

OBJECTIVE:

- To enrich the understanding of various types of materials and their applications in engineering and technology

INTENDED OUTCOME:

		Bloom's Level
C203.1	Explain the ideas of classical and quantum electron theories and energy band structures.	K
C203.2	Illustrate the basics of semiconductor physics and its related concepts.	K
C203.3	Compare the different magnetic materials, its properties and infer its role in various fields.	K
C203.4	Identify the properties of superconducting materials and its engineering applications.	S
C203.5	Extend the various polarization techniques and applications of dielectric materials.	K
C203.6	Summarize the basics of nano structures and synthesizing techniques	K

UNIT I CONDUCTING MATERIALS**(9)**

Conductors – classical free electron theory of metals – Electrical and thermal conductivity – Wiedemann – Franz law – Lorentz number – Draw backs of classical theory – Quantum theory – Fermi distribution function – Effect of temperature on Fermi Function – Density of energy states – carrier concentration in metals.

UNIT II SEMICONDUCTING MATERIALS**(9)**

Intrinsic semiconductor – carrier concentration derivation – Fermi level – Variation of Fermi level with temperature – electrical conductivity – band gap determination – extrinsic semiconductors – carrier concentration derivation in n-type semiconductor – variation of Fermi level with temperature and impurity concentration – compound semiconductors – Hall effect – Determination of Hall coefficient – Applications.

UNIT III MAGNETIC AND SUPERCONDUCTING MATERIALS**(9)**

Origin of magnetic moment – Dia and para magnetism – Ferro magnetism – Domain theory – Hysteresis – soft and hard magnetic materials – anti – ferromagnetic materials – Ferrites – applications.
Superconductivity : properties - Types of super conductors – BCS theory of superconductivity(Qualitative) - High Temperature superconductors – Applications of superconductors – magnetic levitation.

UNIT IV DIELECTRIC MATERIALS**(9)**

Electrical susceptibility – dielectric constant – electronic, ionic, orientational and space charge polarization – frequency and temperature dependence of polarisation – internal field – Claussius – Mosotti relation (derivation) – dielectric loss – dielectric breakdown – Applications of dielectric materials – ferroelectricity and applications.

UNIT V ADVANCED MATERIALS**(9)**

Metallic glasses: preparation, properties and applications.
Shape memory alloys (SMA): Characteristics, properties of NiTi alloy, applications.
Composite materials, Aircraft materials and non-metallic materials.

Nano materials: synthesis – Physical and chemical vapour deposition – ball milling - properties of nanoparticles and applications. Carbon nanotubes: structure – properties and applications.

Total- 45

TEXT BOOK:

S.NO	AUTHOR(S) NAME	TITLE OF THE BOOK	PUBLISHER	YEAR OF PUBLICATION
1	Ganesan.S and Baskar.T	Engineering Physics II	GEMS Publisher, Coimbatore-641 001	2 nd Edition-2015

REFERENCES:

S.NO	AUTHOR(S) NAME	TITLE OF THE BOOK	PUBLISHER	YEAR OF PUBLICATION
1	William D Callister Jr	Material Science and Engineering-An Introduction	John Wiley & Sons Inc., New York.	9 th Edition 2013
2	James F Shackelford	Introduction to Materials Science for Engineers	Macmillan Publication Company, New York	8 th Edition 2014
3	Charles Kittel	Introduction to Solid State Physics	John Wiley & sons, Singapore.	8 th Edition 2005

WEBSITES:

<ol style="list-style-type: none"> 1. www.nptel.ac.in 2. www.physicsclassroom.com 3. www.oyc.yale.edu 4. www.physics.org

KARPAGAM UNIVERSITY
COIMBATORE-641 021
DEPARTMENT OF SCIENCE AND HUMANITIES
LECTURE PLAN

SUBJECT: MATERIALS SCIENCE
SUBJECT CODE: 15BECC203/15BTCC203

TOTAL HOURS -52

UNIT-I CONDUCTING MATERIALS HOURS REQUIRED -10

S.No	Topics	Hours
1.	Introduction about conducting materials, Classical free electron theory of metals	1
2.	Electrical conductivity of metals	1
3.	Thermal conductivity of metals	1
4.	Wiedemann – Franz law , Lorentz number	1
5.	Tutorial–I	1
6.	Draw backs of classical theory , Quantum theory	1
7.	Fermi distribution function	1
8.	Effect of temperature on Fermi Function	1
9.	Density of energy states – carrier concentration in metals.	1
10.	Cycle test	1

UNIT-II SEMICONDUCTING MATERIALS HOURS REQUIRED -10

S.No	Topics	Hours
11.	Introduction about semiconductors	1
12.	Intrinsic semiconductor, carrier concentration derivation	1
13.	Fermi level , Variation of Fermi level with temperature	1
14.	Electrical conductivity , band gap determination	1
15.	Tutorial-II	1
16.	Extrinsic semiconductors	1
17.	Carrier concentration derivation in n-type semiconductor	1
18.	Compound semiconductors , Variation of Fermi level with temperature and impurity concentration	1
19.	Hall effect Determination of Hall coefficient , Applications	1
20.	Cycle test	1

UNIT-III MAGNETIC AND SUPERCONDUCTING MATERIALS

HOURS REQUIRED -12

S.No	Topics	Hours
21.	Origin of magnetic moment	1
22.	Bohr magneton , Dia and para magnetism	1

23.	Ferro magnetism	1
24.	Domain theory, Hysteresis	1
25.	Tutorial-III	1
26.	Soft and hard magnetic materials,	1
27.	Anti, ferromagnetic materials, Ferrites & applications	
28.	Properties of superconducting materials and Types of super conductors	1
29.	BCS theory of superconductivity (Qualitative).	1
30.	High Temperature superconductors.	1
31.	Applications of superconductors – SQUID, cryotron, magnetic levitation.	1
32.	Cycle test	1

UNIT-IV DIELECTRIC MATERIALS

HOURS REQUIRED -10

S.No	Topics	Hours
33.	Introduction about dielectric materials	1
34.	Electrical susceptibility – dielectric constant	1
35.	Electronic, ionic, orientational and space charge polarization	1
36.	Frequency and temperature dependence of polarization	1
37.	Internal field	1
38.	Tutorial-IV	1
39.	Claussius – Mosotti relation (derivation)	1
40.	Dielectric loss – dielectric breakdown, Applications of dielectric materials	1
41.	Ferroelectricity and applications	1
42.	Cycle test	1

UNIT-V ADVANCED MATERIALS

HOURS REQUIRED -10

S.No	Topics	Hours
43.	Basics of glass materials, Preparation of metallic glasses, properties and applications.	1
44.	Characteristics Shape memory alloys (SMA), Properties of NiTi alloy and Application, advantages and disadvantages of SMA	1
45.	Introduction and applications Composite materials	1
46.	Tutorial-V	1
47.	Synthesis of Nanomaterials, Top down and bottom up approach.	1
48.	Physical and Chemical vapour deposition,	1
49.	Sol-gels , Electrodeposition & Ball milling	
50.	Properties of nanoparticles and Applications.	1
51.	Structure carbon nanotubes, Properties and applications of carbon nanotubes.	1
52.	Cycle test	1

UNIT II

ELECTRONIC MATERIALS

INTRODUCTION

Materials can be broadly classified into three types based on conductivity. They are,

1. Conductors (Example: metals),
2. Semi – conductors (Example: germanium, silicon) and
3. Insulators (Example: wood, mica, glass).

Conductors:

- Conductivity is the ability or power to conduct or transmit heat, electricity, or sound.
- Conductors are materials that electricity easily passes through, that do not resist the flow of electricity.
- Examples are copper, aluminum, steel, silver, gold, electrolytes.
- Low resistive materials are generally called as conducting materials.
- The conducting property of the solid is due to valence electrons or free electrons.

ELECTRON THEORY OF METALS

The electron theory of metals explain the following concepts

- Structural, electrical and thermal properties of materials.
- Elasticity, cohesive force and binding in solids.
- Behaviour of conductors, semi conductors, insulators etc.

So far **three electron theories** have been proposed.

1. Classical Free electron theory

- It is a macroscopic theory.
- Proposed by Drude and Lorentz in 1900.
- It explains the free electrons in lattice
- It obeys the laws of classical mechanics.

2. Quantum Free electron theory

- It is a microscopic theory.
- Proposed by Sommerfield in 1928.
- It explains that the electrons move in a constant potential.
- It obeys the Quantum laws.

3. Brillouin Zone theory or Band theory:

- Proposed by Bloch in 1928.
- It explains that the electrons move in a periodic potential.
- It also explains the mechanism of semi conductivity, based on bands and hence called band theory.

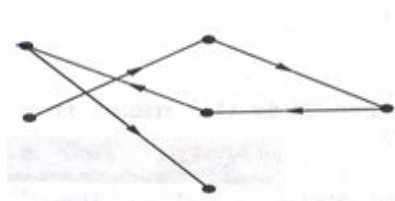
CLASSICAL FREE ELECTRON THEORY OF METALS

After the discovery of electron, Drude and Lorentz attempted for an explanation of electrical and thermal conductivities based on the assumption that metal contains a certain number of free electrons and hence called **free electron theory**. All the free electrons freely move in the crystal like molecules of a gas in a container. Mutual repulsion between electrons is ignored and hence potential energy is taken as zero. Therefore the total energy of the electron is equal to its kinetic energy.

Postulates of Classical free electron theory:

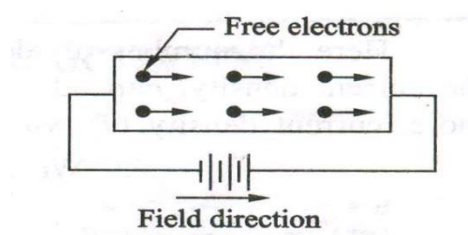
In the absence of Electric field:

All the atoms are composed of atoms. Each atom have central nucleus around which there are revolving electrons. The electrons are free to move in all possible directions about the whole volume of metals. In the absence of an electric field the electrons move in random directions making collisions from time to time with positive ions which are fixed in the lattice or other free electrons. All the collisions are elastic i.e.; no loss of energy.



In the presence of Electric field:

When an external field is applied the free electrons are slowly drifting towards the positive potential. Since the electrons are assumed to be a perfect gas they obey classical kinetic theory of gasses. Classical free electrons in the metal obey Maxwell-Boltzmann statistics.



Drift velocity (V_d):

The average velocity acquired by the free electron in a particular direction due to the application of electric field is called as Drift velocity.

Mobility (μ):

Mobility is defined as the drift velocity acquired by the free electrons per unit electric field (E) applied to it.

$$\mu = \frac{V_d}{E}$$

Where, l is the distance travelled by the electron.

Relaxation time (τ):

It is the time taken by the free electron to reach its equilibrium position from its disturbed position in the presence of applied field.

$$\tau = \frac{l}{V_d}$$

Collision time (τ_c):

It is the average time taken by the free electron between two successive collision.

$$\tau = \frac{\lambda}{v}$$

Where, λ is the mean free path.

Mean free path:

The average distance travelled between two successive collisions is called mean free path.

(i.e) $\lambda = \bar{c}\tau_c$, where \bar{c} is the root mean square velocity of the electron.

QUANTUM FREE ELECTRON THEORY

Classical free electron theory could not explain many physical properties. In 1928, Sommerfeld developed a new theory applying quantum mechanical concepts and Fermi-Dirac statistics to the free electrons in the metal. This theory is called quantum free electron theory. Classical free electron theory permits all electrons to gain energy. But quantum free electron theory permits only a fraction of electrons to gain energy.

According to Classical free electron theory the particles (electrons) of a gas at zero kelvin will have zero kinetic energy and hence all the particles are found to be in rest. But according to quantum theory when all the particles are at rest, all of them should be filled only in the ground state energy level, which is impossible and is controversial to the Pauli's exclusion principle.

Thus inorder to fill the electrons in a given energy level, we should know the following.

- i. Energy distribution of electrons
- ii. Number of available energy states
- iii. Number of filled energy states
- iv. Probability of filling an electron in a given energy state

As the “free electron gas” obeys Fermi-Dirac statistics, all the above can be very easily determined using it.

Fermi energy level (E_F)

Fermi energy level is the maximum energy level upto which the electrons can be filled at 0K.

Importance:

1. Fermi energy level act as a reference level which seperates the vacant and filled states at 0K.
2. It gives the information about the filled electron states and the empty states.
3. At 0K, below Fermi energy level electrons are filled at above Fermi energy level it will be empty.
4. When the temperature is increased, few electron gains the thermal energy and it goes to higher energy levels.

FERMI DISTRIBUTION FUNCTION

Fermi distribution function $F(E)$ represents the probability of an electron occupying a given energy state. To find out the energy states actually occupied by the free electron at any temperature (T) we can apply the Fermi – Dirac statistics. The Fermi – Dirac statistics deals with the particles (Electrons) having half integral spin, named as Fermions.

$$F(E) = \frac{1}{1 + e^{\left(\frac{E - E_F}{K_B T}\right)}} \quad \dots(1)$$

Where E_F is the Fermi energy

K_B is the Boltzmann constant

EFFECT OF TEMPERATURE ON FERMION FUNCTION

The effect of temperature on Fermi function $F(E)$ can be discussed with respect to equation (1).

(i) At 0 kelvin

At 0 kelvin, the electrons can be filled only upto a maximum energy level called Fermi energy (E_{F_0}), above E_{F_0} all the energy levels will be empty. It can be proved from the following conditions.

(i) When $E < E_F$, equation (1) becomes,

$$F(E) = \frac{1}{1+e^{-\infty}} = \frac{1}{1} = 1$$

[i.e., 100% chance for the electron to be filled within the Fermi energy level]

(ii) When $E > E_F$, equation (1) becomes,

$$F(E) = \frac{1}{1+e^{\infty}} = \frac{1}{\infty} = 0$$

[i.e Zero % chance for the electron not to be filled within the Fermi energy level]

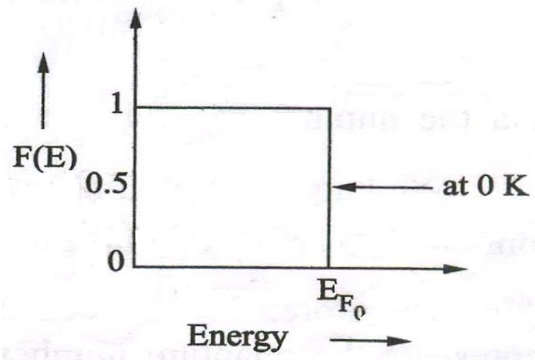
(i) When $E = E_F$, equation (1) becomes,

$$F(E) = \frac{1}{1+1} = \frac{1}{2} = 0.5$$

[i.e 50% chance for the electron to be filled and not to be filled within the Fermi energy level]

This clearly shows that 0 kelvin all the energy states below E_{F_0} are filled and all those above it are empty.

The Fermi function at 0 kelvin (E_{F_0}) can also be represented graphically as shown in fig. It is seen from the figure that the curve has step-like character at 0 kelvin.

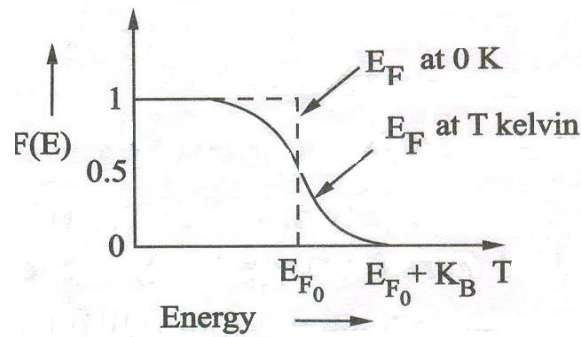


(i.e) $F(E) = 1$ below (E_{F_0})

and $F(E) = 0$ above (E_{F_0})

(i) At any temperature T kelvin:

When the temperature is raised slowly from absolute zero, the Fermi distribution function smoothly decreases to zero as shown in fig.



Explanation:

Due to the supply of thermal energy the electrons within the range of $K_B T$ below the Fermi level (E_{F_0}) alone takes the energy ($=K_B T$) and goes to higher energy state. Hence at any temperature (T), empty states will also be available below E_{F_0} .

DENSITY OF STATES AND CARRIER CONCENTRATION IN METALS

The Fermi Function $F(E)$ gives only the probability of filling up of electrons in a given energy state, it does not give the information about the number of electrons that can be filled in a given energy state. To know that we should know the number of available energy states so called density of states.

Definition:

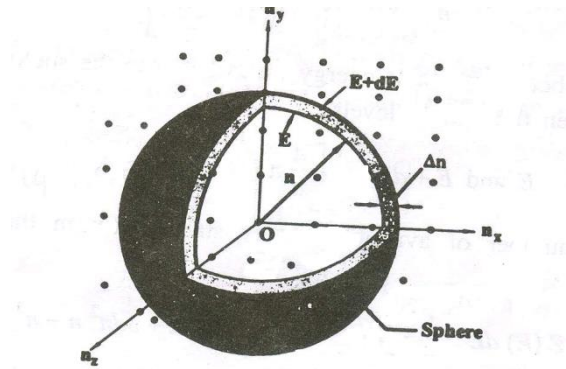
Density of States $Z(E) dE$ is defined as the number of available energy states per unit volume in an energy interval (dE).

Explanation:

In order to fill the electrons in an energy state we have to first find the number of available energy states within a given energy interval.

We know that a number of available energy levels can be obtained for various combinations of quantum numbers n_x , n_y and n_z ((i.e) $n^2 = n_x^2 + n_y^2 + n_z^2$)

Therefore, let us construct a three dimensional space of points which represents the quantum numbers as shown in fig. In this space each point represents an energy level.



Number of energy levels in a cubical metal piece:

To find the energy levels in a cubical metal piece and to find the number of electrons that can be filled in a given energy level, let us construct a sphere of radius 'n' in the space.

The sphere is further divided into many shells and each of this shell represents a particular combination of quantum numbers (n_x , n_y and n_z) and therefore represents a particular energy value.

Let us consider two energy values E and E+dE. The number of energy states between E and E+dE can be found by finding the number of energy states between the shells of radius n and n+, from the origin.

The number of available energy states within the sphere of radius

$$'n' = \left[\frac{4}{3} \pi n^3 \right]$$

Since we will have only positive values, we have to take only one octant of the sphere (i.e) $1/8^{\text{th}}$ of the sphere volume.

The number of available energy states within the sphere of radius

$$'n' = \frac{1}{8} \left[\frac{4}{3} \pi n^3 \right]$$

Similarly, the number of available energy states within the sphere of radius

$$n + dn = \frac{1}{8} \left[\frac{4}{3} \pi (n + dn)^3 \right]$$

Therefore, the number of available energy states between the shells of radius n and n + dn (or) between the energy levels E and E + dE

$$= \frac{1}{8} \left[\frac{4}{3} \pi (n+dn)^3 - \frac{4}{3} \pi n^3 \right]$$

(i.e) The number of available energy states between the energy interval dE is

$$Z(E) dE = \frac{1}{8} \frac{4\pi}{3} (n^3 + 3n^2 dn + 3n dn^2 + dn^3 - n^3)$$

Since the higher powers of dn are very small, dn^2 and dn^3 terms can be neglected.

$$Z(E) dE = \frac{\pi}{6} 3n^2 dn$$

(or)

$$Z(E) dE = \frac{\pi}{2} n^2 dn \quad \dots (1)$$

We know the energy of the electron in a cubical metal piece of sides 'l',

$$E = \frac{n^2 h^2}{8ml^2}$$

$$(or) \quad n^2 = \frac{8ml^2 E}{h^2} \quad \dots (2)$$

$$n = \left[\frac{8ml^2 E}{h^2} \right]^{1/2} \quad \dots (3)$$

Differentiating equation (2) we get

$$2n dn = \frac{8ml^2}{h^2} dE$$

$$n dn = \frac{8ml^2 E}{2h^2} dE \quad \dots (4)$$

Equation (1) can be written as

$$Z(E) dE = \frac{\pi}{2} n(n dn)$$

Substituting equation (3) and (4) in the above equation we have

$$\begin{aligned} Z(E) dE &= \frac{\pi}{2} \left[\frac{8ml^2 E}{h^2} \right]^{1/2} \left[\frac{8ml^2}{2h^2} \right] dE \\ &= \frac{\pi}{2} \cdot \frac{1}{2} \left[\frac{8ml^2 E}{h^2} \right]^{1/2} \left[\frac{8ml^2}{2h^2} \right] dE \\ &= \frac{\pi}{4} \left[\frac{8ml^2}{h^2} \right]^{3/2} E^{1/2} dE \\ Z(E) dE &= \frac{\pi}{4} \left[\frac{8m}{h^2} \right]^{3/2} E^{1/2} l^3 dE \end{aligned}$$

Here l^3 represents the volume of the metal piece.

If $l^3 = 1$, then we can write that

The number of available energy states per unit volume (i.e) Density of states.

$$Z(E) dE = \frac{\pi}{4} \left[\frac{8m}{h^2} \right]^{3/2} E^{1/2} dE \quad \dots (5)$$

Since each energy level provides 2 electron states one with spin up and another with spin down (Pauli's exclusion principle), we have

Density of states

$$Z(E) dE = 2 \cdot \frac{\pi}{4} \left[\frac{8m}{h^2} \right]^{3/2} E^{1/2} dE$$

$$Z(E)dE = \frac{\pi}{2} \left[\frac{8m}{h^2} \right]^{3/2} E^{1/2} dE \quad \dots(6)$$

CARRIER CONCENTRATION IN METALS

Let $N(E) dE$ represents the number of filled energy states between the interval of energy dE . Normally all the energy states will not be filled. The probability of filling of electrons in a given energy state is given by Fermi Function $F(E)$.

$$N(E) dE = Z(E) dE \cdot F(E) \quad \dots (7)$$

Substituting equation (6) in equation (7), we get

Number of filled energy states per unit volume

$$N(E) dE = \frac{\pi}{2} \left[\frac{8m}{h^2} \right]^{3/2} E^{1/2} dE \cdot F(E) \quad \dots(8)$$

$N(E)$ is known as carrier distribution function (or) Carrier concentration in metals.

