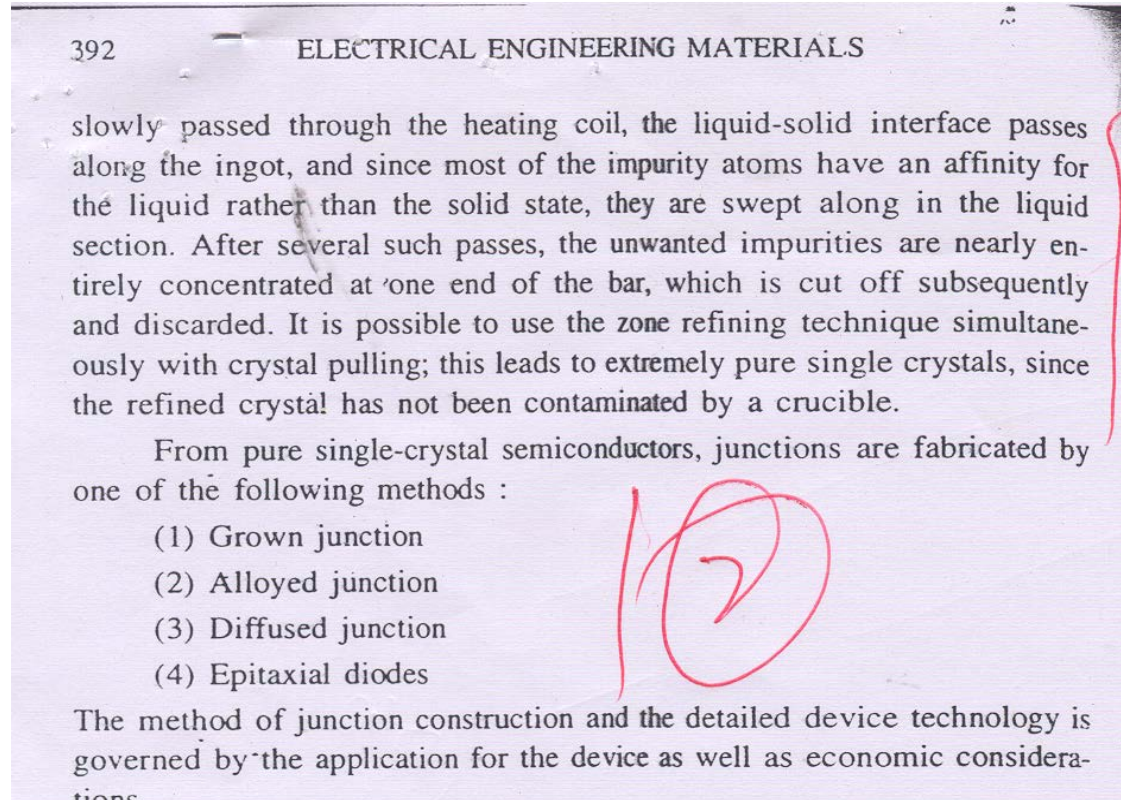
Basic fabrication technology of  $p-n$  junctions will be discussed which will help to determine the relevance and the limitations of the various approximate theories when applied to practical diodes.

Methods for growing and refining pure semiconductor single crystal samples, which are a necessary ingredient of all junction devices, will be presented.

A procedure for growing single crystals which has found wide commercial use, known as the *Czochralski method*, employs a suitably oriented *seed crystal* which is partly immersed in the *molten semiconductor*. The melt temperature is then reduced slightly until the semiconductor begins to freeze onto the seed, which is then slowly withdrawn. If the withdrawal rate and temperature are correct, the liquid-solid interface is maintained near the surface of the melt and a single-crystal ingot is pulled from it. The process is carried out in an *inert atmosphere* to prevent oxidation. A further refinement is that the seed and pulled crystal are continuously rotated to stir the melt and produce a more homogeneous crystal. It is possible to produce single crystals *several cms. in diameter* and *tens of cms. long* by this technique.

The semiconductor used for the melt is usually purified beforehand using a technique known as *zone-refining*. In this a semiconductor ingot is selectively heated locally, often using an induction heating coil so as to produce a short molten section. Surface tension prevents the material in the liquid state separating from the solid ingot. If the semiconductor is





#### Text Book

1. **Materials Science and Engineering – A First Course by V. Raghavan, Fifth Edition, Thirty-Fourth Print, April 2007 Edition, Prentice-Hall Of India Pvt Ltd**
2. **Introduction to Electrical Engineering Materials by C.S. Indulkar and S. Thiruvengadam, 4th Edition, Reprint 2006, S. Chand and Company Ltd**