Fermi Energy at 0 Kelvin:

We know at 0K maximum energy level that can occupied by the electron is called Fermi energy level (E_{F_0})

(i.e) at 0 Kelvin for $E < E_F$ and

Therefore $F(E) = 1$

Integrating equation (8) within the limits 0 to E_{F_0} we can get the number of energy states electrons (N) within the Fermi energy E_{F_0}

$$\begin{aligned} \int N(E) dE &= \frac{\pi}{2} \left[\frac{8m}{h^2} \right]^{3/2} \int_0^{E_{F_0}} E^{1/2} E \cdot dE \\ &= \frac{\pi}{2} \left(\frac{8m}{h^2} \right)^{3/2} \frac{E_{F_0}^{3/2}}{3/2} \end{aligned}$$

$$\text{(or) Number of filled energy states at zero} = \frac{\pi}{3} \left(\frac{8m}{h^2} \right)^{3/2} E_{F_0}^{3/2} \quad \dots(9)$$

(or)

$$E_{F_0}^{3/2} = \frac{3N}{\pi} \left(\frac{h^2}{8m} \right)^{3/2}$$

$$\text{Fermi energy} \quad E_{F_0} = \frac{h^2}{8m} \left(\frac{3N}{\pi} \right)^{2/3} \quad \dots(10)$$

Average energy of an electron at 0K:

Average energy of an electron

$$(E_{\text{ave}}) = \frac{\text{Total energy of the electrons at 0K } (E_T)}{\text{Number of energy states at 0K } (N)} \quad \dots(11)$$

Here, the total energy of the electrons at 0K = (Number of energy states at 0K) X (Energy of the electron)

$$\begin{aligned} \text{(i.e.) } E_T &= \int_0^{E_{F_0}} N(E) dE \cdot E \\ &= \frac{\pi}{2} \left(\frac{8m}{h^2} \right)^{\frac{3}{2}} \int_0^{E_{F_0}} E^{\frac{1}{2}} E \cdot dE \quad [F(E) = 1] \\ &= \frac{\pi}{2} \left(\frac{8m}{h^2} \right)^{\frac{3}{2}} \frac{E_{F_0}^{\frac{5}{2}}}{\frac{5}{2}} \\ E_T &= \frac{\pi}{5} \left(\frac{8m}{h^2} \right)^{\frac{3}{2}} E_{F_0}^{\frac{5}{2}} \quad \dots(12) \end{aligned}$$

Substituting equation 9 and 12 in 11 we get

$$\begin{aligned} E_{\text{ave}} &= \frac{\frac{\pi}{5} \left(\frac{8m}{h^2} \right)^{\frac{3}{2}} E_{F_0}^{\frac{5}{2}}}{\frac{\pi}{3} \left(\frac{8m}{h^2} \right)^{\frac{3}{2}} E_{F_0}^{\frac{3}{2}}} \\ E_{\text{ave}} &= \frac{3}{5} E_{F_0}^{\frac{5}{2}} E_{F_0}^{\frac{-3}{2}} \end{aligned}$$

The average energy of an electron at 0K is $E_{\text{ave}} = \frac{3}{5} E_{F_0}$

ENERGY BAND THEORY OF SOLIDS

Energy band theory of solids plays a very important role in determining whether a solid is a conductor, insulator or a semiconductor. This theory explains how an energy band occurs in a solid.

i. FREE AND BOUND ELECTRONS

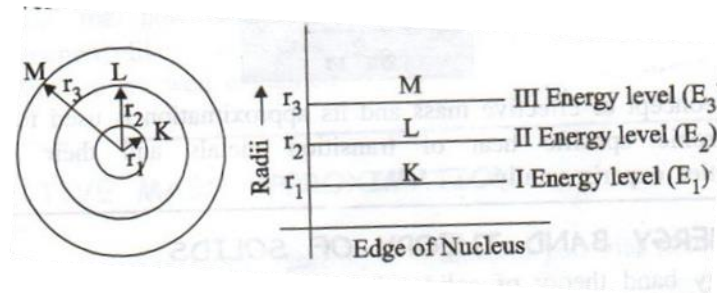
In an isolated atom all the electron are tightly bounded within the central positive nucleus and revolves around various orbits. The number of electrons at outer most orbit are called valence electrons. In the outer most orbits, the attractive force between the nucleus and electrons will be very less, so that electrons can be easily detached from the nucleus. These detached electrons from the outer shell orbits are called free electrons. But in innermost orbits electrons are tightly bound to the nucleus, and hence they are called as bound electrons. The free and bound electrons as shown in figure.

ii. ENERGY LEVELS

We know that each orbit of an atom has fixed amount of energy associated with it. The electrons moving in a particular orbit possess the energy of orbit. The larger the orbit, the greater is its energy. So, the outermost orbit of electrons possess more energy than inner orbit electrons.

The energy of different orbits are called energy levels. As shown in figure.

Let E_1 be the energy level of K-shell, E_2 be the energy level of M-shell, E_3 be the energy level of L-shell and so on.

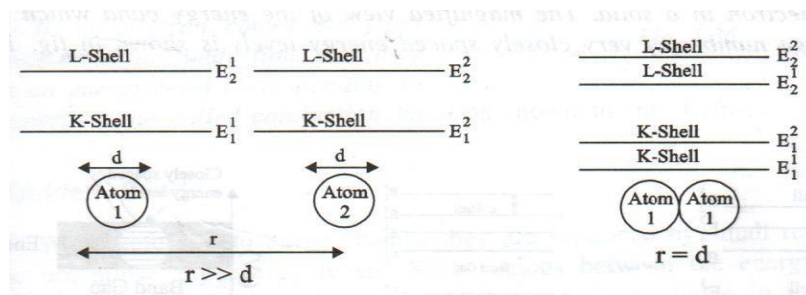


From the figure, it is clear that the electrons can revolve only in certain permitted orbits of radii r_1, r_2, r_3, \dots and not in arbitrary orbit.

1. Therefore the electrons cannot fill in spacing of energy levels.
2. Electrons fill the lowest energy levels first. A specific quantity of energy must be supplied to move an electron to the next higher level.
3. Pauli Exclusion Principle states that no two electrons can occupy the same quantum state. Not more than two electrons can occupy any one energy level.

iii. ENERGY BANDS:

A set of closed spaced energy levels is called an energy band. let us consider two identical atoms of diameter (d) separated at a distance (r), so that electronic energy levels of one atom [E_1^1 (K-shell) and E_2^1 (L-shell)] do not affect the electronic energy levels of the other atom [E_1^2 (K-shell) and E_2^2 (L-shell)] as shown in figure.



Now, when we bring the atoms close together, some force of attraction occurs between them and according to quantum mechanics, their wave functions will start overlapping, therefore the two atoms are brought closer, it does not remain as two independent atoms, rather it forms a single two-atom system with two different energy levels to form energy band as shown in figure.

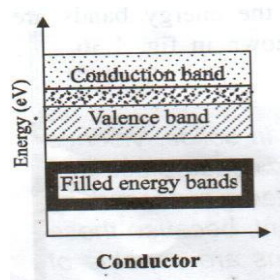
CLASSIFICATION OF MATERIALS INTO METALS, SEMICONDUCTORS AND INSULATORS ON THE BASIS OF BAND THEORY:

Based on band theory, and on the basis of presence of forbidden band gap the materials are classified into three categories, viz.

- i. Metals (or) Conductors
- ii. Semiconductors
- iii. Insulators

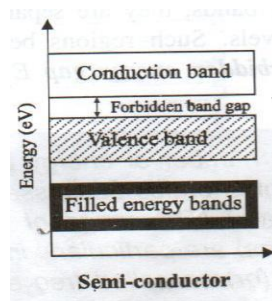
i. Metals (or) Conductors

In conductors, there is no forbidden energy gap. Here the valence band and conduction band overlap each other as shown in figure a. In metals the availability of free electrons will be very high due to the overlapping of conduction band and valence band. Hence even small field is applied to it, the electrons in valence band freely enter into the conduction band and produce current. **EX. Copper, Aluminium, Iron.,**



ii. Semiconductors

In Semiconductors, the forbidden energy gap is very small, in the order 0.5eV to 1.5eV and hence there will be a very small gap between the valence and conduction band as shown in figure b. **Ex. Ge, Si.**



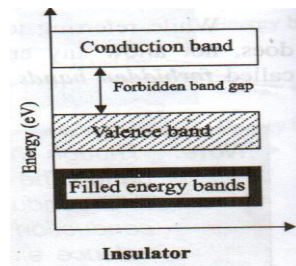
Generally, in Semiconductors the availability of free electrons in conduction band will be less compared to metals, due to the presence of forbidden band gap between the valence band and

conduction band. Therefore, when external field of energy, equal to (or) greater than forbidden band gap energy (E_g) is applied to a semiconductor, immediately the conduction will take place.

iii. Insulators

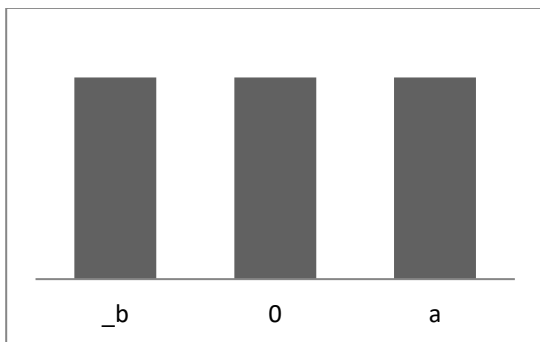
Insulators, the forbidden band gap is very wide, in the range of 3 eV to 5.47 eV and hence there will be very large gap between the valence band and conduction band as shown in figure c. Since the forbidden band gap is very very high in the case of insulators, so that very large amount of external field is required for conduction to occur.

Ex: Diamond, Dielectrics etc..



KRONIG PENNY MODEL

The Kronig Penny model is simplified model for an electron in one dimensional periodic potential the possible states that the electron can occupy are determined by Schrodinger equation.



The corresponding Schrodinger equation for the two regions I and II

$$\frac{d^2 \psi}{dx^2} + \frac{8\pi^2 m}{h^2} E \psi = 0 \quad , \quad 0 < x < a$$

$$\frac{d^2 \psi}{dx^2} + \alpha^2 \psi = 0 \quad \text{_____} (1)$$

$$\alpha^2 = \frac{8\pi^2 m}{h^2} E \quad \text{_____}(2)$$

$$\frac{d^2 \Psi}{dx^2} + \frac{8\pi^2 m}{h^2} (E - V_0) \Psi = 0 \quad -b < x < 0$$

$$\frac{d^2 \Psi}{dx^2} + \beta^2 \Psi = 0 \quad \text{_____}(3)$$

$$\beta^2 = \frac{8\pi^2 m}{h^2} (E - V_0) \quad \text{_____}(4)$$

The general solution of the above equation (1) , (3)

$$\Psi_1(x) = Ae^{i\alpha x} + Be^{-i\alpha x} \quad \text{_____}(5)$$

$$\Psi_2(x) = Ce^{\beta x} + De^{-\beta x} \quad \text{_____}(6)$$

Where A, B, C, D are arbitrary constants. The expected solution of the above Schroedinger equation must have the same form as that of Bloch function.

Now applying boundary condition we obtain the following modified equation

$$A + B = C + D$$

$$i\alpha (A - B) = \beta (C - D)$$

$$Ce^{\beta b} + De^{-\beta b} = e^{ik(a+b)}[Ae^{i\alpha a} + Be^{-i\alpha a}]$$

$$\beta Ce^{\beta b} + \beta De^{-\beta b} = i\alpha e^{ik(a+b)}[Ae^{i\alpha a} - Be^{-i\alpha a}]$$

The solution of above equation can be found by following determinant.

$$\begin{vmatrix} 1 & 1 & -1 & -1 \\ i\alpha & -i\alpha & -\beta & \beta \\ -e^{ik(a+b)+i\alpha a} & -e^{ik(a+b)-i\alpha a} & e^{-\beta b} & e^{\beta b} \\ -i\alpha e^{ik(a+b)+i\alpha a} & i\alpha e^{ik(a+b)-i\alpha a} & \beta e^{-\beta b} & \beta e^{\beta b} \end{vmatrix} = 0 \quad \text{_____}(7)$$

On simplifying this determinant we obtain

$$\cos ka = \left(\frac{\beta^2 - \alpha^2}{2\alpha\beta} \right) \beta b \sin \alpha a \sinh \beta b + \cos \alpha a \cosh \beta b \quad \text{_____}(8)$$

In order to simplify above equation Kronig Penny assumes that the potential energy is 0 at lattice sites and equals to V_0 inbetween them hence equation (8) becomes

$$\cos ka = \left(\frac{\beta^2 - \alpha^2}{2\alpha\beta} \right) \beta b \sin \alpha a + \cos \alpha a \quad \text{_____}(9)$$

$$\begin{aligned} \beta^2 - \alpha^2 &= \frac{8\pi^2 m}{h^2} (E - V_0) - \frac{8\pi^2 m}{h^2} E \\ &= \frac{8\pi^2 m V_0}{h^2} \quad \text{_____}(10) \end{aligned}$$

Sub. Eqn (10) in (9)

$$\cos ka = \frac{8\pi^2 m V_0}{2\alpha \beta h^2} \beta b \sin \alpha a + \cos \alpha a$$

$$\cos ka = P b \frac{\sin \alpha a}{\alpha a} + \cos \alpha a \quad \text{_____ (11)}$$

$$\text{Where } P = \frac{4\pi^2 m V_0 b}{h^2}$$

$$P \frac{\sin \alpha a}{\alpha a} = 0$$

$$\frac{\sin \alpha a}{\alpha a} = 0$$

$$\sin \alpha a = 0$$

$$\alpha a = \sin^{-1}(0) = n\pi$$

$$\alpha = \frac{n\pi}{a}$$

$$\alpha^2 = \frac{n^2 \pi^2}{a^2} \quad \text{_____ (12)}$$

Comparing equations (2) and (12)

$$\frac{n^2 \pi^2}{a^2} = \frac{8\pi^2 m}{h^2} E \quad \text{_____ (13)}$$

$$E = \frac{n^2 \pi^2}{8a^2 m}$$

Effective mass of electron:

The mass acquired by an electron when it is accelerated in a periodic potential is called effective mass of an electron.

When an electron is accelerated by an electrical or magnetic field in a periodic potential, the mass of an electron is not a constant. But, it varies with respect to the field applied. This varying mass is called effective mass (m^*).

Consider a crystal subjected to an electric field of intensity 'E'. Due to this applied field, the electron gains a velocity which can be

PROBLEMS

1. Energy required to remove an electron from sodium metal is 2.3e V. Does Sodium exhibit photoelectric effect from an orange light having wavelength 2800Å?

Solution:

Given: 2800 Å, $E_g = 2.3$

Energy required to remove an electron from sodium = 2.3

$$E = hv = \frac{hc}{\lambda}$$
$$= \frac{6.625 \times 10^{-34} \times 3 \times 10^8}{2800 \times 10^{-10} \times 1.6 \times 10^{-19}}$$

By using orange light having wavelength 2800 the energy produced is

Since, the above calculated energy 4.4 e V i.e energy produced is greater than the required (i.e) 2.3e

V. **Sodium exhibits photo-electric effect** from an orange light having wavelength 2800 Å

2. Calculate the drift velocity of electrons in copper and current density in wire of diameter 0.16cm which carries a steady current of 10A. Given $n = 8.46 \times 10^{28}/m^3$

Solution:

Current density $J = \frac{\text{Current}}{\text{Area of cross section}}$

$$= \frac{10}{\frac{\pi \times (0.16 \times 10^{-2})^2}{4}}$$

$$J = 497.3 \times 10^4 \text{ A/m}^2$$

UNIT III

SEMICONDUCTORS

INTRODUCTION

The materials are classified on the basis of conductivity and resistivity. The resistivity of a semiconductor is in the order of 10^{-4} to 0.5 ohm-metre. A semiconductor is a solid which has the energy band similar to that of an insulator. It acts as an insulator at absolute zero and as a conductor at high temperatures and in the presence of impurities.

PROPERTIES OF SEMICONDUCTOR

1. The resistivity of semiconductors lies between conducting and insulating materials. (i.e.,) 10^{-4} to 0.5 ohm-metre.
2. At 0K they behave as insulators.
3. When the temperature is raised or when impurities are added, their conductivity increases.

$$\text{i.e., } \rho \propto 1/T$$

4. They have negative temperature co-efficient of resistances.
5. Total conductivity (σ) = $\sigma_e + \sigma_h$

Where, σ_e – conductivity due to electrons

σ_h - Conductivity due to holes

6. They are formed by covalent bond.
7. They have empty conduction band at ok.
8. They have almost filled valence band.
9. They small energy gap.
10. If impurities add in semiconductor, the electrical conductivity increases. When the temperature is increased, electrical conductivity is decreases.

CLASSIFICATION OF SEMICONDUCTORS

There are two types

i. Elemental Semiconductors

ii. Compound Semiconductors

Elemental semiconductors

Elemental semiconductors are made up of single element and are called as indirect band gap semiconductors. Heat is produced during recombination process. Ex: Ge, Si

Compound semiconductors

Compound semiconductors are made up of compounds and are called as direct band gap semiconductors. Photons are emitted during recombination process.

Ex: GaP, MgO

TYPES OF SEMICONDUCTORS

Based on the purity, semiconductors are classified into the following two types:

- i. Intrinsic semiconductor
- ii. Extrinsic semiconductor

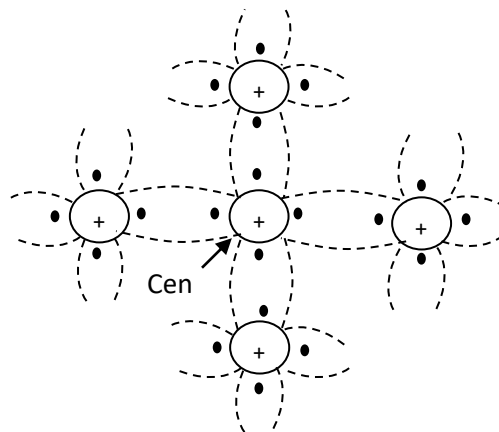
INTRINSIC SEMICONDUCTOR

A semiconductor in an extremely pure form is called as intrinsic semiconductors.

Ex: Ge, Si

Let us consider two atoms of Germanium brought closer to each other. Now the positive core of one atom interacts with one of the electrons from the other atom and the two electrons are shared by two atoms. These electrons are called Electron Pairs. When the attractive force is balanced, by the repulsive force between the two positive cores, a covalent bond is formed.

Explanation

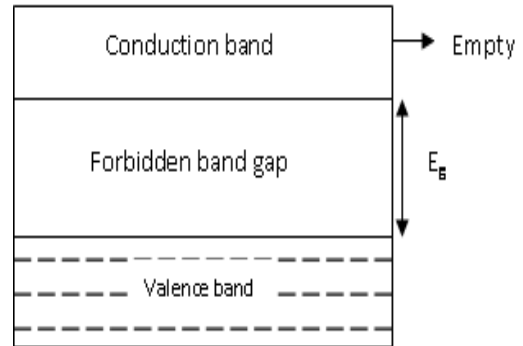


- In the case of Ge or Si we have 4 valence electrons.
- It is the tendency of each germanium atom to have 8 electrons in the outer most shell.
- To do so, each germanium atom arranges itself between four other germanium atoms as shown in fig.
- Here neighbouring atoms share one valence electron with the central atom.
- So, by this sharing, the central atom completes its last orbit by having 8 electrons.
- Hence all the four valence electrons of the central atom gets tightly bound to the nucleus.
- Similar such bonding occurs among all the other atoms giving rise to extremely stable structure and hence has low conductivity.
- In these semiconductors the electrons and holes can be created only by thermal agitation.
- As there are no impurities the number of free electrons must be equal to the number of holes.

Effect of Temperature on intrinsic semiconductors

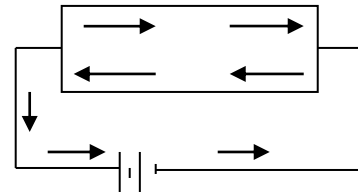
i. At absolute zero:

- At absolute zero, all the electrons are tightly bound to the nucleus.
- The inner orbit electrons are bound, whereas the valence electrons are bonded, with covalent bond, with other atoms.
- Hence at absolute zero, no valence electron can reach the conduction band to become free electron.
- So the valence band is completely filled and the conduction band is empty.



ii. At absolute zero:

- At absolute zero, all the electrons are tightly bound to the nucleus.
- The inner orbit electrons are bound, whereas the valence electrons are bonded, with covalent bond, with other atoms.
- Hence at absolute zero, no valence electron can reach the conduction band to become free electron.
- So the valence band is completely filled and the conduction band is empty.



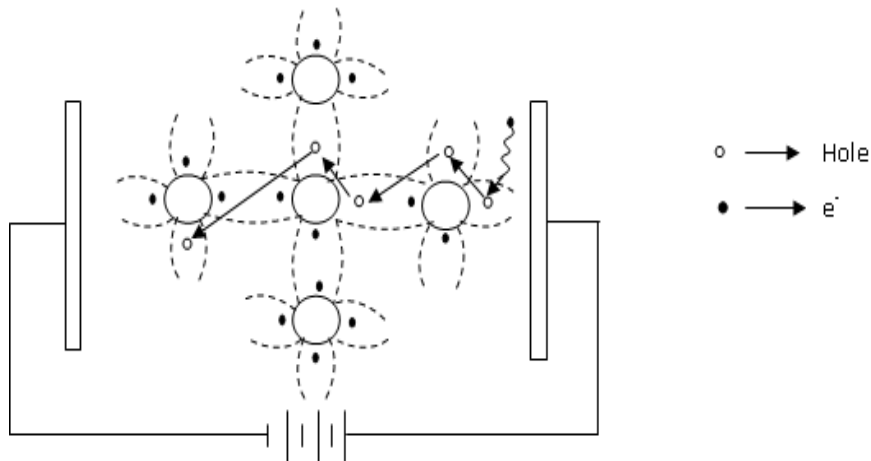
iii. Above absolute zero:

- When the temperature is raised some of the covalent bonds break due to thermal energy supplied.
- Due to the breaking of bonds the electrons are released from the covalent bonds and become free electrons.
- Now if a potential difference is applied across the semiconductor, these free electrons move with respect to field direction and produce a tiny electric current as shown in fig.
- This shows that the resistance of semiconductor decreases with the rise in temperature. i.e., it has **Negative temperature co efficient of resistance**.
- The no. of free electrons that move to conduction band will be exactly equal to the number of holes created in the valence band.

Hole Current

- Similar to the normal current which is due to free electrons another current called the hole current also flows in the semiconductor.

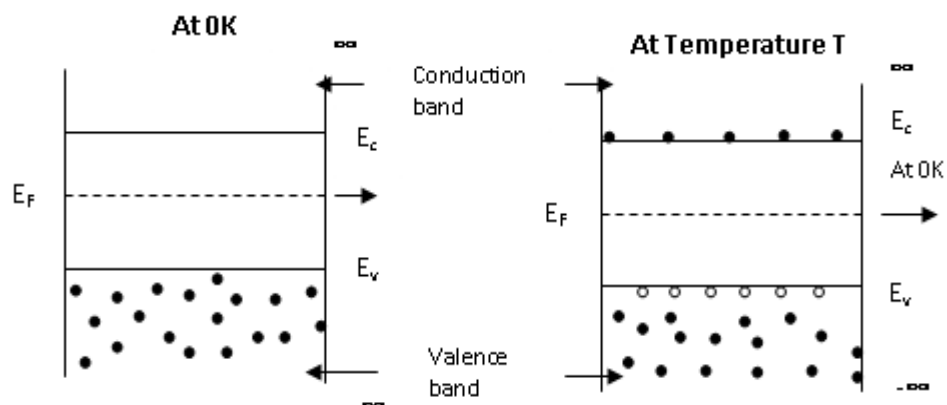
- Due to thermal energy if one electron enters conduction band from valence band, one hole is created in the valence band. Due to thermal energy hole- electron pairs are created.



- Definition: It is noted that hole current is due to the movement of valence electrons from one covalent bond to another bond.

CARRIER CONCENTRATION IN INTRINSIC SEMICONDUCTORS

- We know at 0 K intrinsic pure semiconductor behaves as insulator.
- But as temperature increases some electrons move from valence band to conduction band as shown in figure.
- Therefore both electrons in conduction band and holes in valence band will contribute to electrical conductivity.
- Assume that electron in the conduction band is a free electron of mass m_e^* and the hole in the valence band behaves as a free particle of mass m_h^* .
- The electrons in the conduction band have energies lying from E_c to ∞ and holes in the valence band have energies from $-\infty$ to E_v as shown in figure.



- Here E_c represents the energy of the bottom (or) lowest level of conduction band and E_v represents the energy of top (or) the highest level of the valence band.

Density of electrons in conduction band

$$\text{Density of electrons in conduction band } n_e = \int_{E_c}^{\infty} Z(E) \cdot F(E) dE \quad \dots\dots\dots (1)$$

From Fermi-Dirac statistics we can write

$$Z(E)dE = 2 \cdot \frac{\pi}{4} \left[\frac{8m_e^*}{h^2} \right]^{\frac{3}{2}} E^{\frac{1}{2}} dE \quad \dots\dots\dots (2)$$

Considering minimum energy of conduction band as E_c and the maximum energy can go upto ∞ we can write eqn (2) as

$$Z(E)dE = \frac{\pi}{2} \left[\frac{8m_e^*}{h^2} \right]^{\frac{3}{2}} (E - E_c)^{\frac{1}{2}} dE \quad \dots\dots\dots (3)$$

$$\text{We know Fermi function, } F(E) = \frac{1}{1 + e^{(E-E_F)/TK_B}} \quad \dots\dots\dots (4)$$

Sub. Eqn (4) and (3) in eqn (1) we have Density of electrons in conduction band within the limits E_c to ∞

$$n_e = \frac{\pi}{2} \left[\frac{8m_e^*}{h^2} \right]^{\frac{3}{2}} \int_{E_c}^{\infty} \frac{(E-E_c)^{\frac{1}{2}}}{1 + e^{(E-E_F)/TK_B}} \cdot dE \quad \dots\dots\dots (5)$$

Since to move an electron from valence band to conduction band the energy required is greater than $4K_B T$. (i.e) $e^{(E-E_F)/TK_B} \gg 1$ & $1 + e^{(E-E_F)/TK_B} = e^{(E-E_F)/TK_B}$

Eqn. (5) becomes

$$n_e = \frac{\pi}{2} \left[\frac{8m_e^*}{h^2} \right]^{\frac{3}{2}} \int_{E_c}^{\infty} (E - E_c)^{\frac{1}{2}} \cdot e^{(E-E_F)/TK_B} dE \quad \dots\dots\dots (6)$$

Let us assume that $E-E_c = xK_B T$ Differentiating we get $dE = K_B T \cdot dx$,

Limits: when $E=E_c$; $x=0$, when $E=\infty$; $x=\infty$ Therefore limits are 0 to ∞

By solving Eqn (6) using this limits we can get,

$$\text{Density of electrons in conduction band is } n_e = 2 \left[\frac{2\pi m_e^* K_B T}{h^2} \right]^{\frac{3}{2}} \cdot e^{(E-E_F)/TK_B} \quad \dots\dots\dots (7)$$

Density of holes in valence band

- We know, $F(E)$ represents the probability of filled state.
- As the maximum probability will be 1, the probability of unfilled states will be $[1-F(E)]$
- Example, if $F(E) = 0.8$, then $1-F(E) = 0.2$
- Let the maximum energy in valence band be E_v and the minimum energy be $-\infty$. So density of holes in valence band n_h is given by

$$n_h = \int_{-\infty}^{E_v} Z(E) \cdot [1 - F(E)] dE \quad \dots\dots\dots (8)$$

$$\text{We know } Z(E)dE = \frac{\pi}{2} \left[\frac{8m_e^*}{h^2} \right]^{\frac{3}{2}} (E - E_c)^{\frac{1}{2}} dE \quad \dots\dots\dots (9)$$

$$1-F(E) = e^{(E-E_F)/TK_B} \quad \dots\dots\dots (10)$$

Sub eqn (10) and (9) in (8), we get

$$n_h = \frac{\pi}{2} \left[\frac{8m_h^*}{h^2} \right]^{\frac{3}{2}} \int_{-\infty}^{E_v} (E - E_c)^{\frac{1}{2}} \cdot e^{(E-E_F)/TK_B} dE \quad \dots\dots\dots (11)$$

Let us assume that $E_v - E = xK_B T$ Differentiating we get $dE = -K_B T \cdot dx$,

Limits: when $E = -\infty$; we have $E_v - (-\infty) = x$ Therefore $x = \infty$

When $E = E_v$; $x = 0$,

Therefore limits are ∞ to 0

Using these limits we can solve eqn (11) and we can get the Density of holes.

Density of holes in valence band is

$$n_h = 2 \left[\frac{2\pi m_h^* K_B T}{h^2} \right]^{\frac{3}{2}} \cdot e^{(E_v - E_F)/TK_B} \quad \dots\dots\dots (12)$$

VARIATION OF FERMI ENERGY LEVEL AND CARRIER CONCENTRATION WITH TEMPERATURE IN AN INTRINSIC SEMICONDUCTOR

For an intrinsic semiconductor number of electrons (i.e.,) electron density will be the same as that of number of holes (i.e.,) hole density.

$$(i.e.,) n_e = n_h$$

Equating equns (7) and (12), we can write

$$[m_e^*]^{\frac{3}{2}} \cdot e^{(E - E_F)/TK_B} = [m_h^*]^{\frac{3}{2}} \cdot e^{(E_v - E_F)/TK_B}$$

By solving this equn and taking log on both sides we can get

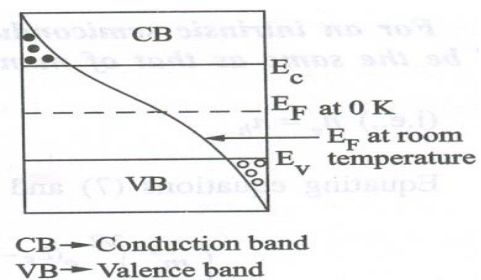
$$E_F = \frac{E_c + E_v}{2} + \frac{3}{4} K_B T \log\left(\frac{m_h^*}{m_e^*}\right) \quad \dots\dots\dots (13)$$

If $m_h^* = m_e^*$, then $\log\left(\frac{m_h^*}{m_e^*}\right) = 0$

and equn (13) becomes

$$E_F = \frac{E_c + E_v}{2} \quad \dots\dots\dots (14)$$

The Fermi energy level lies in the midway between E_c and E_v as shown in figure. But in actual case $m_h^* > m_e^*$ and Fermi energy level slightly increases with the increase in temperature as shown in figure.



Density of electrons and holes interms of E_g

In terms of energy gap (E_g) where $E_g = E_c - E_v$ we can get the expression of n_e and n_h by substituting the value of E_F in terms of E_c and E_v .

Substituting equation (13) in (7) we get

$$\begin{aligned}
 n_e &= 2 \left(\frac{2\pi m_e^* K_B T}{h^2} \right)^{3/2} \exp \left[\frac{\frac{E_c + E_v}{2} + \frac{3}{4} K_B T \log_e \left(\frac{m_h^*}{m_e^*} \right) - E_c}{K_B T} \right] \\
 &= 2 \left(\frac{2\pi K_B T}{h^2} \right)^{3/2} (m_e^*)^{3/2} \exp \left[\frac{2E_c + 2E_v + 3K_B T \log_e \left(\frac{m_h^*}{m_e^*} \right) - 4E_c}{4K_B T} \right] \\
 &= 2 \left(\frac{2\pi K_B T}{h^2} \right)^{3/2} (m_e^*)^{3/2} \exp \left[\frac{2(E_v - E_c)}{4K_B T} + \frac{3}{4} \log_e \left(\frac{m_h^*}{m_e^*} \right) \right]
 \end{aligned}$$

Since $E_g = E_c - E_v$, we can write

$$n_e = 2 \left\{ \frac{2\pi K_B T}{h^2} \right\}^{3/2} (m_e^*)^{3/2} \exp \left[\frac{-E_g}{2K_B T} + \log_e \left(\frac{m_h^*}{m_e^*} \right)^{3/4} \right]$$

$$(\text{or}) \quad n_e = 2 \left\{ \frac{2\pi K_B T}{h^2} \right\}^{3/2} (m_e^*)^{3/2} \frac{(m_h^*)^{3/4}}{(m_e^*)^{3/4}} e^{-E_g/2K_B T}$$

$$(\text{or}) \quad n_e = 2 \left\{ \frac{2\pi K_B T}{h^2} \right\}^{3/2} (m_e^*)^{3/4} (m_h^*)^{3/4} e^{-E_g/2K_B T}$$

$$n_e = 2 \left\{ \frac{2\pi K_B T}{h^2} \right\}^{3/2} (m_e^* m_h^*)^{3/4} e^{-E_g/2K_B T} \quad \dots(15)$$

Similarly by substituting equation (13) in (12) we get

$$n_h = 2 \left\{ \frac{2\pi K_B T}{h^2} \right\}^{3/2} (m_h^* m_e^*)^{3/4} e^{-E_g/2K_B T} \quad \dots(16)$$

Thus, it is found that $n_e = n_h = n_i$ where n_i is the intrinsic carrier concentration.

Results

- » In an intrinsic semiconductor the density of electrons in conduction band is equal to the density of holes in valence band. (i.e.,) $n_e = n_h$
- » n_e and n_h increases exponentially as the temperature increases.

Intrinsic Carrier Concentration

We know that, $n_i = n_e = n_h$ and $n_i^2 = n_e \cdot n_h$

Substituting from equations (15) and (16), we have

$$\begin{aligned}
 n_i^2 &= 2^2 \left[\left\{ \frac{2\pi K_B T}{h^2} \right\}^{3/2} \right]^2 \left[(m_h^* \cdot m_e^*)^{3/4} e^{-E_g/2K_B T} \right]^2 \\
 n_i^2 &= 4 \left[\frac{2\pi K_B T}{h^2} \right]^3 (m_e^* m_h^*)^{3/2} e^{-E_g/K_B T} \\
 \text{(or)} \quad n_i &= 2 \left[\frac{2\pi K_B T}{h^2} \right]^{3/2} (m_e^* m_h^*)^{3/4} e^{-E_g/2K_B T} \quad \dots(17)
 \end{aligned}$$

Therefore for intrinsic semiconductor even if impurity is added to increase n_e there will be decrease in n_h and hence the product $n_p n_h$ will remain constant. This is called law of mass action.

MOBILITY AND ELECTRICAL CONDUCTIVITY OF INTRINSIC SEMICONDUCTORS

The electrical conductivity of an intrinsic semiconductor in terms of mobility of charge carriers is given by,

$$\text{The electrical conductivity } \sigma_i = n_i e (\mu_e + \mu_h) \quad \dots\dots\dots(1)$$

Where

n_i is intrinsic carrier concentration

e is charge of electron

μ_e is mobility of electrons

μ_h is mobility of holes.

According to intrinsic carrier concentration

$$\sigma = 2e \left\{ \frac{2\pi K_B T}{h^2} \right\}^{3/2} (m_h^* \cdot m_e^*) e^{-\frac{E_g}{2K_B T}} (\mu_e + \mu_h)$$

Here the electrical conductivity depends on the exponential of forbidden energy gap between valence band and conduction band and on the mobility of charge carriers, both μ_e and μ_h .

But the term $(\mu_e + \mu_h)$ has temperature dependence and it will cancel with the $T^{3/2}$ term and hence we can write

$$\sigma_i = Ce^{-E_g/2K_B T} \quad \dots\dots\dots (2)$$

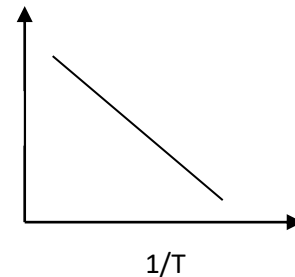
Where, C is a constant.

Taking log on both sides we have

$$\log \sigma_i = \log C - (E_g/2K_B T)$$

If a plot is made between $\log \sigma_i$ and $1/T$ we get a straight line.

Here σ_i increases with temperature as shown in figure.



DETERMINATION OF BAND GAP ENERGY

We know for intrinsic semiconductor $\sigma_i = Ce^{-E_g/2K_B T}$

We know resistivity $\rho_i = 1/\text{Conductivity}$

$$\rho_i = \frac{1}{C} e^{E_g/2K_B T} \quad \dots\dots\dots (1)$$

We know resistivity is resistance per unit area per unit length

$$\rho_i = \frac{R_i a}{l} \quad \dots\dots\dots (2)$$

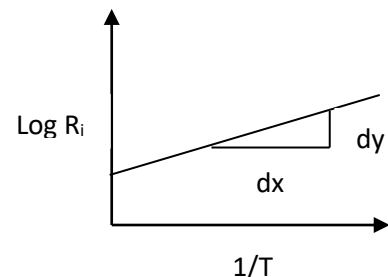
Where ρ_i – Resistance,

a – Cross sectional area,

l – Length

Equating eqns (1) and (2) and Taking log on both sides we get,

$$\log R_i = \log C_1 + (E_g/2K_B T)$$



The resistance can be found using meter bridge or Carey

Foster's bridge or post office box experiments at various temperatures.

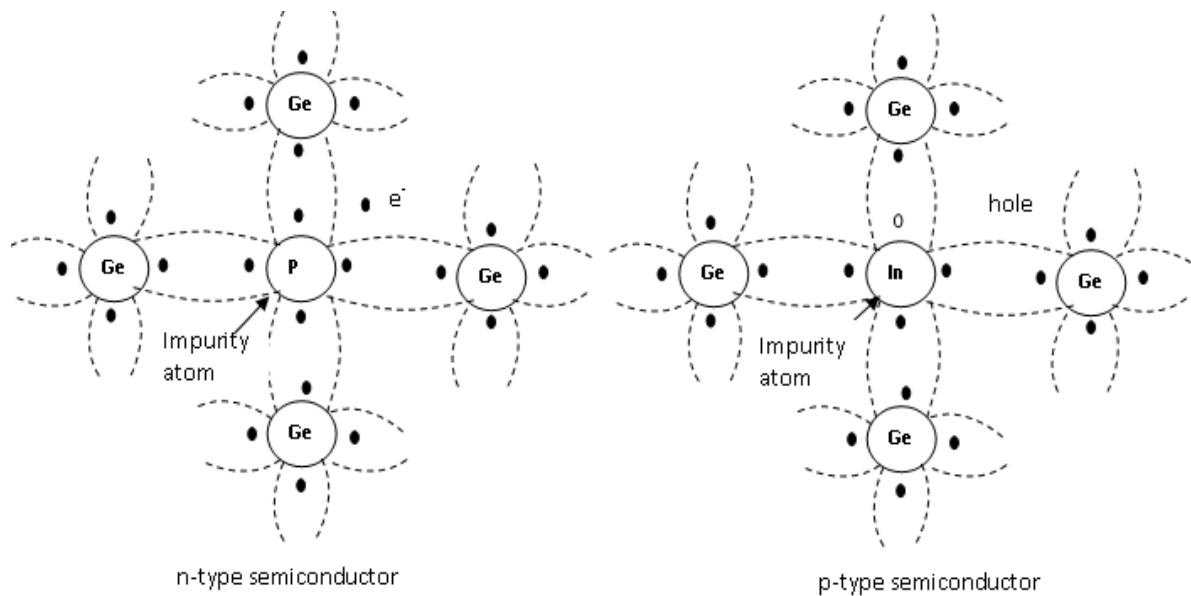
If a graph is plotted between $1/T$ and $\log R_i$ a straight line is obtained as shown in figure, with a slope $dy/dx = E_g/2K_B$.

Therefore by finding the slope of line we can calculate the energy band gap E_g with the following expression.

$$E_g = 2K_B(dy/dx) \text{ Joules}$$

EXTRINSIC SEMICONDUCTOR

- Impure semiconductors in which the charge carriers are produced due to impurity atoms are called extrinsic semiconductors.
- They are obtained by doping an intrinsic semiconductor with impurity atoms.
- Based on the type of impurity added they are classified into n-type semiconductor and p-type semiconductor.



(i) n-type semiconductor

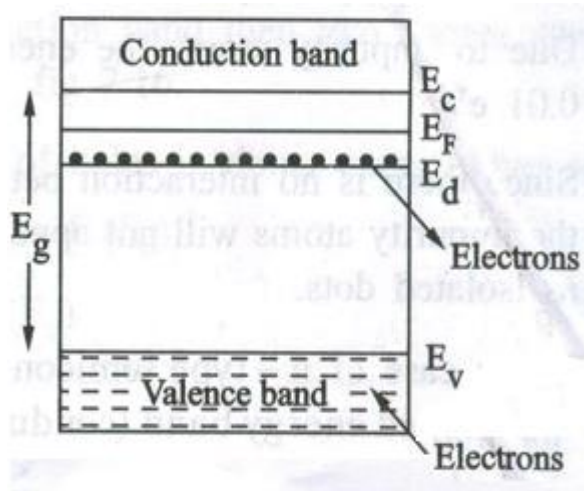
- N-type semiconductor is obtained by doping an intrinsic semiconductor with pentavalent impurity atoms like phosphorus, arsenic, antimony, etc.,
- The four valence electrons of the impurity atoms bond with 4 valence electrons of the semiconductor atom and the remaining 1 electron of the impurity atom is left free as shown in figure.
- Since electrons are donated in this type of semiconductor the energy level of these donated electrons is called donor energy level (E_d) as shown in figure.
- E_d is very close to conduction band and hence even at room temperature the electrons are easily excited to conduction band.
- The current flow in this type of semiconductor is due to electrons.

(ii) P-type semiconductor

- P-type semiconductor is obtained by doping an intrinsic semiconductor with trivalent impurity atoms like boron, Gallium, Indium, etc.,
- The three valence electrons of the impurity atom pairs with three valence electrons of semiconductor atom and one position of the impurity atom remains vacant, this is called hole as shown in figure.
- Therefore the no. of holes is increased with the impurity atoms added to it.
- Since holes are produced in excess, they are the majority charge carriers in p-type semiconductor and electrons are the minority charge carriers.
- Since the impurity can accept the electrons this energy level is called acceptor energy level (E_a) and is present just above the valence band as shown in figure.
- Here the current conduction is mainly due to holes.

CARRIER CONCENTRATION IN N-TYPE SEMICONDUCTOR

- The energy band structure of n-type semiconductor is as shown in figure.



- At 0 K, E_F will lie exactly between E_c and E_d , but even at low temperature some electrons may go from E_d to E_c .
- Let us assume that $E_c - E_F > K_B T$.
- Then the density of electrons in conduction band can be written as

$$n_e = 2 \left[\frac{2\pi m_e^* K_B T}{h^2} \right]^{\frac{3}{2}} \cdot e^{(E - E_F)/TK_B} \dots\dots\dots (1)$$

- Let N_d be the number of donor energy levels per cm^3 (i.e.,) density of state $Z(E_d)dE$, which has energy E_d below the conduction band.
- If some of the electrons are donated from donor energy level to conduction band say for example if two electrons go to conduction band then two vacant sites will be created in E_d levels as shown in figure.
- Thus in general we can write the density of holes in donor energy level as

$$\begin{aligned} N(E_d)dE &= Z(E)dE \cdot (1 - F(E_d)) \\ n_h &= N_d (1 - F(E_d)) \dots\dots\dots (2) \end{aligned}$$

we know

$$F(E_d) = \frac{1}{1 + e^{(E_d - E_F)/TK_B}}$$

$$\text{And} \quad 1 - F(E_d) = \frac{e^{(E_d - E_F)/TK_B}}{1 + e^{(E_d - E_F)/TK_B}} \dots\dots\dots (3)$$

$$e^{(E_d - E_F)/TK_B} \ll 1$$

$$1 + e^{(E_d - E_F)/TK_B} = 1$$

Equation (3) becomes

$$1 - F(E_d) = e^{(E_d - E_F)/TK_B} \dots\dots\dots (4)$$

Substituting equn (4) in (2)

$$n_h = N_d e^{(E_d - E_F)/TK_B} \dots\dots\dots (5)$$

At equilibrium condition

No. of electrons per unit volume In conduction band	=	No. of holes per unit volume in donar energy level
--------------------------------------------------------	---	-------------------------------------------------------

Equating equn (1) & equn (5) and taking log on both sides we get

$$E_F = \frac{E_c + E_d}{2} + \frac{K_B T}{2} \log \left[\frac{N_d}{2 \left(\frac{2\pi m_e^* K_B T}{h^2} \right)} \right] \dots\dots\dots (6)$$

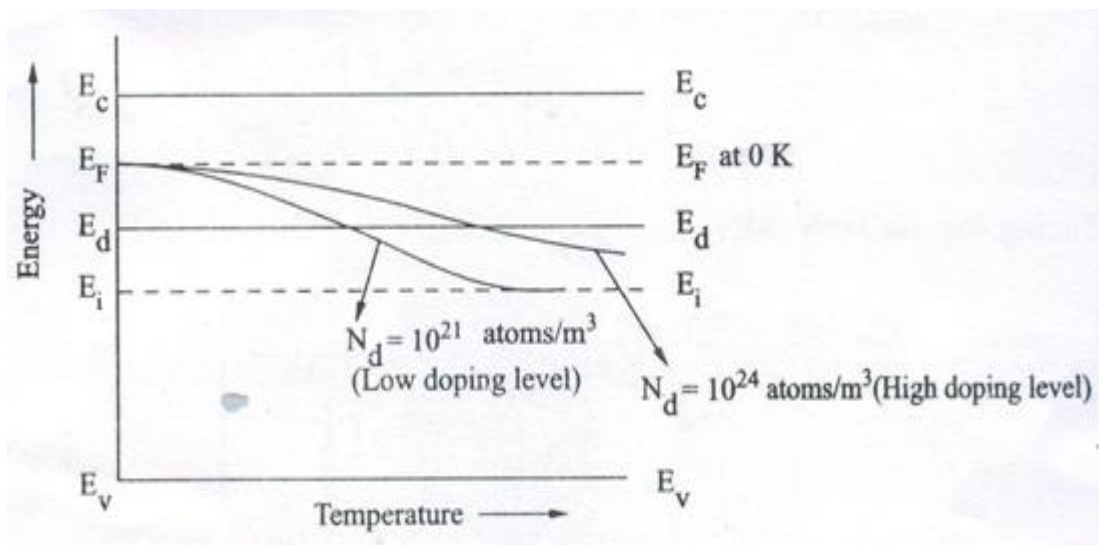
At 0K when T=0,

we can write the above equation as $E_F = (E_c + E_d)/2$ (7)

Eqn (7) shows that, at 0 K, E_F will lie exactly in the midway between E_c and E_d .

VARIATION OF FERMİ ENERGY LEVEL WITH TEMPERATURE AND IMPURITY CONCENTRATION IN n-TYPE SEMICONDUCTOR

- When the temperature is increased some electrons in E_d level may be shifted to conduction band and hence some vacant sites will be created in E_d levels.
- Therefore the Fermi level shifts down to separate that empty levels and the filled valence band level as shown in figure, for the doping level of $N_d = 10^{21}$ atoms/m³.



- From the figure it can be seen that for the same temperature, if the impurity atoms i.e., doping level is increased, the electron concentration increases and hence the Fermi level increases.

Expression for Density of Electrons in Conduction Band in terms of N_d

Substituting equation (6) in (1) we get

$$n_e = 2 \cdot \left\{ \frac{2\pi m_e^* K_B T}{h^2} \right\}^{3/2} \cdot \exp \left\{ \frac{\left(\frac{E_c + E_d}{2} + \frac{K_B T}{2} \log \left(\frac{N_d}{2 \cdot \left\{ \frac{2\pi m_e^* K_B T}{h^2} \right\}^{3/2}} \right) - E_c \right)}{K_B T} \right\}$$

$$(\text{or}) \quad n_e = 2 \left(\frac{2\pi m_e^* K_B T}{h^2} \right)^{3/2} \exp \left[\frac{E_c + E_d - 2E_c}{2K_B T} + \frac{1}{2} \log \left(\frac{N_d}{2 \left(\frac{2\pi m_e^* K_B T}{h^2} \right)^{3/2}} \right) \right]$$

$$n_e = 2 \cdot \left\{ \frac{2\pi m_e^* K_B T}{h^2} \right\}^{3/2} \cdot \exp \left[\frac{(E_d - E_c)}{2K_B T} + \log \left\{ \frac{N_d^{1/2}}{(2)^{1/2} \left[\left(\frac{2\pi m_e^* K_B T}{h^2} \right)^{3/2} \right]^{1/2}} \right\} \right]$$

$$(\text{or}) \quad n_e = 2 \left(\frac{2\pi m_e^* K_B T}{h^2} \right)^{3/2} \exp \left[\frac{E_d - E_c}{2K_B T} \right] \exp \left[\log \left\{ \frac{N_d^{1/2}}{2^{1/2} \left[\frac{2\pi m_e^* K_B T}{h^2} \right]^{3/4}} \right\} \right]$$

$$n_e = 2 \left\{ \frac{2\pi m_e^* K_B T}{h^2} \right\}^{3/2} e^{(E_d - E_c)/2K_B T} \left(\frac{N_d^{1/2}}{2^{1/2} \left\{ \frac{2\pi m_e^* K_B T}{h^2} \right\}^{3/4}} \right)$$

$$(\text{or}) \quad n_e = (2N_d)^{1/2} \left[\frac{2\pi m_e^* K_B T}{h^2} \right]^{3/4} e^{(E_d - E_c)/2K_B T}$$

Here $E_c - E_d = \Delta E$ is called as **Ionisation energy of donors** (i.e.) ΔE represents the amount of energy required to transfer an electron from donor energy level (E_d) to conduction band (E_c).

\therefore We can write

$$n_e = (2N_d)^{1/2} \left(\frac{2\pi m_e^* K_B T}{h^2} \right)^{3/4} e^{-\Delta E/2K_B T} \quad \dots(8)$$

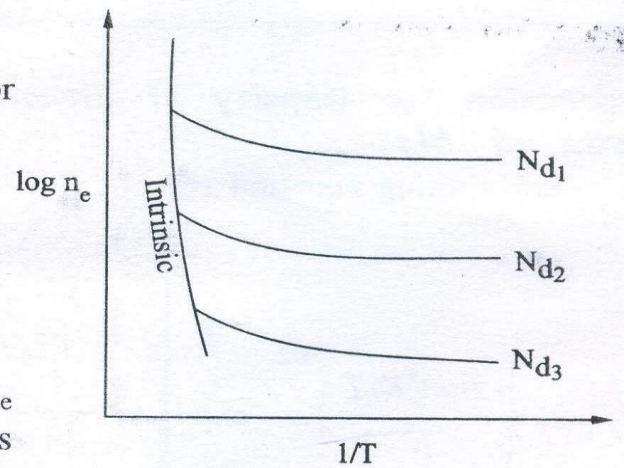
Ionisation Energy of Donor

To find the ionisation energy of donor equation (8) can be written as

$$n_e = C e^{-\Delta E/2K_B T}, \text{ where } C \text{ is a constant}$$

$$(\text{or}) \frac{\log n_e}{1/T} = -\Delta E/2K_B$$

If a graph is plotted between $\log n_e$ and $1/T$ we get lines (fig. 2.2) for various values of donor impurity levels. From the slope $-\Delta E/2K_B$, the value of ionisation energy of donor can be calculated.



Results

- » Density of electrons (n_e) in conduction band is proportional to the square root of donor concentration (N_d).
- » When temperature is increased the Fermi level falls below the donor level and may approach only upto E_i (Fermi level of the intrinsic semi conductor).

Electrical Conductivity of n-type

We know the electrical conductivity (σ) is given by

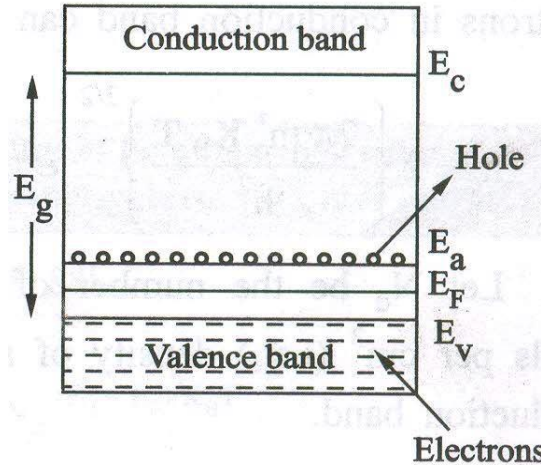
$$\sigma = n_e e (\mu_e + \mu_h)$$

For n-type semiconductor the acceptors are at the most zero. Therefore the mobility of charge carriers (holes) is zero. i.e., $\mu_h = 0$.

$$\therefore \sigma = n_e e \mu_e$$

CARRIER CONCENTRATION IN P-TYPE SEMICONDUCTOR

- For p-type at absolute zero E_f will be exactly between E_a and E_v .
- At low temperatures some electron from valence band fills the holes in the acceptor energy levels as shown in figure.



- We know the density of holes in the valence band,

$$n_h = 2 \left[\frac{2\pi m_h^* k_B T}{h^2} \right]^{\frac{3}{2}} \cdot e^{(E_v - E_F)/TK_B} \dots\dots\dots (1)$$

- Let N_a be the number of acceptor energy levels per cm^3 (i.e.,) density of state $Z(E_a)dE$, which has energy E_a below the conduction band.
- If some of the electrons are accepted by the acceptor energy level from valence band say for example if two electrons are accepted to fill the hole sites in the acceptor levels, then two holes will be created in valence band as shown in figure.
- Thus in general we can write the density of holes in donor energy level as

$$N(E_a)dE = Z(E_a)dE \cdot F(E_a)$$

$$n_e = N_a \cdot F(E_a) \dots\dots\dots (2)$$

we know

$$F(E_a) = \frac{1}{1 + e^{(E_a - E_F)/TK_B}}$$

And

$$e^{(E_a - E_F)/TK_B} \gg 1$$

$$1 + e^{(E_a - E_F)/TK_B} = e^{(E_a - E_F)/TK_B}$$

$$F(E_a) = \frac{1}{e^{(E_a - E_F)/TK_B}} \dots\dots\dots (3)$$

Substituting equn (3) in (2)

$$n_e = N_a \frac{N_a}{e^{(E_a - E_F)/TK_B}} \dots\dots\dots (4)$$

At equilibrium condition

No. of holes per unit volume In valence band	=	No. of electrons per unit volume in acceptor energy level
-------------------------------------------------	---	--------------------------------------------------------------

Equating equn (1) & equn (4) and taking log on both sides we get

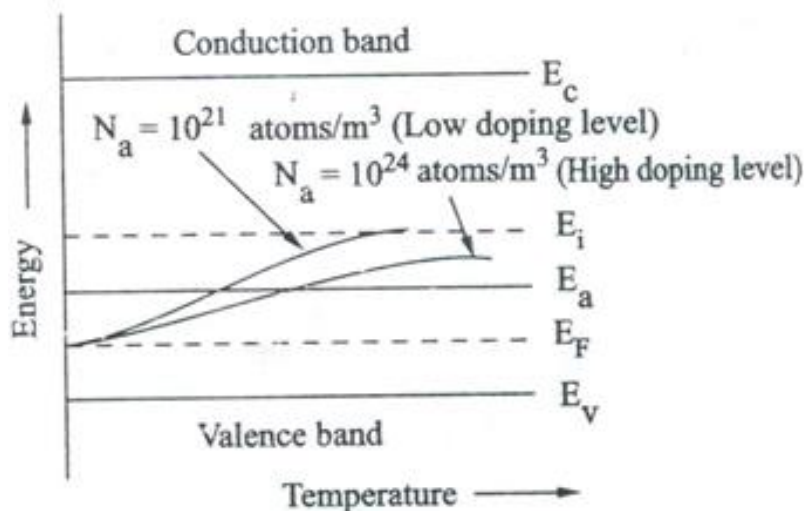
$$E_F = \frac{E_v + E_a}{2} + \frac{K_B T}{2} \log \left[\frac{N_a}{2 \left\{ \frac{2\pi m_h^* K_B T}{h^2} \right\}} \right] \dots\dots\dots (5)$$

At 0K when T=0K,

We can write the above equation as $E_f = (E_v + E_a)/2$ (6)

VARIATION OF FERMİ ENERGY LEVEL WITH TEMPERATURE AND IMPURITY CONCENTRATION IN P-TYPE SEMICONDUCTOR

- When the temperature is increased, some of the electrons in the valence band will go to acceptor energy levels by breaking up the covalent bonds and hence the Fermi level is shifted in upward direction for doping level of $N_d = 10^{21}$ atoms/m³ as shown in figure.



- From the figure it can be seen that for the same temperature, if the impurity atoms doping level is increased say $N_a = 10^{24}$ atoms/m³, the hole concentration increases and hence the Fermi level decreases.
- Therefore at low temperature the Fermi energy level may be increased upto the level of intrinsic energy level (E_i)

Expression for Density of Holes in Terms of N_a

Substituting equation (5) in (1) we get

$$n_h = 2 \cdot \left\{ \frac{2\pi m_h^* K_B T}{h^2} \right\}^{3/2} \cdot \exp \left\{ \frac{E_v - \left[\frac{(E_v + E_a)}{2} - \frac{K_B T}{2} \log \left(\frac{N_a}{2 \cdot \left\{ \frac{2\pi m_h^* K_B T}{h^2} \right\}^{3/2}} \right)} \right]}{K_B T} \right\}$$

$$(or) n_h = 2 \left(\frac{2\pi m_h^* K_B T}{h^2} \right)^{3/2} \exp \left[\frac{2E_v - E_v - E_a}{2K_B T} + \frac{1}{2} \log \left(\frac{N_a}{2 \left(\frac{2\pi m_h^* K_B T}{h^2} \right)^{3/2}} \right) \right]$$

$$n_h = 2 \cdot \left\{ \frac{2\pi m_h^* K_B T}{h^2} \right\}^{3/2} \cdot \exp \left\{ \frac{(E_v - E_a)}{2 K_B T} + \frac{1}{2} \log \left(\frac{(N_a)}{2 \left\{ \frac{2\pi m_h^* K_B T}{h^2} \right\}^{3/2}} \right) \right\}$$

$$n_h = 2 \left[\frac{2\pi m_h^* K_B T}{h^2} \right]^{3/2} \exp \left[\frac{E_v - E_a}{2K_B T} \right] \exp \left[\log \left(\frac{N_a^{1/2}}{(2)^{1/2} \left[\left(\frac{2\pi m_h^* K_B T}{h^2} \right)^{3/2} \right]^{1/2}} \right) \right]$$

$$(or) n_h = 2 \cdot \left\{ \frac{2\pi m_h^* K_B T}{h^2} \right\}^{3/2} \cdot e^{(E_v - E_a)/2K_B T} \cdot \left(\frac{N_a^{1/2}}{2^{1/2} \cdot \left\{ \frac{2\pi m_h^* K_B T}{h^2} \right\}^{3/4}} \right)$$

$$n_h = (2N_a)^{1/2} \cdot \left[\frac{2\pi m_h^* K_B T}{h^2} \right]^{3/4} \cdot e^{(E_v - E_a)/2K_B T} \quad \dots(7)$$

Here $E_a - E_v = \Delta E$ is known as **ionisation energy of acceptors** i.e., ΔE represents the energy required for an electron to move from valence band (E_v) to acceptor energy level (E_a).

Therefore equation (7) becomes

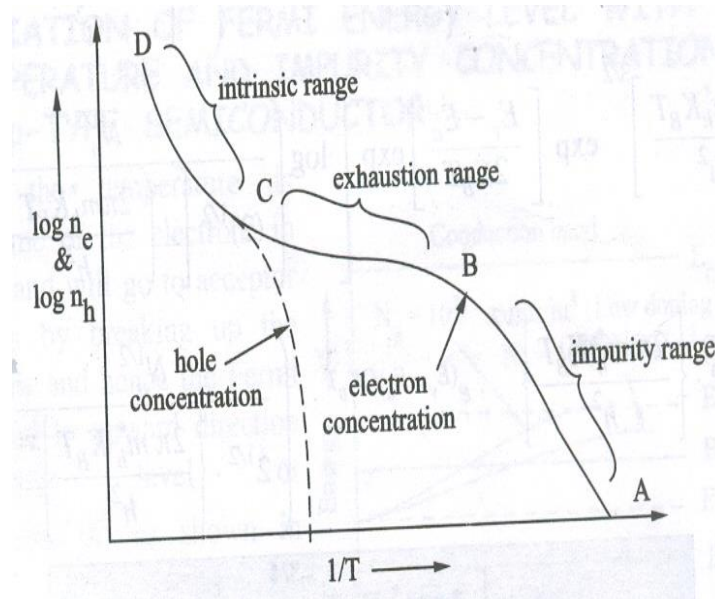
$$n_h = (2N_a)^{1/2} \cdot \left[\frac{2\pi m_h^* K_B T}{h^2} \right]^{3/4} \cdot e^{-\Delta E/2K_B T} \quad \dots(8)$$

VARIATION OF CARRIER CONCENTRATION WITH TEMPERATURE

- The carrier concentration in n-type semiconductor varies with the increase in the temperature.

Electron concentration

- At very low temperature at 0 K, $1/T$ is high, the Fermi level will be exactly in the middle between E_c and E_d and the carrier concentration is at the most zero in the conduction band and hence point A is obtained in the graph.



- Now when the temperature is slowly increased, the donor atom gets ionized and the electrons move towards conduction band.
- Hence the carrier concentration increases slowly in the conduction band for electrons.
- Since this range is obtained due to impurity atoms, it is called impurity range shown by curve AB in figure.
- The range is obtained due to exhaustion of donor atoms it is called exhaustion range, shown by curve BC in figure.
- Since the number of available electrons in donor energy level is almost exhausted, many number of electrons are shifted from valence band to conduction band and thus the carrier concentration increases rapidly, tracing the curve CD.
- Since the material practically becomes intrinsic in this range, this range is known as intrinsic range.

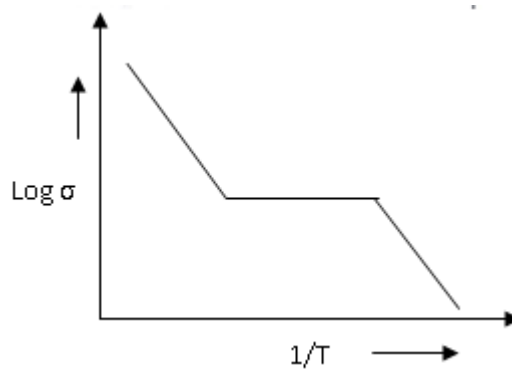
Hole Concentration

- At 0K electrons concentration is zero in conduction band.
- Now when temperature is increased slowly the electrons will move from donor energy level to conduction band.

- Now when temperature is very high the electrons are transferred from valence band to conduction band and holes are created in valence band.
- The electron concentration in conduction band equalizes the hole concentration in valence band.
- So electron concentration curve and hole concentration curve overlaps only in the intrinsic region.

Conductivity of Extrinsic semiconductor

- The variation in the conductivity of an extrinsic semiconductor, with the increase in temperature is as shown in figure.



- When the temperature is slowly increased from 0K impurity atoms are slowly ionized and goes to conduction band and hence conductivity increases.
- When all the impurities are ionized the mobility of charge carriers decreases slightly and therefore $\log \sigma$ becomes constant (or) may slightly decrease.

Carrier transport

In semiconductor electrons and holes are called carriers, which moves from one position to another and this movement of charge carriers is called Carrier transport.

In the absence of field (Random Motion)

In the absence of external field, the charge carrier moves in random direction due to its thermal energy. The path of the charge carrier changes due to scattering by the vibration of the lattice points and by the coulomb force of ionised donar and acceptor atoms in the semiconductor.

In the presence of field (Drift)

Now when the charge carriers are subjected to external fields, then they move with a velocity called drift velocity, and reaches steady state.

At steady state

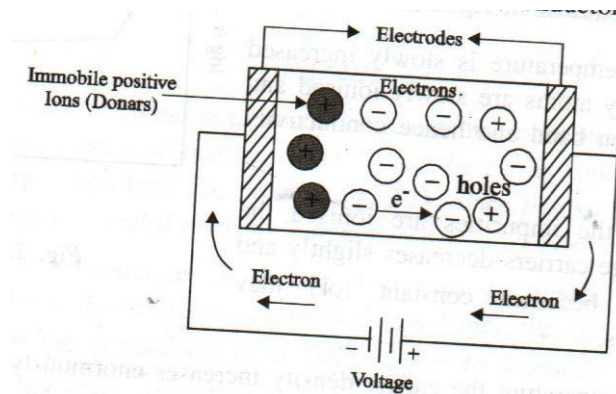
The rate of momentum gained due to external field = The rate of momentum lost due to scattering

Thus during steady state a steady current flows due to the carrier transport in semiconductors.

i. Carrier transport in n -type semiconductor

We know that in n -type semiconductor the electrons are majority charge carriers and holes are minority charge carriers. Apart from this, there will be equal number of immobile positive ions (grey shaded) in n -type semiconductor.

Let us consider an n -type semiconductor placed between a pair of electrodes, for which a voltage is applied as shown in figure.



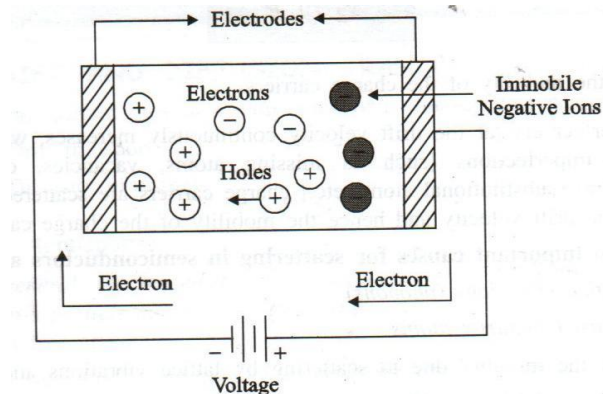
Due to the field applied the electrons in the semiconductor move towards the positive terminal and they disappear. At the same time equal numbers of electrons are generated at the negative terminal. These electrons are attracted by the immobile positive ions present in the semiconductor and therefore a continuous flow of electrons from one terminal to other terminal takes place through the semiconductor.

The net current flow in the semiconductor depends on the biasing voltage.

ii. Carrier transport in p -type semiconductor

We know that in p -type semiconductor the holes are majority charge carriers and electrons are minority charge carriers. Apart from this, there will be equal number of immobile negative ions (grey shaded) in p -type semiconductor.

Let us consider a p -type semiconductor placed between a pair of electrodes, for which a voltage is applied as shown in figure.



Due to the field applied the holes in the semiconductor move towards the negative terminal and they combine with the electrons coming out from the negative terminal and disappears. At the same time equal numbers of holes are generated near the positive terminal. These holes are attracted by the immobile negative ions present in the semiconductor towards the positive terminal and thus current to continuous flow.

During this process an electron is lost by the acceptor atom and therefore it try to get back an electron from the adjacent atom to fill that hole in the semiconductor. This process continues and hole current occurs inside the semiconductor.

PROBLEMS

1. Find the resistance of an intrinsic Ge rod 1cm long, 1mm wide and 1mm thick at 3000k.

$$\begin{aligned}\text{For Ge } n_i &= 2.5 \times 10^{19}/\text{m}^3 \\ \mu_e &= 0.39 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1} \\ \mu_h &= 0.19 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}\end{aligned}$$

Solution

Conductivity of an intrinsic semiconductor is $\sigma_i = n_i e (\mu_e + \mu_h)$

$$\begin{aligned}\sigma &= 2.5 \times 10^{19} \times 1.6 \times 10^{-19} (0.39 + 0.19) \\ \sigma &= 2.32\end{aligned}$$

$$\text{Resistance } R = \rho l / A$$

$$R = 1 \times 10^{-2} / 2.32 \times (1 \times 10^{-3} \times 1 \times 10^{-3})$$

$$\mathbf{R = 4310 \text{ ohm.}}$$

2. The sample of silicon is doped with 10^{16} phosphor atoms / m^3 . Find the hall voltage in a sample with thickness 500 mm, area of cross section $2.25 \times 10^{-3} \text{ m}^2$, current 1A and magnetic field $10 \times 10^4 \text{ Wb/m}^2$.

Solution

Given data:

$$n_e = 10^{16} \text{ m}^3, B = 10^4 \text{ Wb/m}^2$$

$$J_x = 1/2.55 \times 10^{-3}$$

$$= 444.44 \text{ A/m}^2$$

$$T = 500 \text{ mm}$$

$$R_H = 1/n_e e$$

$$R_H = 1/10^{16} \times 1.6 \times 10^{-19}$$

$$R_H = 625$$

$$\text{Hall Voltage } V_H = R_H J_x B t$$

$$V_H = 625 \times 444.44 \times 10 \times 10^4 \times 5000 \times 10^{-3}$$

$$\mathbf{V_H = 1.3888 \times 10^{10} \text{ Volts}}$$

UNIT III

MAGNETIC MATERIALS

3.1 INTRODUCTION

Magnetic materials are the materials which can be made to behave as magnets. When these materials are kept in an external magnetic field, they will create a permanent magnetic moment in it. Diamagnetic, Paramagnetic, Ferromagnetic, Antiferromagnetic and Ferromagnetic materials are the magnetic materials type.

Magnetism originates from the magnetic moment of the magnetic materials due to the rotational motion of the charged particles. When an electron revolves around the positive nucleus, orbital magnetic arises and due to the spinning of electrons, spin magnetic moment arises. Let us see some of the basic definitions in magnetism.

3.2 BASIC DEFINITIONS

Magnetic dipole moment

A system having two opposite magnetic poles separated by a distance 'd' is called as a magnetic dipole. If 'm' is magnetic pole strength and 'l' is the length of the magnet, then its dipole moment is given by

$$M = ml$$

Magnetic moment can also be defined as $M = ia$, where i is the electric current that flows through a circular wire of an area of cross section 'a'.

Bohr Magnetron

The total magnetic moment and the spin magnetic moment of an electron in an atom can be expressed in terms of atomic unit of magnetic moment called Bohr magneton.

$$1 \text{ Bohr magneton} = e\hbar/2m = 9.27 \times 10^{-24} \text{ Am}^2$$

Magnetic field

The space around the magnet or the current carrying conductor where the magnetic effect is felt is called magnetic field.

Magnetic lines of force

Magnetic field is assumed to consist of lines of magnetic forces. These lines of forces travel externally from North Pole to South Pole as shown in figure. Hence a magnetic line of force is defined as the continuous curve in a magnetic field. The tangent drawn at any point on the curve gives the direction of the resultant magnetic intensity at that point.

Magnetic induction (or) Magnetic flux density (B)

It is defined as the number of magnetic lines of force passing normally through unit area of cross section at that point.

Magnetic field intensity (H)

It is defined as the force experienced by a unit North Pole placed at the given point in a magnetic field

Magnetisation (or) Intensity of Magnetisation (I)

The magnetization is the process of converting a non-magnetic material into a magnetic material. It measures the magnetization of the magnetized specimen. It also defined as the magnetic moment per unit volume

Magnetic susceptibility (χ_m)

It is defined as the ratio between intensity of magnetization (I) and the magnetic field intensity (H)

$$\chi_m =$$

Magnetic permeability (μ)

It is defined as the ratio between the magnetic flux density (B) and the magnetic field intensity (H)

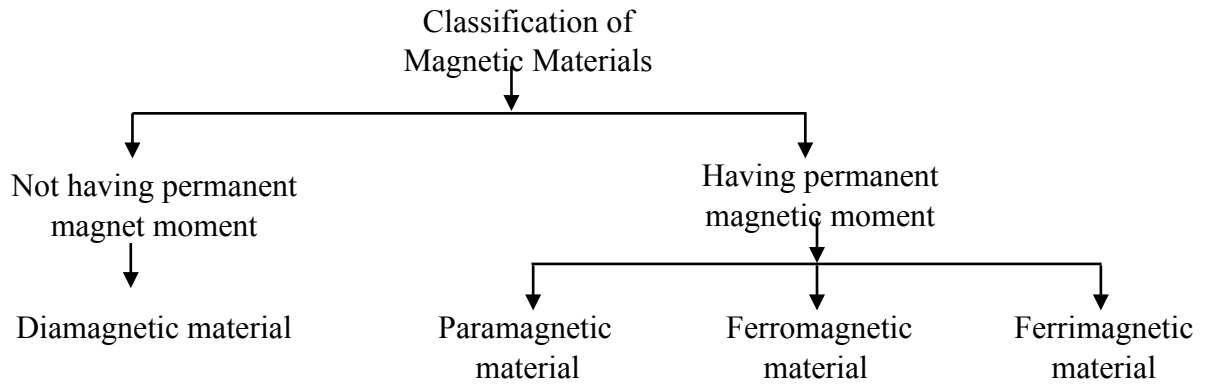
$$\mu =$$

3.3 CLASSIFICATION OF MAGNETIC MATERIALS ON THE BASIS OF MAGNETIC MOMENT

Magnetic materials are classified according to the presence or absence of the permanent magnetic dipoles. Generally, every two electrons in an energy state of an atom will form a pair with opposite spins. Thus the resultant spin magnetic moment is zero. Hence they don't have permanent magnetic moments and they are called as diamagnetic materials.

Example: Gold, germanium, silicon, etc.

But in some magnetic materials like iron, cobalt, etc., there exists unpaired electrons. The spin magnetic moment of these unpaired electrons interact with the adjacent atoms unpaired electron spin magnetic moment in a parallel manner resulting in enormous permanent spin magnetic moment. These materials are classified into para, ferro and ferromagnetic materials with respect to the electron spins.



3.3.1 DIAMAGNETIC MATERIAL

In a diamagnetic material, the electron orbits are more or less random, and mostly all the magnetic moments are cancelled. Similarly all the spin moments are almost paired i.e., they have even number of electrons and has equal number of electrons spinning in two opposite directions. Hence the net magnetic moment in the diamagnetic material is zero. Therefore most of the materials do not have magnetism in the absence of magnetic field.

Effect of external field

When an external magnetic field is applied, the electrons reorient in such a way that they align perpendicular to the field direction and their magnetic moments opposes the external magnetic field. This will reduce the magnetic induction present in the specimen.

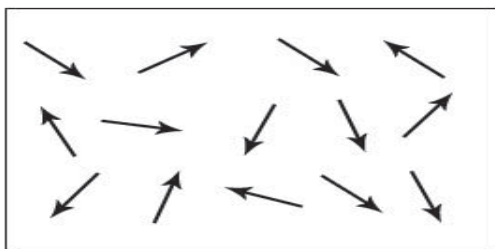
Properties

1. They repel the magnetic lines of force
2. Susceptibility is negative and it is independent of temperature and applied magnetic field strength
3. Permeability is less than 1
4. There is no permanent dipole moment, so they are called weak magnets
5. When temperature is less than critical temperature diamagnetic become normal material

Examples: Gold, Germanium, Silicon, etc.,

3.3.2 PARAMAGNETIC MATERIALS

In the case of paramagnetic materials, the spins in two opposite directions will not be equal. There exist some unpaired electrons which gives rise to spin magnetic moment. Hence the resultant magnetic will not be equal to zero.



However in the absence of external field the magnetic moments are oriented randomly. Due to its random orientation some magnetic moments get cancelled and the materials possess very less magnetization in it.

Effect of external field

When an external field is applied, the magnetic moments of individual molecules reorient itself along the direction of the magnetic field and the material is magnetized.

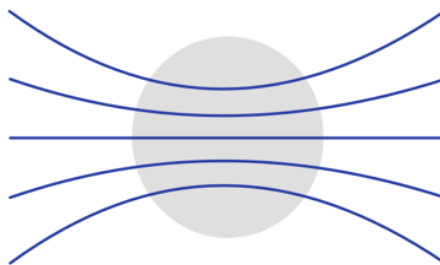
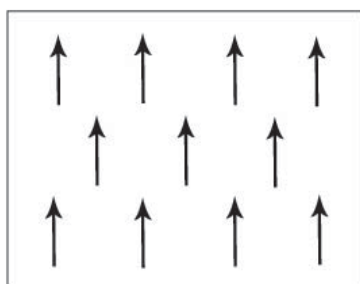
Properties

1. The magnetic lines of force pass through the material
2. Magnetic susceptibility is positive and it is given by
3. Permeability is greater than one
4. They possess permanent dipole moment
5. When the temperature is less than Curie temperature, paramagnetic materials becomes diamagnetic material.

Examples: CuSO_4 , MnSO_4 , Platinum etc.

3.3.3 FERROMAGNETISM

In a ferromagnetic material the numbers of unpaired electrons are more. Most of these spin magnetic moments point in one direction as shown in figure.



Hence even in the absence of external field, the magnetic moments align themselves parallel to each other and give rise to magnetic field.

Effect of magnetic field

To these materials even if a small external magnetic field is applied, the magnetic moments which are already aligned parallel, reorient itself along the direction of the magnetic field and they become very strong magnets.

Properties

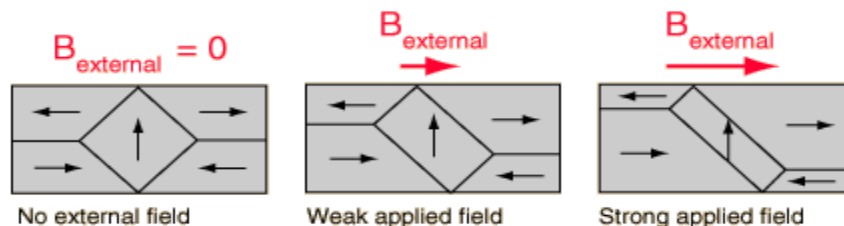
1. Since some magnetization is already existing in these materials, all the magnetic lines of force passes through it
2. They have permanent dipole moment. So they act as strong magnets.
3. They exhibit magnetization even in the absence of external field. This property is called Spontaneous magnetization.
4. Its susceptibility is positive and high and it is given by
5. When the temperature is greater than Curie temperature, ferromagnetic material becomes paramagnetic material.
6. Permeability is very much greater than 1

Examples: Ni, Co, Fe, etc.,

3.4 FERROMAGNETIC DOMAINS

We can observe that a ferromagnetic material such as iron does not have magnetization unless they have been previously placed in an external magnetic field. But according to Weiss theory, the molecular magnets in the ferromagnetic material are said to be aligned in such a way that, they exhibit a magnetization even in the absence of an external magnetic field. This is called spontaneous magnetization. i.e., it should have some internal magnetization due to quantum exchange energy.

Thus according to Weiss hypothesis, a single crystal of ferromagnetic material is divided into large number of small regions called domains. These domains have spontaneous magnetization due to the parallel alignment of spin magnetic moments in each domain. But the directions of spontaneous magnetization vary from domain to domain and are oriented in such a way that the net magnetization of the specimen is zero as shown in figure.



Due to this reason the iron does not have any magnetization in the absence of an external field.

Now, when the magnetic field is applied, then the magnetization occurs in the specimen by two ways

1. By the movement of domain walls
2. By rotation of domain walls

(i) By the movement of domain walls

The movement of domain walls takes place in weak magnetic fields. Due to this weak field applied to the specimen the magnetic moment increases and hence the boundaries of domains are displaced, so that the volume of the domains changes as shown in figure.

(ii) By rotation of domain walls

The rotation of domain walls takes place in strong magnetic fields. When the external field is high (strong) then the magnetization changes by means of rotation of the direction of magnetization towards the direction of the applied field as shown in figure.

3.5 DOMAIN THEORY OF FERROMAGNETISM

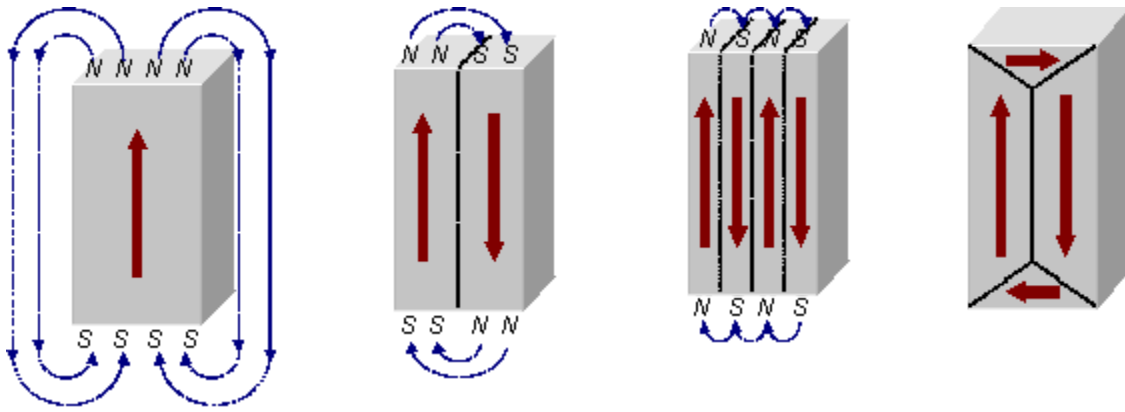
The domain in ferromagnetic solid is understandable from the thermo dynamical principle, (i.e.,) in equilibrium the total energy of the system is minimum. For this, first we consider the total energy of the domain structure and then how it is minimized. The total energy of the domain comprises the sum of following energies. Viz,

1. Exchange energy
2. Anisotropy energy
3. Domain wall energy
4. Magneto-strictive energy

(i) Exchange energy (or) magnetic field energy (or) magneto-static energy

The interaction energy which makes the adjacent dipoles to align themselves is known as exchange energy (or) magnetic field energy. The exchange energy has established a single domain in a specimen of ferromagnetic and it is shown in figure.

Because of the development of the free poles at the domain, an external field will be produced around it and the configuration will have a high value of magnetic field energy. In other words it is the energy required in assembling the atomic magnets into a single domain and this work done is stored as potential energy.



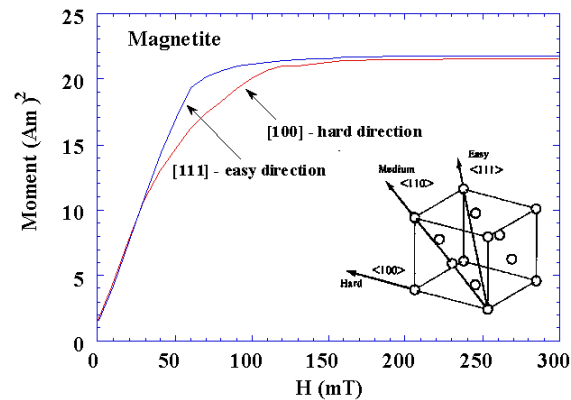
The magnetic energy can be reduced by dividing the specimen into two domains as shown in figure. The process of subdivision may be carried further, until the reduction of magnetic energy is less than the increase in energy to form another domain and its boundary. This boundary is called as domain wall (or) Block wall.

(ii) Anisotropy energy

In ferromagnetic crystals there are two direction of magnetization, viz,

- (i) Easy direction
- (ii) Hard direction

In easy direction of magnetization, weak field can be applied and in hard direction of magnetization, strong field should be applied. For producing the same saturation magnetization along both the hard and easy direction, strong fields are required in the hard direction than the easy direction.



For example in Iron easy direction is [100], medium direction is [110] and the hard direction is [111] and it is as shown in figure. From the figure we can see that very strong field is required to produce magnetic saturation in hard direction [111] compared to the easy direction [100].

Therefore the excess of energy required to magnetize the specimen along hard direction over that required to magnetize the specimen along easy direction is called crystalline anisotropy energy.

(iii) Domain wall energy (or) Bloch wall energy

Bloch wall is a transition layer which separates the adjacent domains, magnetized in different directions. The energy of domain wall is due to both exchange energy and anisotropic energy.

Based on the spin alignments, two types of Bloch walls may arise, namely

- (i) Thick wall (ii) Thin wall

Thick wall: When the spins at the boundary are misaligned and if the direction of the spin changes **gradually** as shown in figure, it leads to a thick Bloch wall. Here the misalignments of spins are associated with exchange energy.



Thin wall: When the spins at the boundaries changes **abruptly**, then the anisotropic energy becomes very less. Since the anisotropic energy is directly proportional to the thickness of the wall, this leads to a thin Bloch wall.

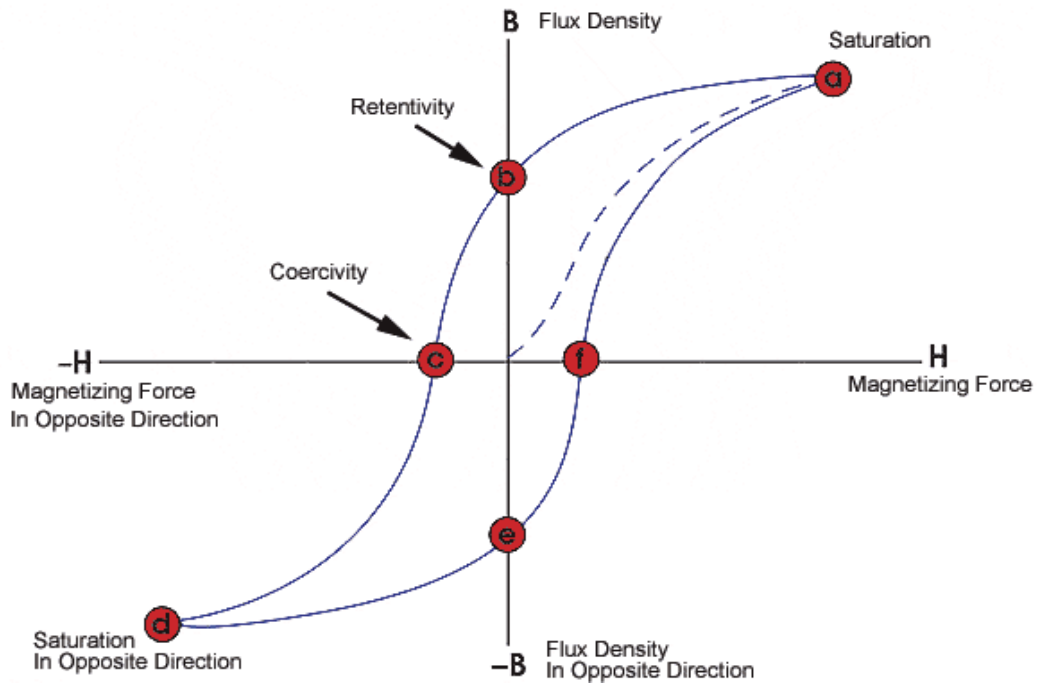
(iv) Magnetostrictive energy

When the domains are magnetized in different directions, they will either expand (or) shrink. Therefore there exists a deformation (i.e.,) change in dimension of the material, when it is magnetized. This phenomenon is known as magnetostriction and the energy produced in this effect is known as magnetostriction energy.

The deformation is different along different crystal directions and the change in dimension (increase or decrease) depends upon the nature of the material. For example in Ni the length decreases; and in permalloy the length increases. But both the increase (and) decrease is due to the mechanical stress generated by domain rotation.

3.6 HYSTERESIS

When a ferromagnetic material is made to undergo through a cycle of magnetization, the variation of B with respect to H can be represented by a closed hysteresis loop (or) curve. i.e., it refers to the lagging of magnetization behind the magnetizing field.



If a magnetizing field H is applied to a ferromagnetic material and if H is increased to H_{\max} the material acquires the magnetism. So the magnetic induction also increases, represented by 'oa' in the figure.

Now if the magnetic field is decreased from H_{\max} to zero, the magnetic induction will not fall rapidly to zero, but falls to 'b' rather than zero. This shows that even when the applied field is zero or removed, the material still acquires some magnetic induction (ob) which is so called Residual magnetism or Retentivity.

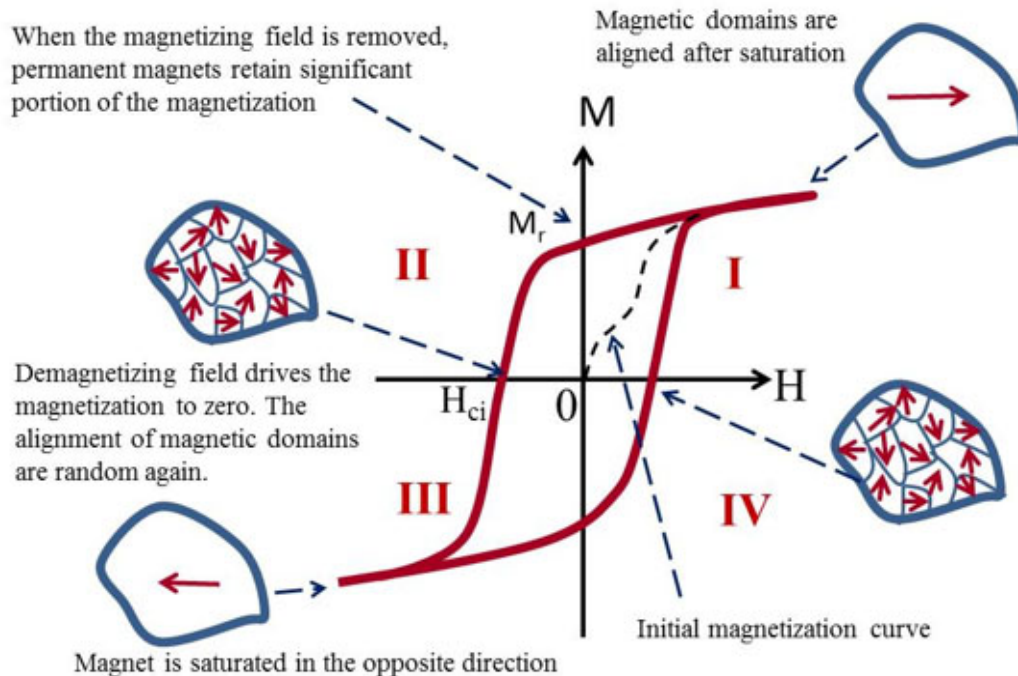
Now, to remove this residual magnetism, the magnetic field strength is reversed and increased to $-H_{\max}$ represented as 'oc' so called coercivity and hence we get the curve 'bcd'. Then the reverse field ($-H$) is reduced to zero and the corresponding curve 'de' is obtained and by further increasing H to H_{\max} the curve 'efa' is obtained.

3.7 EXPLANATION OF HYSTERESIS ON THE BASIS OF DOMAINS

We know when the ferromagnetic material is subjected to external field, there is an increase in the value of the resultant magnetic moment due to two process, viz.,

1. The movement of domain walls
2. Rotation of domain walls

When a small external field is applied, the domains walls are displaced slightly in the easy direction of magnetization. This gives rise to small magnetization corresponding to the initial portion of the hysteresis curve (OA) as shown in figure.



Now, if the applied field is removed, then the domains returns to its original state, and is known as reversible domains.

When the field is increased, large number of domains contributes to the magnetization and thus the magnetization increases rapidly with H .

Now, even when the field is removed, because of the displacement of the domain wall to a very large distance, the domain boundaries do not come back to their original position. This process is indicated as AB in figure and these domains are called irreversible domains.

At point 'B' all the domains have got magnetized along the easy direction. Now, when the field is further increased, the domains starts rotating along the field direction and the anisotropic energy is stored in the hard direction, represented as BC in the figure.

Thus the specimen is said to attain the maximum magnetization. At this position, even after the removal of external field the material possess maximum magnetization, called residual magnetization or retentivity, represented by OD in figure.

Actually after the removal of the external field, the specimen will try to attain the original configuration by the movement of Bloch wall. But this movement is stopped due to the presence of impurities, lattice imperfections etc. Therefore to overcome this, a large amount of reverse magnetic field is applied to the specimen. The amount of energy spent to reduce the magnetization to zero is called as coercivity represented by 'OE' in the figure.

Hysteresis loss

It is the loss of energy in taking a ferromagnetic specimen through a complete cycle of magnetization and the area enclosed is called hysteresis loop.


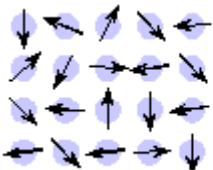
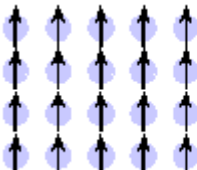
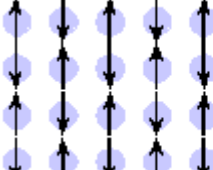
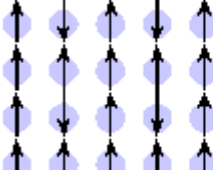
Based on the area of the hysteresis loop, the magnetic materials are classified into soft and hard magnetic materials.

3.8 DIFFERENCE BETWEEN HARD AND SOFT MAGNETIC MATERIALS

S.No	Hard Magnetic Materials	Soft Magnetic Materials
1	Materials which retain their magnetism and are difficult to demagnetize are called hard magnetic materials. These materials retain their magnetism even after the removal of the applied magnetic field. Hence these materials are used for making permanent magnets. In permanent magnets the movement of the domain wall is prevented. They are prepared by heating the magnetic materials to the required temperature and then quenching them. Impurities increase the strength of hard magnetic materials.	Soft magnetic materials are easy to magnetize and demagnetize. These materials are used for making temporary magnets. The domain wall movement is easy. Hence they are easy to magnetize. By annealing the cold worked material, the dislocation density is reduced and the domain wall movement is made easier. Soft magnetic materials should not possess any void and its structure should be homogeneous so that the materials are not affected by impurities.
2	They have large hysteresis loss due to large hysteresis loop area.	They have low hysteresis loss due to small hysteresis area.
3	Susceptibility and permeability are low.	Susceptibility and permeability are high.
4	Coercivity and retentivity values are large.	Coercivity and retentivity values are less.
5	Magnetic energy stored is high.	Since they have low retentivity and coercivity, they are not used for making permanent magnets.
6	They possess high value of BH product.	Magnetic energy stored is less.
7	The eddy current loss is high.	The eddy current loss is less because of high

		resistivity.
--	--	--------------

Classification of magnetism

<i>Type of Magnetism</i>	<i>Susceptibility</i>	<i>Atomic / Magnetic Behaviour</i>	<i>Example / Susceptibility</i>
Dia magnetism	Small & negative.	Atoms have no magnetic moment 	Au -2.74×10^{-6} Cu -0.77×10^{-6}
Para magnetism	Small & positive.	Atoms have randomly oriented magnetic moments 	β -Sn 0.19×10^{-6} Pt 21.04×10^{-6} Mn 66.10×10^{-6}
Ferro magnetism	Large & positive, function of applied field, microstructure dependent.	Atoms have parallel aligned magnetic moments 	Fe $\sim 100,000$
Antiferro magnetism	Small & positive.	Atoms have mixed parallel and anti-parallel aligned magnetic moments 	Cr 3.6×10^{-6}
Ferri magnetism	Large & positive, function of applied field, microstructure dependent	Atoms have anti-parallel aligned magnetic moments 	Ba ferrite ~ 3

3.9 ENERGY PRODUCT

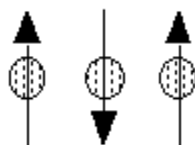
Hard magnetic materials have high magnetization, retentivity and coercivity. The shape of the hysteresis loop in the second quadrant gives the effectiveness of permanent magnetism in the specimen.

Therefore, a product of retentivity (B_r) and coercivity (H_c) is made and this product is called energy product, which gives the maximum amount of energy stored in the specimen.

The energy product curve is as shown in figure. Here two curves (i.e.,) (i) 1st quadrant of the plot between energy product ($B_r H_c$) and B_r , which represents magnetization and (ii) 2nd quadrant.

3.10 ANTI – FERROMAGNETISM

In this the spins are aligned in antiparallel manner due to unfavourable exchange interaction among them, resulting in zero magnetic moment. Even when the field is increased, it has almost zero induced magnetic moment.



Properties

1. The susceptibility is very small and is positive, It is given by for $T > T_N$ where T_N is the Neel temperature.
2. Initially, the susceptibility increases slightly as the temperature increases and beyond a particular temperature, known as Neel temperature, the susceptibility decreases with temperature.

Antiferro-magnetic materials

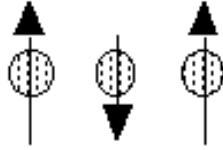
1. Ferrous oxide (FeO)
2. Manganese oxide (MnO_2)
3. Manganese Sulphide (MnS)
4. Chromium Oxide (Cr_2O_3)
5. Ferrous Chloride (FeCl_2) and salts of transition elements.

These elements will be wide range of applications in magnetic storage devices.

3.11 FERRIMAGNETISM AND FERRITES

It is a special case of magnetic material and it is composed of two sets of different transition metal ions having different values of magnetic moment with antiparallel alignment as shown in figure.

Hence these materials have antiparallel magnetic moments of different magnitudes, giving rise to fairly large magnetic moment in the presence of external magnetic field.



Properties

1. The susceptibility is very large and is positive represented by χ when $T > T_N$
2. Beyond the Neel temperature, χ decreases.
3. These materials have low eddy current losses, and low hysteresis losses.
4. They have hysteresis loop in the form of a square and hence will have low coercivity.

Structure of Ferrites

Ferrites are the magnetic compounds consisting of two or more different kinds of atoms. Generally ferrites are expressed as $X^{2+}Fe_2^{3+}O_4$ where X^{2+} stands for suitable divalent metal ion such as Mg^{2+} , Zn^{2+} , Fe^{2+} , Mn^{2+} , Ni^{2+} etc.

Examples,

1. If X^{2+} is replaced by Ni^{2+} , then the ferrite ($Ni^{2+}Fe_2^{3+}O_4$) is formed, thus named as nickel ferrite.
2. If X^{2+} is replaced by Fe^{2+} then the ferrite ($Fe^{2+}Fe_2^{3+}O_4$) is formed, thus named as ferrous ferrite.

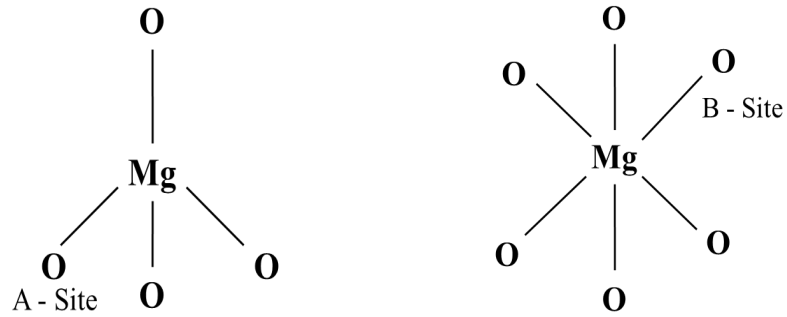
Ferrites formed usually have a face centered cubic structure of oxygen ions closely packed together with the divalent and trivalent metal ions in the interstitial sites. This structure is called spinel structure. There are two types of ferrite structures

(i) Regular spinel

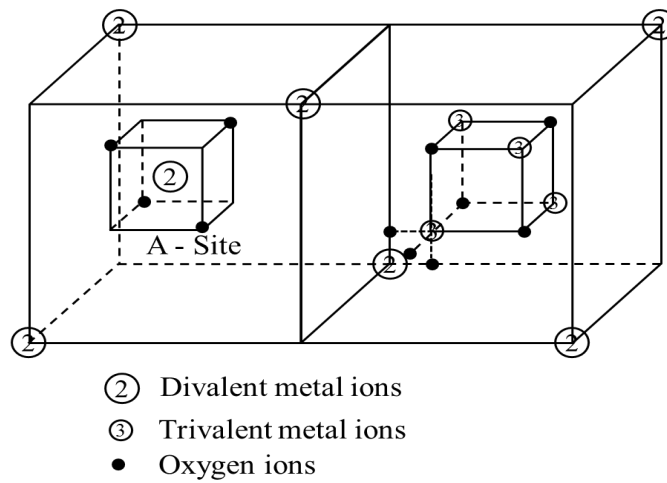
(ii) Inverse spinel

Regular spinel: Eg., $Mg^{2+}Fe_2^{3+}O_4$

In this type each metal atom is surrounded by four O^{2-} ions in a tetragonal fashion. For example, if the metal atom is Mg^{2+} , then the structure is as shown in figure and it is called A site. Totally in a unit cell, there will be 8 tetrahedral (8A) sites.

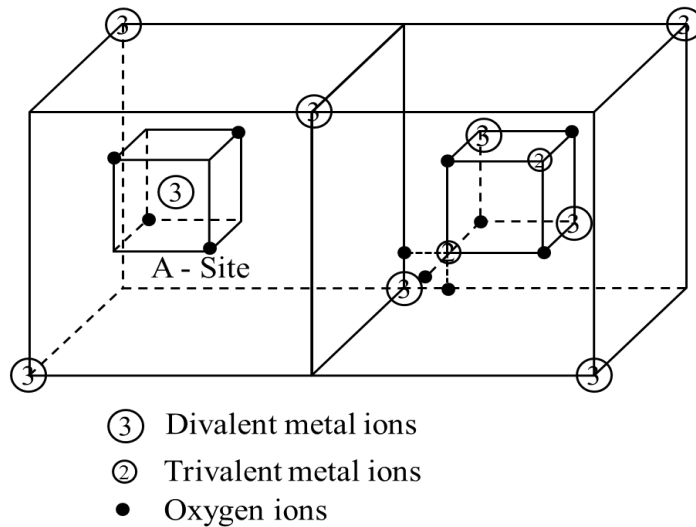


Each Fe^{3+} is surrounded by six O^{2-} ions and forms an octahedral fashion as shown in figure. Totally, there will be 16 such octahedral sites in the unit cell. This is indicated by B site.



Thus in a regular spinel, each divalent metal ion (Mg^{2+}) exists in a tetrahedral form (A site) and each trivalent metal ion (Fe^{3+}) exists in an octahedral form (B site). Hence the sites A and B combine together to form a regular spinel ferrite structures as shown in figure.

Inverse spinel: Eg., $\text{Fe}^{3+}[\text{Fe}^{2+}\text{Fe}^{3+}]\text{O}_4$



In this, the Fe^{3+} ions (trivalent) occupies all the A sites (tetrahedral) and half of the B sites (Octahedral) also. Thus the left out B sites will be occupied by the divalent (Fe^{2+}). The inverse spinel structure is as shown in figure.

Types of interaction present in the ferrites

The spin arrangement between the A site and B site is in an antiparallel manner and it was explained by Neel. According to him, in ferrites, the spin arrangement is antiparallel and there exists some interaction between the A and B sites which is represented as AB interaction.

Apart from this, there are two more interactions (i.e.,) AA and BB interaction which is negative and considerably weaker than AB interaction.

The tendency of AB interaction is to align all A spins parallel to each other and antiparallel to all B spins, but the tendency of AA and BB interaction is to spoil the parallel arrangement of A and B spins respectively.

Since AB is very strong as compared with AA and BB, the effect of AB interaction dominates and gives rise to antiparallel spin arrangement.

3.12 MAGNETIC MOMENT OF A FERRITE MOLECULE

Bohr magnet

The orbital magnetic moment and the spin magnetic moment of an electron in an atom can be expressed in terms of atomic unit of magnetic moment called Bohr magneton.

$$1 \text{ Bohr Magnetron} = e\hbar/2m = \mu_B = 9.27 \times 10^{-24} \text{ Am}^2$$

Saturation magnetization of a ferrite molecule can be calculated from the number of unpaired spins of Fe^{2+} and Fe^{3+}

Let us consider an example of Ferrite say Ferrous ferrite having the formula $\text{Fe}^{2+}\text{Fe}^{3+}\text{O}^4$ for calculating the magnetic moment.

In ferrous ferrite we have two types of ions viz. Fe^{2+} and Fe^{3+}

- (i) Here Fe^{2+} ions have six electrons in 3d shell. Out of 6 electrons two electrons are paired with each other and hence left with 4 unpaired electrons.

The Fe^{2+} gives rise to 4 Bohr magneton.

- (ii) Fe^{3+} ions have five electrons in 3d shell and hence all these 5 are unpaired electrons.

The Fe^{3+} gives rise to 5 Bohr magneton.

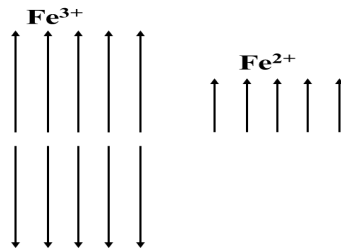
Since we have two Fe^{3+} , totally, the Fe^{3+} gives rise to $2 \times 5 = 10$ Bohr magneton.

Total magnetization of $\text{Fe}^{2+} + \text{Fe}_2^{3+} = 4 + 10 = 14$ Bohr magneton.

(i.e.,) $14 \mu\text{B}$.

Theoretically we get $14 \mu\text{B}$ but experimentally the total magnetic moment got is only $4.08 \mu\text{B}$. The reason for this discrepancy is as follows:

If all the spins are aligned parallel then we will get the total magnetization as $14 \mu\text{B}$. But in ferrites half of the magnetic spins of Fe_2^{3+} ions are parallel to one direction and the remaining half of Fe_2^{3+} ions are parallel in opposite direction as shown in figure and hence they cancel each other. Therefore, the net magnetic moment is only due to Fe^{2+} ions alone (i.e.,) hence we get the total magnetization as $4\mu\text{B}$, which has a good agreement with the experiment value i.e., $4.08\mu\text{B}$.



Similarly we can calculate the total magnetic moment of any ferrite molecule with respect to the number of unpaired electrons in the divalent metal ions.

3.13 APPLICATIONS OF FERRITES

- (i) They are used to produce ultrasonics by magnetostriction principle.
- (ii) Ferrites are used in audio and video transformers.
- (iii) Ferrites rods are used in radio receivers to increase the sensitivity.
- (iv) Since the ferrites have low hysteresis loss and eddy current loss, they are used in two port devices such as gyrator, circulator and isolator.

Gyrator: It transmits the power freely in both directions with a phase shift of π radians.

Circulator: It provides sequential transmission of power between the ports.

Isolator: It is used to display differential attenuation.

- (i) They are also used for power limiting and harmonic generation.
- (ii) Ferrites are used in parametric amplifiers so that the input can be amplified with low noise figures.
- (iii) They are used in computers and data processing circuits.
- (iv) Ferro cubes are used in switching circuits and in matrix storage devices of computers.
- (v) Ferrites are not metals, but their resistivity lies in the range of insulator or semiconductor. Thus, the power losses due to eddy currents are reduced in this type of materials and hence they are used in microwave frequency applications.
- (vi) Ferrites are used in storage devices such as magnetic tapes, floppy discs, hard discs, ferrite core memories and in bubble memories.

PROBLEMS

1. The saturation magnetic induction of nickel is 0.65 Wb/m². If the density of Nickel is 8906 kg/m³ and atomic weight is 58.7. Calculate the magnetic moment of the nickel atom in Bohr magneton.

Given, $B_s = 0.65 \text{ Wb/m}^2$

$$\rho = 89.6 \text{ kg/m}^3$$

$$\text{Atomic weight} = 58.7$$

$$\mu_m = B_s / N\mu_o$$

$$N = \rho A / \text{Atomic weight}$$

$$N = (8906 \times 6.023 \times 10^{26}) / 58.7$$

$$= 9.14 \times 10^{28} \text{ atoms/m}^3$$

$$\mu_m = 0.65 / (9.14 \times 10^{28} \times 4\pi \times 10^{-7})$$

$$= 5.66 \times 10^{-24} \text{ Am}^2$$

$$(1 \text{ Bohr magneton} = 9.27 \times 10^{-24} \text{ Am}^2)$$

$$= (5.66 \times 10^{-24} / 9.27 \times 10^{-24})$$

$$\mu_m = 0.61 \text{ Bohr magneton } (\mu_B)$$

2. The rare earth element gadolinium is ferromagnetic below 16°C with 7.1 Bohr magneton per atom. Calculate the magnetic moment per gram. What is the value of saturation magnetisation, given that the atomic weight of gadolinium is 157.26 and its density is $7.8 \times 10^3 \text{ kg/m}^3$.

$$\begin{aligned} \text{Number of atoms per kg} &= (6.025 \times 10^{26} \times 7.8 \times 10^3) / (157.26) \\ &= 2.9883 \times 10^{28} \end{aligned}$$

$$\text{Number of atoms per gram} = 2.9883 \times 10^{25}$$

$$(i) \quad \text{Magnetic moment per gram} = 2.9883 \times 10^{25} \times 7.1 \text{ Bohr magneton}$$

$$\text{Since 1 Bohr magneton} = 9.27 \times 10^{-24} \text{ Am}^2$$

$$\text{Magnetic moment per gram} = 2.9883 \times 10^{25} \times 7.1 \times 9.27 \times 10^{-24}$$

$$m = 1966.809 \text{ Am}^2$$

$$(ii) \quad \text{Saturation magnetization } B_s = N\mu_o\mu_m$$

$$= 2.9883 \times 10^{28} \times 4\pi \times 10^{-7} \times 9.27 \times 10^{-24}$$

$$= 0.3481 \text{ Wbm}^{-2}$$

3. A paramagnetic material has a magnetic field intensity of 10^4 A/m . If the susceptibility of the material at room temperature is 3.7×10^{-3} . Calculate the magnetization and flux density in the material.

$$(i) \quad \text{Susceptibility } \chi = I/H$$

$$\text{Intensity of magnetization } I = \chi H$$

$$= 3.7 \times 10^{-3} \times 10^4$$

$$= 37 \text{ Am}^{-1}$$

$$(iii) \quad \text{Flux density } B = \mu_o [H + I]$$

$$= 4\pi \times 10^{-7} \times [10^4 + 37]$$

$$= 0.012612 \text{ Wb/m}^2$$

SUPERCONDUCTING MATERIALS

3.14 INTRODUCTION

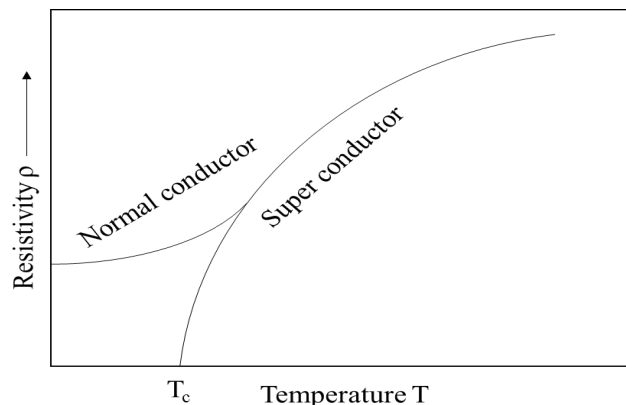
Before the discovery of superconductivity, it was thought that the electrical resistance of a conductor becomes zero only at absolute zero. But, it is found that, in some materials the electrical resistance becomes zero, when they are cooled to very low temperatures.

For ex, the electrical resistance of pure mercury suddenly drops to zero, when it is cooled below 402 kelvin and becomes a super conductor. This phenomenon was first observed by H.KamerlinghOnnes in 1911. This phenomenon of losing the resistivity absolutely, when cooled to sufficiently low temperature is called Super Conductivity.

Transition Temperature or Critical Temperature

The temperature at which a normal conductor loses its resistivity and becomes a super conductor is known as transition temperature (or) Critical Temperature (T_c) as shown in figure.

1. If the transition temperature is low, then the super conductors are known as low temperature super conductors.
2. If the transition temperature is high (even 30 kelvin) then it is known as high temperature super conductors.



The transition temperature depends on the properties of that material. It is found that the super conducting transition is reversible (i.e.,) above critical temperature (T_c), the super conductor again becomes normal conductor. Also, T_c is definite for any particular material.

3.15 TEMPERATURE DEPENDENCE OF RESISTANCE AND SUPER CONDUCTING PHENOMENA

We know conduction in materials is due to flow of electrons, which are loosely bound to the outer most orbits in an atom. If a small amount of energy is supplied to this atom the free electrons

become conduction electrons. These electrons leave the atoms to which they were originally bound and the atoms become positive ion cores.

Due to thermal excitation these positive ions vibrate in equilibrium positions. These vibrations are called Lattice Vibrations. The quanta of energy which are emitted during these vibrations are called Phonons.

In metals the electrical resistivity (ρ) is due to

1. Presence of impurities in it (ρ_0)
2. Lattice vibrations, which depends on temperature [$\rho(T)$]

(i.e.,) According to **Mathiessen's Rule**

$$\rho = \rho_0 + \rho(T)$$

Where, ρ = Residual resistivity due to scattering by impurities.

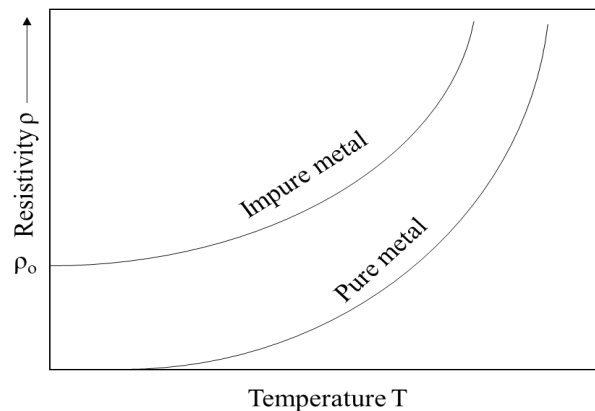
$\rho(T)$ = Ideal resistivity due to scattering by phonons.

In both the above said cases, the moving electrons will be SCATTERED and gives rise to electrical resistivity. The electrical resistivity at high temperature and low temperature are discussed below.

At High Temperature

Case (i) Impure metals

In the case of impure metals the resistivity exists due to impurities and also due to phonon vibrations as shown in figure



Case (ii) Pure metals

When a pure metal is taken, the resistivity due to impurities is minimized. Still, due to higher temperatures, scattering by phonons act as resistance and hence $\rho \approx \rho(T)$, which increase linearly with temperature as shown in figure.

$$\rho = \rho_0 + \rho(T)$$

At Low Temperature

Case (i) Impure metals

When the temperature is reduced to 0K, the resistivity of the impure metal doesn't become zero, because there exists some impurities which give rise to minimum resistivity known as residual resistivity (ρ_0), as shown in figure.

$$\rho = \rho_0 \text{ [since } \rho(T) = 0 \text{]}$$

Case (ii) Pure metals

In a pure metal, when the temperature is lowered, the electrons are ordered in a particular direction. The resistivities due to both the impurities and phonon vibration are absent and hence the resistivity $\rho \approx 0$. Hence the material becomes a super conductor, below the critical temperature as shown in figure.

Thus at low temperature the electrons move freely over the lattice points and have very less vibrations giving rise to the phenomenon of super conductivity.

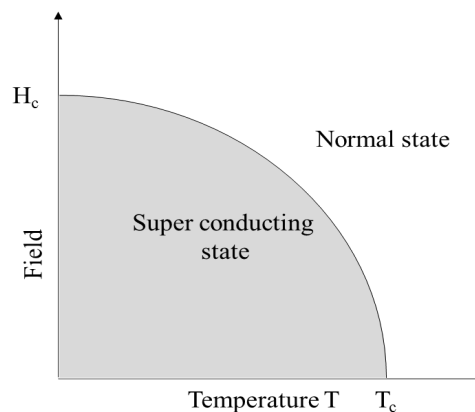
3.16 PROPERTIES OF SUPER CONDUCTORS

1. Electrical Resistance

The electrical resistance of a super conducting material is very less and is of the order of $10^{-5} \Omega \text{ cm}$.

2. Magnetic Property

When super conducting materials are subjected to very large value of magnetic field, the super conducting property is destroyed.



The field required to destroy the super conducting property is called as critical magnetic field (H_c) given as

$$H_c = H_0 [1 - (T/T_c)^2]$$

Where, H_0 = critical field at 0K, T_c = Transition temperature

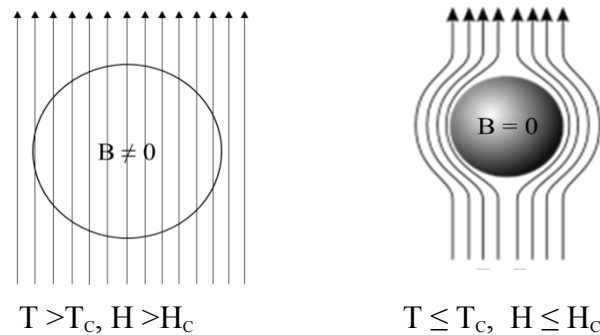
From the figure, we can find that when the temperature of the material increases, the value of the critical magnetic field decreases. Hence the value of the critical field will be different for different materials.

3. Diamagnetic Property – MEISSNER EFFECT

When a superconducting material is placed in a magnetic field of flux density 'B' the magnetic lines of force penetrates through the material as shown in figure.

Now, when the material is cooled below its transition temperature (i.e.,) When ($T \leq T_c$) then the magnetic lines of forces are expelled (or) ejected out from the material as shown in figure.

We know that a diamagnetic material have the tendency to expel the magnetic lines of forces. Since the super conductor also expels the magnetic lines of forces it behaves as a perfect diamagnet. This behavior is first observed by Meissner and hence called as **Meissner effect**.



Meissner effect

When the super conducting material is placed in magnetic field, under the condition when $T \leq T_c$ and $H \leq H_c$ the flux lines are excluded from the material. Thus the material exhibits perfect diamagnetism. This phenomenon is called as Meissner effect.

Proof:

We know, $\mathbf{B} = \mu_o (\mathbf{H} + \mathbf{I})$

When $B = 0$ we get $0 = \mu_o (H + I)$

Since $\mu_o \neq 0$ we can write $H + I = 0$

(or) $-H = +I$ (or) $I/H = -1 = \chi$

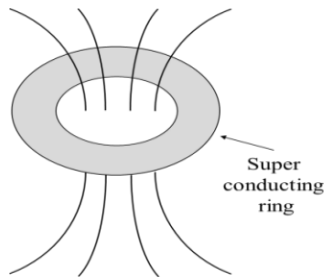
Since the susceptibility is negative, this shows that super conductor is a perfect **diamagnet**.

4. Effect of electric current

When a large value of a.c. current is applied to a super conducting material it induces some magnetic field in the material and because of this magnetic field, the super conducting property of the material is destroyed.

5. Persistant Current

When d.c. current of large magnitude is once induced in a super conducting ring then the current persists in the ring even after the removal of the field as shown in figure. This is known as persistent current.



This is due to the diamagnetic property (i.e.,) the magnetic flux inside the ring will be trapped in it and hence the current persists.

6. Thermal Properties

- (a) The entropy and specific heat decreases at transition temperature.
- (b) The thermal conductivity of type I super conductor is low.
- (c) The thermo-elastic effect disappears in the super conducting state.

7. Isotope effect

The transition temperature varies due to presence of isotopes.

Example

The atomic mass of mercury varies from 199.5 to 203.4, and hence the transition temperature varies from 4.185 K to 4.146 K.

Due to the relationship (i.e.,)

$$[T_c \propto 1/M^\alpha]$$

Where, M = atomic weight, α = constant (≈ 0.5)

8. General Properties

- (a) There is no change in elastic properties, photo electric properties and crystal structure.
- (b) The transition temperature is unchanged with the frequency variation.

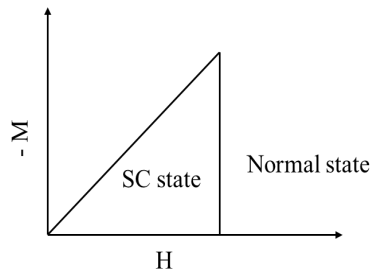
3.17 TYPES OF SUPER CONDUCTORS

There are two types of super conductors based on their variation in magnetization, due to external magnetic field applied. viz.

- (i) Type I super conductor (or) Soft super conductor
- (ii) Type II super conductor (or) Hard super conductor

Type I (soft) super conductor

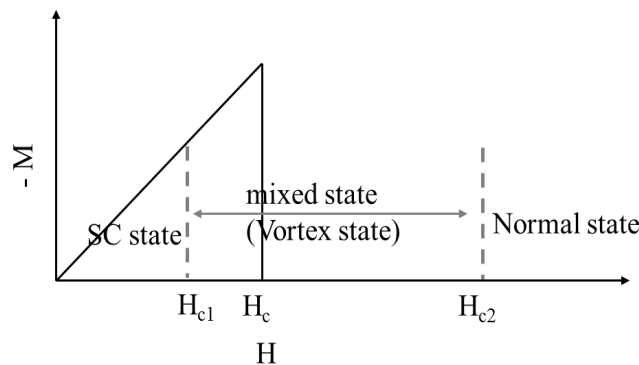
When the super conductor is kept in the magnetic field and if the field is increased the super conductor becomes a normal conductor abruptly at critical magnetic field as shown in figure. This type of materials is termed as Type I superconductors.



Below critical field, the specimen excludes all the magnetic lines of force and exhibits perfect Meissner effect. Hence Type I super conductors are perfect diamagnets, represented by the negative sign in magnetization.

Type II (hard) super conductor

When the super conductor is kept in the magnetic field and if the field is increased, below the lower critical field H_{c1} , the material exhibits perfect diamagnetism (i.e.,) it behaves as a superconductor and above H_{c1} , the magnetization decreases and hence the magnetic flux starts penetrating through the material. The specimen is said to be in a mixed state between H_{c1} and H_{c2} . Above H_{c2} (upper critical field) it becomes a normal conductor as shown in figure.



The material which loses its super conducting property gradually due to the increase in magnetic field is called Type II (hard) super conductors.

3.18 BCS [Bardeen, Cooper and Schrieffer] THEORY OF SUPER CONDUCTIVITY

Principle

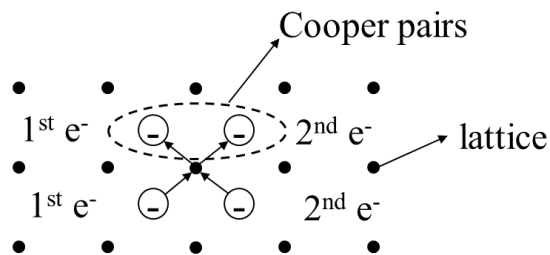
This theory states that the electrons experience a special kind of attractive interaction, overcoming the coulomb forces of repulsion between them, as a result cooper pairs (i.e.,) electron pairs are formed. At low temperature, these pairs move without scattering (i.e.,) without any resistance

through the lattice points and the material becomes super conductor. Here the electrons – lattice – electrons interactions should be stronger than electron – electrons interaction.

Electron – Lattice (phonos) – electron interaction

When an electron moves through the lattice, it will be attracted by the core of the lattice. Due to this attraction, ion core is distributed and it is called as lattice distortion. The lattice vibrations are quantized in terms of phonons.

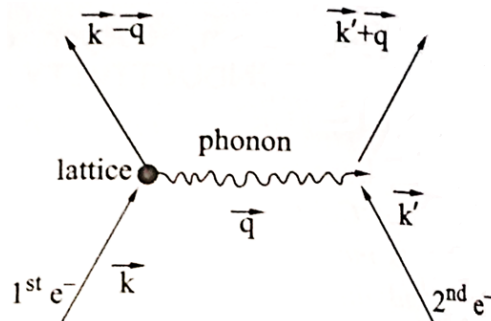
The deformation produces a region of increased positive charge. Thus, if another electron moves through this region as shown in figure, it will be attracted by the greater concentration of positive charge and hence the energy of the 2nd electron is lowered.



Hence the two electrons interact through the lattice or the phonons field resulting in lowering the energy of electrons. This lowering of energy implies that the force between the two electrons is attractive. This type of interaction is called Electron – Lattice – electron interaction. The interaction is strong only when the two electrons have equal and opposite momenta and spins.

Explanation

Consider the 1st electron with wave vector \vec{k} distorts the lattice, thereby emitting a photon of wave vector \vec{q} . This results in the wave vector for the 1st electron. Now, if the 2nd electron with the vector \vec{k}' , seeks the lattice, it takes up the energy from the lattice and its wave vector changes to $\vec{k}' + \vec{q}$ as shown in figure. Two electrons with wave vectors \vec{k} and \vec{k}' form a pair of electrons known as Cooper pairs.



Cooper Pairs

The pair of electrons formed due to electron – lattice – electron interaction by overcoming the electron – electron interaction with equal and opposite momentum and spins (i.e.,) with wave vectors and are called Cooper Pairs.

Temperature

When the temperature (T) is less than critical temperature (T_c), the resistivity due to lattice vibrations will be less. If the electron – lattice – electron is stronger than electron – electron interaction then more number of cooper pair electrons will be generated, these cooper pair electrons will sail (move freely) over the lattice points without any exchange of energy. So, they will not be slowed down. Hence, the material losses its resistive property and the conductivity becomes infinite and exhibiting the phenomenon of as Super Conductivity.

Coherence Length

In the electron – lattice – electron interaction, the electrons will not be fixed, they move in opposite directions and their co-relations may persist over lengths of maximum 10^{-6} m. This length is called coherence length.

3.19 HIGH TEMPERATURE SUPER CONDUCTORS (HTS)

High temperature super conductors are the materials which have transition temperature $T_c > 100\text{K}$. Usually in high temperature super conductors, the charge carriers are holes. Here, crossing the transition temperature of 77K is important, because cooling can be accomplished by liquid Nitrogen instead of liquid Helium, whose cost is more than Nitrogen. The rapid increase of T_c leads to the discovery of La-Sr-Nb-O system, whose T_c is 255K. Super conductors at room temperature are yet to be developed in future.

Examples

1. $\text{BaPb}_{0.75}\text{Bi}_{0.25}\text{O}_3$ (BPBO) for this the transition temperature is $T_c = 12\text{K}$
2. $\text{La}_{1.85}\text{Ba}_{0.15}\text{CuO}_4$ (LBCO) for this the transition temperature is $T_c = 36\text{K}$
3. $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO) for this the transition temperature is $T_c = 90\text{K}$
4. $\text{Tl}_2\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$ (TBCO) for this the transition temperature is $T_c = 120\text{K}$

Characteristics of HTS

1. They have high transition temperature
2. They are referred as 1-2-3 compound
3. They have PEROVSKITE crystal structure
4. They are direction dependent
5. They are reactive, brittle and cannot be easily formed (or) joined

6. They are oxides of copper in combination with other elements

Crystal structure of $\text{YBa}_2\text{Cu}_3\text{O}_7$

Preparation

As it is referred as 1-2-3 compound $\text{YBa}_2\text{Cu}_3\text{O}_7$ is prepared by heating Y_2O_3 , BaCO_3 and CuO in the right combination at a very high temperature say 110°C . Here BaCO_3 decomposes to give BaO and CO_2 , giving rise to the perovskite crystal structure as shown in figure.

Here, the primitive cell is developed by three body centered cubic unit cells stacked one above the other to form a tetragonal ($a = b \neq c$) perovskite structure tripled along the C axis. The distribution of atoms in the unit cell is as follows,

Yttrium atoms

Each Yttrium atoms is shared by one unit cell.

1/1th of the atom is shared by that unit cell

Number of yttrium atoms per unit cell

$$= 1/1 \times \text{total number of Yttrium atoms}$$

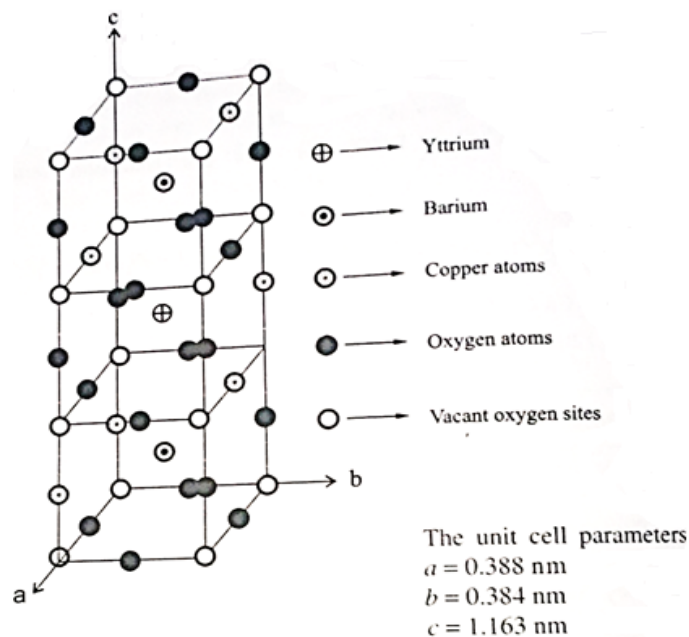
$$= 1/1 \times 1 = 1 \text{ atom/unit cell}$$

Barium atoms

Each Barium atom is shared by one unit cell

1/1th of the atom is shared by that particular unit cell

Number of Barium atoms per unit cell = $1/1 \times 2 = 2 \text{ atoms / unit cell}$



Copper atoms

Each copper atom is shared by 8 unit cells. Therefore $1/8^{\text{th}}$ of the atom is shared by one unit cell.

Number of Copper atoms per unit cell

$$= 1/8 \times \text{total number of copper atoms} \times \text{number of cells}$$

$$= 1/8 \times 8 \times 3$$

$$= 3 \text{ atoms / unit cell}$$

Oxygen atoms

Each oxygen atom is shared by 4 unit cells.

Therefore $1/4^{\text{th}}$ of the atom is shared by one unit cell

$$\text{Number of oxygen atoms per unit cell} = 1/4 \times 12 \times 3$$

$$= 9 \text{ atoms / unit cell}$$

Oxygen defect modification

It is found that actual formula should be $\text{Y}_1\text{Ba}_2\text{Cu}_3\text{O}_9$. But the crystal formed is $\text{Y}_1\text{Ba}_2\text{Cu}_3\text{O}_7$.

Hence the crystal structure of these materials is oxygen defect modification of the perovskite structure, with about one-third of the oxygen positions vacant. Therefore we can say, the number of oxygen atoms per unit cell = 7

The positive and negative ion vacancies are based on $\text{Y}^{+3}\text{Ba}^{+2}\text{Cu}^{+2}\text{O}^{-2}$

Here, positive ion vacancy = Vacancy \times Number of atoms/unit cell

(i.e.,) for $\text{Y}^{+3}\text{Ba}^{+2}\text{Cu}^{+2}$

We have $+3 \times 1 + 2 \times 2 + 2 \times 3 = +13$ vacancies.

(i.e.,) Negative ion vacancy = vacancy \times number of atoms / unit cell

(i.e.,) for O^{-2} we have $-2 \times 7 = -14$ vacancies.

The oxygen content per cell can be changed reversibly from 7 to 6 atoms, simply by pumping oxygen in and out of the parallel chains of CuO .

Conclusions

Hence from the above discussion, the following conclusions can be made.

- (i) At the composition of O_6 i.e., $\text{YBa}_2\text{Cu}_3\text{O}_6$ the crystal is an insulator.
- (ii) An increase in oxygen above $\text{O}_{6.5}$ i.e., $\text{YBa}_2\text{Cu}_3\text{O}_{6.5}$ makes the crystal metallic and non-magnetic and
- (iii) When the composition of oxygen is between and $\text{O}_{6.64}$ and O_7 (i.e.,) for composition between $\text{YBa}_2\text{Cu}_3\text{O}_{6.64}$ and $\text{YBa}_2\text{Cu}_3\text{O}_7$ the crystal behaves as a Super Conductor.

3.20 APPLICATIONS OF SUPER CONDUCTING MATERIALS

3.20.1 Engineering applications

Based on their properties, they have the following applications.

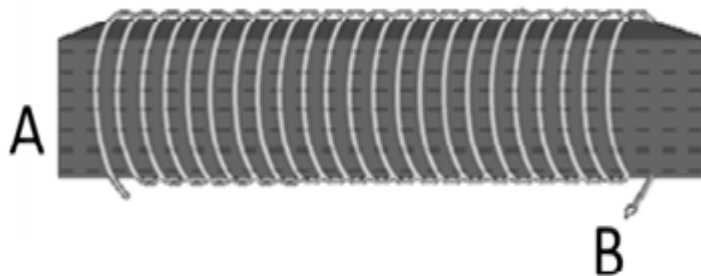
- (i) Since there is no loss in power (zero resistivity) super conductors can be used for the transmission of power over very large distances.
- (ii) Since the super conducting property can be easily destroyed it can be used in switching devices
- (iii) Since the variation in small voltages cause large constant current it can be used in very sensitive electrical instruments. Example: galvanometer.
- (iv) Since the current in a superconducting ring can flow without any change in its value (persistent current), it can be used as a memory (or) storage element in computers.
- (v) Since the size of the specimen can be reduced to about 10^{-4} cm, it can be used to manufacture electrical generators and transformers in small sizes with high efficiency.
- (vi) Apart from this, they are used to design cryotron, Josephson devices, SQUID, magnetic levitated trains (MAGLEV), modulators, rectifiers, communications, etc.,

3.20.2 Medical applications

- (i) Superconducting materials are used in NMR (Nuclear Magnetic Resonance) imaging equipment which is used for scanning purposes.
- (ii) They are applied in the detection of brain wave activity such as brain tumour, defective cells etc.
- (iii) Using super conducting magnets one can separate the damaged cells from the healthy cells.
- (iv) Super conducting solenoids are used in magneto – hydrodynamic power generation to maintain plasma in the body.

3.20.3 Cryotron

It is a magnetically operated current switch.



Principle

The super conducting property disappears when the magnetic field is greater than critical field (H_c).

Explanation

Let us consider a super conducting material 'A' surrounded by another super conducting material 'B' as shown in figure

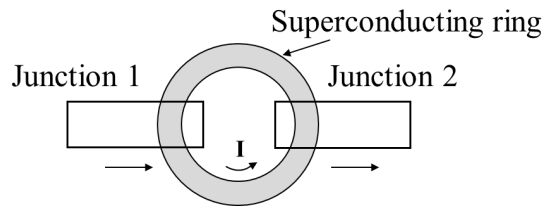
Let the critical field (H_{CA}) of the material A be less than the critical field (H_{CB}) of the material B. Initially, let the temperature of the whole system be below the transition temperature of the two materials (A and B).

Now, at operating temperature, the magnetic field produced by the material B may exceed the critical field of A. Hence the material A becomes normal conductor, because, the critical field of A is less than the critical field of B. Also, B will not become normal conductor at the critical field of A because $H_{CB} > H_{CA}$.

Therefore the current in material A can be controlled by the current in material B and hence this system can act as a Relay or Switching elements.

3.20.4 SQUIDS

SQUIDS (Super conducting Quantum Interference devices) are the improved model of Josephson devices. It has high efficiency, sensitivity and quick performance.



Principle

Small change in magnetic field, produces variation in the flux quantum.

Explanation

It consists of a super conducting ring which can have magnetic fields of quantum values (1,2,3,...) of flux placed in between the two Josephson junctions as shown in figure.

When the magnetic field is applied perpendicular to the plane of the ring, current is induced at the two Josephson junctions and produces interference pattern.

The induced current flows around the ring so that the magnetic flux in the ring can have quantum values of flux, which corresponds to the values of magnetic field applied.

Therefore SQUIDS are used to detect the variation in very minute magnetic signals in term of quantum flux. They are used as storage devices for magnetic flux.

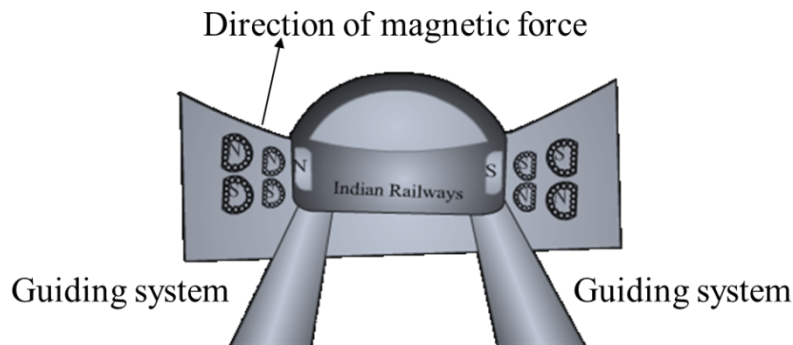
They are also used in the study of earth quakes, removing paramagnetic impurities, detection of magnetic signals from the brain, hearts etc.

3.20.5 Magnetic Levitated Train (MAG LEV)

Magnetic levitated train is the train which cannot move over the rail, rather it floats above the rails, under the condition, when it moves faster.

Principle

Electro-magnetic induction is used as the principle (i.e.,) when there is a relative motion of a conductor across the magnetic field, current is induced in the conductor and vice versa.



Explanation

This train consists of super conducting magnets placed on each side of the train. The train can run in a guidance system which consists of a series of "8" shaped coils as shown in figure.

Initially when the train starts, they slide on the rails. Now, when the train moves faster, the super conducting magnets on each side of the train will induce a current in the "8" shaped coils kept in the guidance system.

This induced current generates a magnetic force in the coils in such a way that the lower half of the 8-shaped coil has the same magnetic pole as that of the superconducting magnet in the train, while the upper half has the opposite magnetic pole. Therefore the total upward magnetic force acts on the train and hence the train is levitated (or) raised above the wheels (i.e.,) the train now floats above the air.

Now, by alternatively changing the poles of the super conducting magnet in the train alternation currents can be induced in the "8" shaped coils. Thus, alternating series of north and south magnetic poles are produced in the coils, which pulls and pushes the super conducting magnets in the train and hence the train is further moved.

This magnetic levitated train can travel a speed of 500 km/hour, which is double the speed of existing faster train.

PROBLEMS

1. Superconducting tin has a critical temperature of 3.7 K at zero magnetic field and a critical field of 0.0306 Tesla at 0K. Find the critical field at 2K.

Given: $T_c = 3.7\text{K}$

$$H_0 = 0.0306 \text{ Tesla}$$

$$T = 2\text{K}$$

$$H_c = ?$$

$$\text{Critical field } H_c = H_0 [1 - (T^2/T_c^2)]$$

$$= 0.0306 [1 - (2^2/3.7^2)]$$

$$= 0.02166 \text{ Teslas}$$

2. The critical temperature for a metal with isotopic mass 199.5 is 4.18K. Calculate the isotopic mass if the critical temperature falls to 4.133K.

Given: $T_{c1} = 4.185\text{K}$, $T_{c2} = 4.133\text{K}$,

$$M_1 = 199.5, M_2 = ?$$

$$\text{Critical Temperature} \quad T_c = 1 / M^a$$

$$\text{At initial critical temperature } 4.185 = 1 / (199.5)^{0.5} \quad \dots\dots\dots (1)$$

$$\text{At final critical temperature } 4.133 = 1 / (M_2)^{0.5} \quad \dots\dots\dots (2)$$

Dividing equation (1) by (2)

$$(4.185 / 4.133) = (M_2)^{0.5} / (199.5)^{0.5}$$

$$(M_2)^{0.5} = (199.5)^{0.5} \times 1.01258$$

$$= 14.124 \times 1.01258 = 14.3016$$

$$M_2 = \sqrt[0.5]{14.3016}$$

$$M_2 = 204.536$$

3. Calculate the critical current which can flow through a long thin superconducting wire of aluminum of diameter 10-3m. The critical magnetic field for aluminum is $7.9 \times 10^3 \text{ A/m}$.

$$\begin{aligned}
 I_c &= 2\pi r H_c \\
 &= 2\pi \times 7.9 \times 10^3 \times (10^{-3}/2) \\
 &= 24.81 \text{ Amp}
 \end{aligned}$$

4. Prove that susceptibility of super conductor is -1 and relative permeability is zero.

$$B = \mu_o(M+H)$$

We know $B = 0$ for superconductor

$$0 = \mu_o(M+H)$$

Since $\mu_o \neq 0$; $M = -H$

$$M = \chi H$$

Therefore $-H = \chi H$

$$\chi = -1$$

$$\chi = \mu_r - 1, \quad \mu_r = -1 + 1 = 0$$

Thus the susceptibility $\chi = -1$ and relative permeability $\mu_r = 0$

UNIT III

DIELECTRICS

INTRODUCTION

Solids which have an energy gap of 3 eV or more are termed as insulators. In these materials, it is almost not possible to excite the electrons from the valence band to the conduction band by an applied field. Generally, dielectrics are also called as insulators, thereby poor conductors of electricity. However, they allow some of the electrons at abnormally high temperatures, causing a small flow of current.

Dielectrics are non-metallic materials of high specific resistance ρ , negative temperature coefficient of resistance ($-\alpha$) and large insulation resistance. Insulation resistance will be affected by moisture, temperature, applied field and age of dielectrics.

FUNDAMENTAL DEFINITIONS AND PROPERTIES

1. Electric polarization

The process of producing electric dipoles inside the dielectrics by an external electric field is called polarization in dielectrics.

2. Polarization vector (P)

If the strength of the electric field E is increased the strength of the induced dipole also increases. The induced dipole moment is proportional to the intensity of the electric field.

$$\mu = \alpha E$$

where, α is the constant of proportionality, called the Polarizability.

If μ is the average dipole moment per molecule and N is the number of molecules per unit volume, the polarization vector is defined as dipole moment per unit volume of the dielectric material.

3. Electric Displacement Vector (D)

Electric Displacement Vector or electric induction (D) is a quantity which is used for analyzing electrostatic fields in the presence of dielectrics, which is given by

$$D = \epsilon_0 E + P \quad \dots(1)$$

We know electric field intensity

$$E = \frac{D}{\epsilon_0} \quad \dots(2)$$

From (1) and (2) we get

$$D = \epsilon_0 E + P \quad \dots (3)$$

Since $\epsilon = \epsilon_0(1 + \chi_e)$ Where, χ_e is the electrical susceptibility.

4. Relation between P and E

We know

Since $P = \epsilon_0 \chi E$, we have

$$\dots (4)$$

Equating (3) and (4)

$$\dots (5)$$

5. Electrical Susceptibility (χ)

The polarization vector (P) is proportional to the applied electric field (E), for field strengths that are not too large. So we can write

$$\dots (1)$$

is a characteristic of every dielectric and which is called electrical susceptibility.

Since

Therefore,

$$\dots (2)$$

6. Dielectric constant (ϵ_r)

Dielectric constant (ϵ_r) is the measure of the polarization produced in the material. It is the ratio between absolute permittivity (ϵ) and the permittivity of free space (ϵ_0).

i.e.,

is a dimensionless quantity and it is a measure of polarization in the dielectrics. The value of for air or vacuum.

For solids, for glass it is 4 to 7, for diamond is 5.68, for silicon it is 12, for germanium it is 16, for ethanol it is 24.3 and for water at 0°C

ACTIVE AND PASSIVE DIELECTRICS

Active Dielectrics

Dielectrics which can be easily adapt itself to store the electrical energy in it is called active dielectrics. Ex: Piezo electrics, Ferro electrics, Pyro electrics.

It is used in production of Ultrasonics.

Passive Dielectrics

Dielectrics which restrict the flow of electrical energy in it are called passive dielectrics.

Ex: Glass, mica, plastic

It is used in production of sheets, pipes etc.

POLAR AND NON-POLAR MOLECULES

POLAR MOLECULES

The molecules have permanent dipole moments even in the absence of an applied field is called polar molecules. These molecules do not have symmetrical structure and do not have centre of symmetry.

Ex: H_2O , N_2O , HCl , NH_3 etc.

Effect of electric field

In the absence of electric field

In the absence of electric field the polar molecule possesses some dipole moment. Since, these dipoles are randomly oriented they cancel each other and the net dipole moment will be very less (approx zero).

In the presence of electric field

When an external electrical field is applied the dipoles in the dielectrics will align themselves parallel to the field direction and produce a net dipole moment.

NON POLAR MOLECULES

The molecules which do not have permanent dipole moments are called Non Polar molecules. These molecules have symmetrical structure and they have centre of symmetry

Ex: N_2 , H_2 , O_2 , CH_4 , CO_2

Effect of electric field

When a non-polar molecule is placed in an external electric field, a force is exerted on each charged particle within the molecule. (i.e.,) the positive particles are pushed along the field direction and the negative charges are pushed opposite to the field direction. Hence the positive and negative charges are separated by some distance from their equilibrium positions, creating a dipole and therefore a net dipole moment will be produced in non-polar molecules.

INTERNAL FIELD OR LOCAL FIELD AND DEDUCTION OF CLAUSIUS MOSOTTI EQUATION

When a dielectric material is kept in an external field it exerts a dipole moment in it. Therefore two fields are exerted, viz.,

- I. Due to external field
- II. Due to dipole moment.

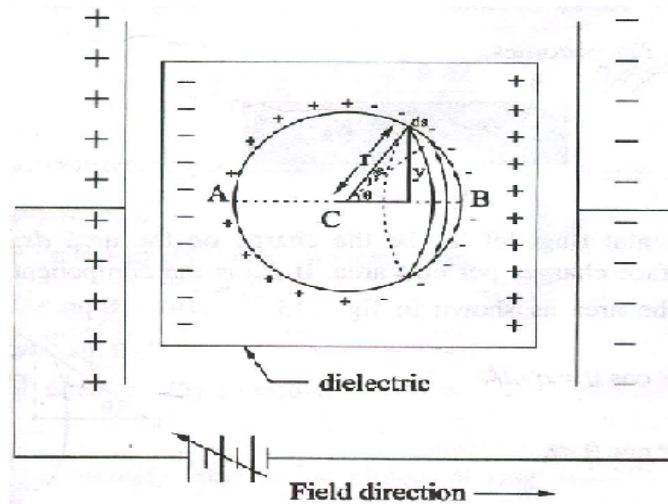
This long range of coulomb forces which is created due to the dipoles is called as internal field or local field. This field is responsible for polarizing the individual atoms or molecules.

Lorentz Method for Finding Internal Field

Let us assume a dielectric material kept in an external electric field. Consider an imaginary sphere in the solid dielectric of radius 'r'.

Here the radius of the sphere is greater than the radius of the atoms. i.e., there are many atomic dipoles within the sphere.

A small elemental ring is cut with thickness ds . Let y be the radius of the small ring as shown in figure.



The electric field at the centre of the sphere is called internal field, which arises due to the following four factors.

$$E_{\text{int}} = E_1 + E_2 + E_3 + E_4 \quad \dots\dots\dots(1)$$

Where,

E_1 - Field due to the charge on the plates.(externally applied)

E_2 - Field due to p[olarization charges on the plane surface of the dielectric.

E_3 - Field due to polarized charges induced at the spherical surface.

E_4 - Field due to atomic dipoles inside the sphere considered.

Macroscopically, we can take $E = E_1 + E_2$ (i.e.). The field externally applied (E_1) and the field induced on the plane surface of the dielectric (E_2) as a single field (E).

If the dielectric is highly symmetric then the dipoles will cancel with each other therefore we can take $E_4 = 0$

Equation (1) becomes

$$E_{int} = E + E_3 \quad \dots\dots\dots(2)$$

To find E_3

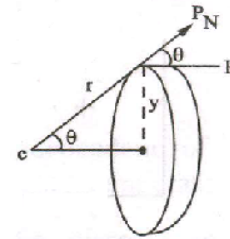
In the elemental ring, let "q" be the charge on the area ds. Polarization is defined as the surface charges per unit area.

If P_N is the component of polarization perpendicular to the area as shown in figure.

Here $P_N = P \cos \theta = -q'/ds$

(or) $q' = P \cos \theta \, ds$

Electric field intensity at 'C' due to charge q' is given by

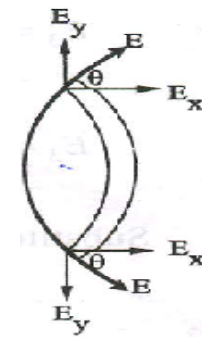


The above intensity is along the radius 'r'. \dots\dots\dots(3)

Resolving the intensity into two components as shown in figure.

Component Parallel to the field direction $E_x = E \cos \theta$

Component Perpendicular to the field direction $E_y = E \sin \theta$



The perpendicular components are in the opposite directions and hence cancel each other. So the parallel components are alone taken into consideration.

If the total surface area of the ring is considered as dA then

$$E_x = E = \quad \dots\dots\dots(4)$$

Where, $dA = \text{circumference} \times \text{thickness}$
 $dA = 2\pi y \times dS$

Since $y = r \sin \theta$ and $dS = r \, d\theta$, we can write

$$dA = 2\pi r \sin \theta \times r \, d\theta$$

(Or) $dA = 2\pi r^2 \sin \theta \, d\theta \quad \dots\dots\dots(5)$

Substitute eqn (5) in (4) we get

Electric field intensity due to the elemental ring

$$= \quad \dots\dots\dots(6)$$

Electrical field intensity due to the whole sphere can be derived by integrating eqn (6) within the limits 0 to π .

$$\dots\dots\dots(7)$$

Substituting eqn (7) in (2) we get

.....(8)
Where, E_i is called internal field or Lorentz field.

Clausius – Mosotti Relation

We know

(Or)

Substituting eqn (9) in eqn (8), we get(9)

Rearranging we get

We know polarization $P = N\alpha E_i$ (10)

Comparing eqn (10) & (11) we get(11)

.....(12)
The above equation is called **Clausius – Mossotti Relation**.

APPLICATIONS OF DIELECTRIC MATERIALS

The dielectric materials has three major applications

- It is used as a dielectric medium in capacitors.
- It is used as insulating materials in transformers.
- It is used in industries and dielectric heating.

DIELECTRICS IN CAPACITORS

For dielectrics to be used in capacitors, it should posses the following properties.

Properties:

- It must have high dielectric constant.
- It should posses high dielectric strength.
- It should have high specific resistance.
- It should have low dielectric loss.

Uses

- Thin sheets of papers filled with synthetic oils are used as dielectrics in the capacitors.
- Tissue papers and polypropylene flims filled with dielectrol are used in power capacitors.
- Mica is used as dielectrics in discrete capacitors.
- An electrolytic solution of sodium phosphate is used in wet type electrolytic capacitors.
- An electrolytic paste made up of ammonium tetraborate and glycol is used in Dry type electrolytic capacitors.

- Ceramic materials such as Barium titanate and calcium titanate are used in disc capacitors and high frequency capacitors respectively.

INSULATING MATERIALS IN TRANSFORMERS

For dielectrics to act as insulating materials, it should possess the following properties.

Properties

- It should have low dielectric constant.
- It should possess low dielectric loss.
- It must have high resistance.
- It must possess high dielectric strength.
- It should have adequate chemical stability.
- It must have high moisture resistance etc.

Uses

- Ceramics and polymers are used as insulators.
- Paper, rubber, plastics, waxes etc are used to form thin films, sheet tapes, rods etc.
- PVC (Poly Vinyl Chloride) is used to manufacture pipes, batteries, cables etc.
- Glass, mica, asbestos, alumina are used in ceramics.
- Porcelain is used in high voltage power lines.
- Liquid dielectrics such as petroleum oils, silicone oils are widely used in transformers, circuit breakers etc.
- Mineral insulating oils obtained from crude petroleum by distillation is used as transformer oil, because of high resistance to oxidation and fire hazards.
- Synthetic oils such as askarels, sovol etc are used as a coolant and insulant in high voltage transformers.
- Gases such as vacuum, air, nitrogen, sulphur hexa fluoride are used in X-ray tubes, switches, high voltage gas filled pressure cables, coolants respectively.

MAGNETIC MATERIALS

INTRODUCTION

Magnetic materials are the materials which can be made to behave as magnets. When these materials are kept in an external magnetic field, they will create a permanent magnetic

moment in it. Diamagnetic, Paramagnetic, Ferromagnetic, Antiferromagnetic and Ferromagnetic materials are the magnetic materials type.

Magnetism originates from the magnetic moment of the magnetic materials due to the rotational motion of the charged particles. When an electron revolves around the positive nucleus, orbital magnetic arises and due to the spinning of electrons, spin magnetic moment arises. Let us see some of the basic definitions in magnetism.

BASIC DEFINITIONS

Magnetic dipole moment

A system having two opposite magnetic poles separated by a distance 'd' is called as a magnetic dipole. If 'm' is magnetic pole strength and 'l' is the length of the magnet, then its dipole moment is given by

$$M = ml$$

Magnetic moment can also be defined as $M = ia$, where i is the electric current that flows through a circular wire of an area of cross section 'a'.

Bohr Magneton

The total magnetic moment and the spin magnetic moment of an electron in an atom can be expressed in terms of atomic unit of magnetic moment called Bohr magneton.

$$1 \text{ Bohr magneton} = e\hbar/2m = 9.27 \times 10^{-24} \text{ Am}^2$$

Magnetic field

The space around the magnet or the current carrying conductor where the magnetic effect is felt is called magnetic field.

Magnetic lines of force

Magnetic field is assumed to consist of lines of magnetic forces. These lines of forces travel externally from North Pole to South Pole as shown in figure. Hence a magnetic line of force is defined as the continuous curve in a magnetic field. The tangent drawn at any point on the curve gives the direction of the resultant magnetic intensity at that point.

Magnetic induction (or) Magnetic flux density (B)

It is defined as the number of magnetic lines of force passing normally through unit area of cross section at that point.

Magnetic field intensity (H)

It is defined as the force experienced by a unit North Pole placed at the given point in a magnetic field

Magnetisation (or) Intensity of Magnetisation (I)

The magnetization is the process of converting a non-magnetic material into a magnetic material. It measures the magnetization of the magnetized specimen. It also defined as the magnetic moment per unit volume

Magnetic susceptibility (χ_m)

It is defined as the ratio between intensity of magnetization (I) and the magnetic field intensity (H)

$$\chi_m =$$

Magnetic permeability (μ)

It is defined as the ratio between the magnetic flux density (B) and the magnetic field intensity (H)

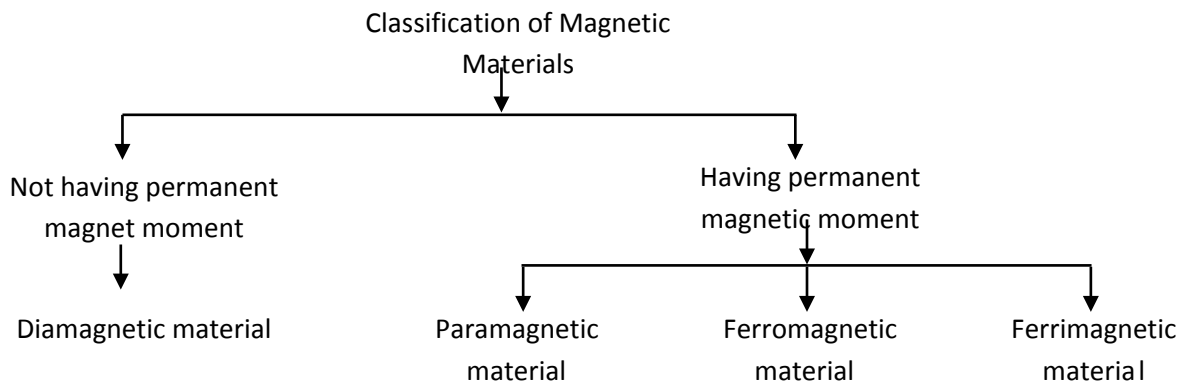
$$\mu =$$

CLASSIFICATION OF MAGNETIC MATERIALS ON THE BASIS OF MAGNETIC MOMENT

Magnetic materials are classified according to the presence or absence of the permanent magnetic dipoles. Generally, every two electrons in an energy state of an atom will form a pair with opposite spins. Thus the resultant spin magnetic moment is zero. Hence they don't have permanent magnetic moments and they are called as diamagnetic materials.

Example: Gold, germanium, silicon, etc.

But in some magnetic materials like iron, cobalt, etc., there exists unpaired electrons. The spin magnetic moment of these unpaired electrons interact with the adjacent atoms unpaired electron spin magnetic moment in a parallel manner resulting in enormous permanent spin magnetic moment. These materials are classified into para, ferro and ferrimagnetic materials with respect to the electron spins.



DIAMAGNETIC MATERIAL

In a diamagnetic material, the electron orbits are more or less random, and mostly all the magnetic moments are cancelled. Similarly all the spin moments are almost paired i.e., they have even number of electrons and has equal number of electrons spinning in two opposite directions. Hence the net magnetic moment in the diamagnetic material is zero. Therefore most of the materials do not have magnetism in the absence of magnetic field.

Effect of external field

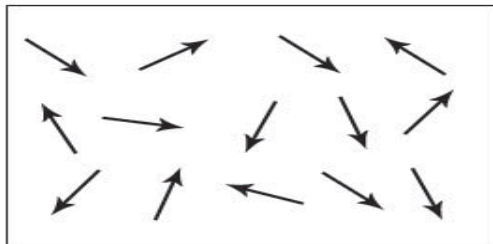
When an external magnetic field is applied, the electrons reorient in such a way that they align perpendicular to the field direction and their magnetic moments oppose the external magnetic field. This will reduce the magnetic induction present in the specimen.

Properties

1. They repel the magnetic lines of force
 2. Susceptibility is negative and it is independent of temperature and applied magnetic field strength
 3. Permeability is less than 1
 4. There is no permanent dipole moment, so they are called weak magnets
 5. When temperature is less than critical temperature diamagnetic become normal material
- Examples: Gold, Germanium, Silicon, etc.,

PARAMAGNETIC MATERIALS

In the case of paramagnetic materials, the spins in two opposite directions will not be equal. There exist some unpaired electrons which gives rise to spin magnetic moment. Hence the resultant magnetic will not be equal to zero.



However in the absence of external field the magnetic moments are oriented randomly. Due to its random orientation some magnetic moments get cancelled and the materials possess very less magnetization in it.

Effect of external field

When an external field is applied, the magnetic moments of individual molecules reorient itself along the direction of the magnetic field and the material is magnetized.

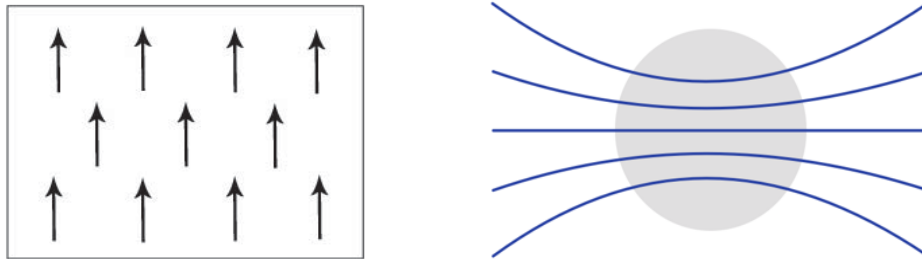
Properties

1. The magnetic lines of force pass through the material
2. Magnetic susceptibility is positive and it is given by
3. Permeability is greater than one
4. They possess permanent dipole moment
5. When the temperature is less than Curie temperature, paramagnetic materials becomes diamagnetic material.

Examples: CuSO_4 , MnSO_4 , Platinum etc.

FERROMAGNETISM

In a ferromagnetic material the numbers of unpaired electrons are more. Most of these spin magnetic moments point in one direction as shown in figure.



Hence even in the absence of external field, the magnetic moments align themselves parallel to each other and give rise to magnetic field.

Effect of magnetic field

To these materials even if a small external magnetic field is applied, the magnetic moments which are already aligned parallel, reorient itself along the direction of the magnetic field and they become very strong magnets.

Properties

1. Since some magnetization is already existing in these materials, all the magnetic lines of force passes through it
2. They have permanent dipole moment. So they act as strong magnets.
3. They exhibit magnetization even in the absence of external field. This property is called Spontaneous magnetization.
4. Its susceptibility is positive and high and it is given by

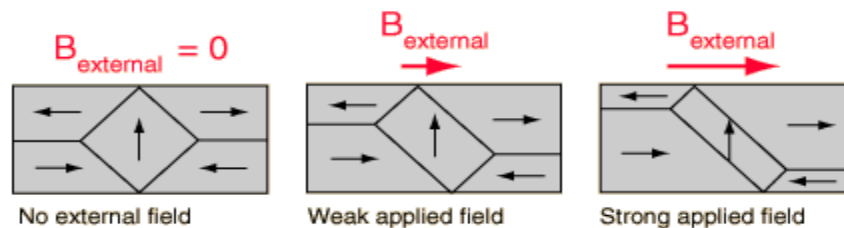
5. When the temperature is greater than Curie temperature, ferromagnetic material becomes paramagnetic material.
6. Permeability is very much greater than 1

Examples: Ni, Co, Fe, etc.,

FERROMAGNETIC DOMAINS

We can observe that a ferromagnetic material such as iron does not have magnetization unless they have been previously placed in an external magnetic field. But according to Weiss theory, the molecular magnets in the ferromagnetic material are said to be aligned in such a way that, they exhibit a magnetization even in the absence of an external magnetic field. This is called spontaneous magnetization. i.e., it should have some internal magnetization due to quantum exchange energy.

Thus according to Weiss hypothesis, a single crystal of ferromagnetic material is divided into large number of small regions called domains. These domains have spontaneous magnetization due to the parallel alignment of spin magnetic moments in each domain. But the directions of spontaneous magnetization vary from domain to domain and are oriented in such a way that the net magnetization of the specimen is zero as shown in figure.



Due to this reason the iron does not have any magnetization in the absence of an external field.

Now, when the magnetic field is applied, then the magnetization occurs in the specimen by two ways

1. By the movement of domain walls
2. By rotation of domain walls

(i) By the movement of domain walls

The movement of domain walls takes place in weak magnetic fields. Due to this weak field applied to the specimen the magnetic moment increases and hence the boundaries of domains are displaced, so that the volume of the domains changes as shown in figure.

(ii) By rotation of domain walls

The rotation of domain walls takes place in strong magnetic fields. When the external field is high (strong) then the magnetization changes by means of rotation of the direction of magnetization towards the direction of the applied field as shown in figure.

DOMAIN THEORY OF FERROMAGNETISM

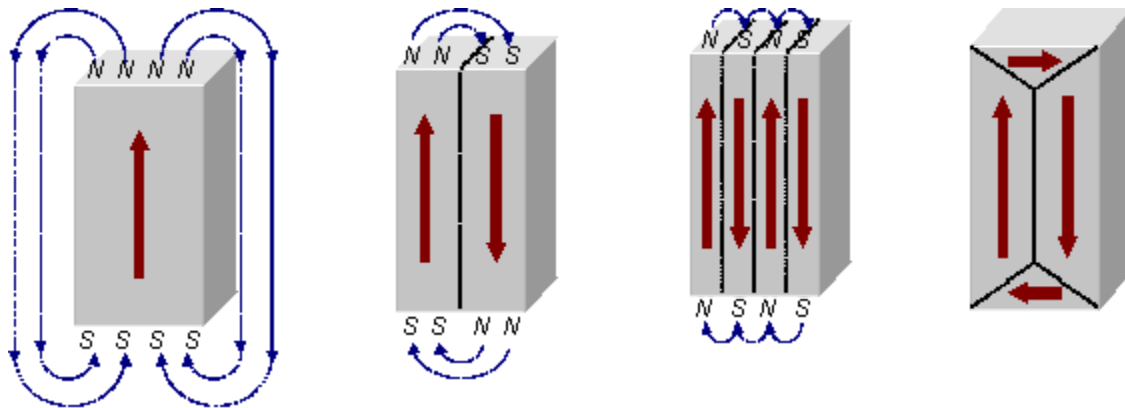
The domain in ferromagnetic solid is understandable from the thermo dynamical principle, (i.e.,) in equilibrium the total energy of the system is minimum. For this, first we consider the total energy of the domain structure and then how it is minimized. The total energy of the domain comprises the sum of following energies. Viz,

1. Exchange energy
2. Anisotropy energy
3. Domain wall energy
4. Magneto-strictive energy

(i) Exchange energy (or) magnetic field energy (or) magneto-static energy

The interaction energy which makes the adjacent dipoles to align themselves is known as exchange energy (or) magnetic field energy. The exchange energy has established a single domain in a specimen of ferromagnetic and it is shown in figure.

Because of the development of the free poles at the domain, an external field will be produced around it and the configuration will have a high value of magnetic field energy. In other words it is the energy required in assembling the atomic magnets into a single domain and this work done is stored as potential energy.



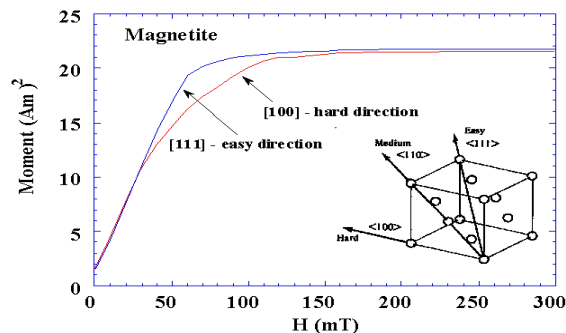
The magnetic energy can be reduced by dividing the specimen into two domains as shown in figure. The process of subdivision may be carried further, until the reduction of magnetic energy is less than the increase in energy to form another domain and its boundary. This boundary is called as domain wall (or) Block wall.

(ii) Anisotropy energy

In ferromagnetic crystals there are two direction of magnetization, viz,

- (i) Easy direction
- (ii) Hard direction

In easy direction of magnetization, weak field can be applied and in hard direction of magnetization, strong field should be applied. For producing the same saturation magnetization along both the hard and easy direction, strong fields are required in the hard direction than the easy direction.



For example in Iron easy direction is [100], medium direction is [110] and the hard direction is [111] and it is as shown in figure. From the figure we can see that very strong field is required to produce magnetic saturation in hard direction [111] compared to the easy direction [100].

Therefore the excess of energy required to magnetize the specimen along hard direction over that required to magnetize the specimen along easy direction is called crystalline anisotropy energy.

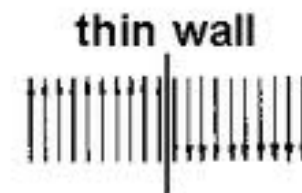
(iii) Domain wall energy (or) Bloch wall energy

Bloch wall is a transition layer which separates the adjacent domains, magnetized in different directions. The energy of domain wall is due to both exchange energy and anisotropic energy.

Based on the spin alignments, two types of Bloch walls may arise, namely

- (i) Thick wall
- (ii) Thin wall

Thick wall: When the spins at the boundary are misaligned and if the direction of the spin changes **gradually** as shown in figure, it leads to a thick Bloch wall. Here the misalignments of spins are associated with exchange energy.



Thin wall: When the spins at the boundaries changes **abruptly**, then the anisotropic energy becomes very less. Since the anisotropic energy is directly proportional to the thickness of the wall, this leads to a thin Bloch wall.

(iv) Magnetostrictive energy

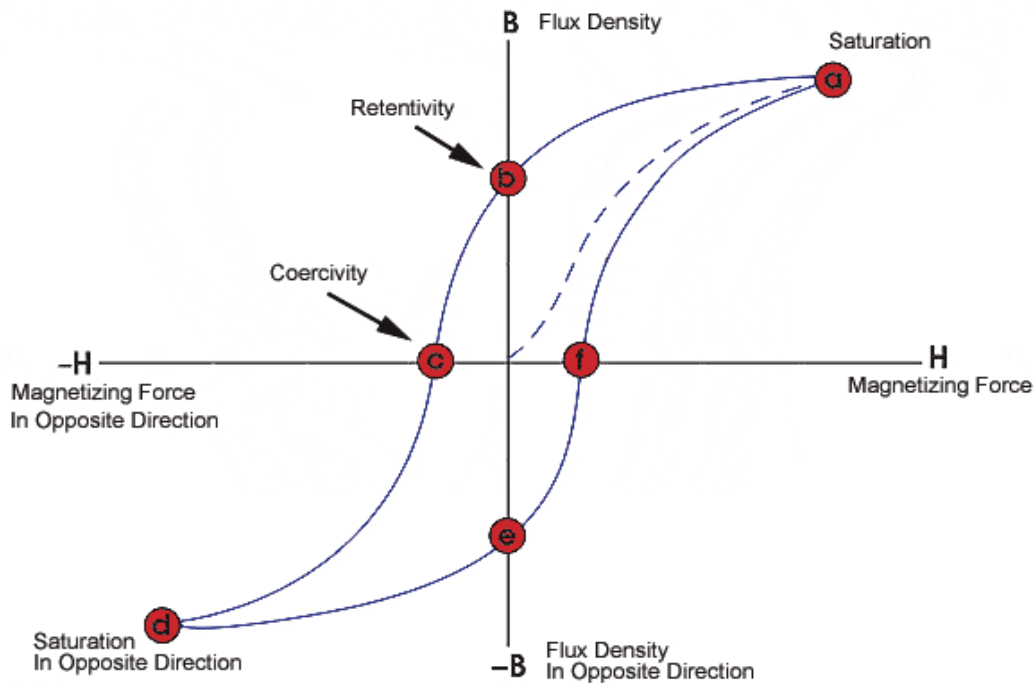
When the domains are magnetized in different directions, they will either expand (or) shrink. Therefore there exists a deformation (i.e.,) change in dimension of the material, when it is

magnetized. This phenomenon is known as magnetostriction and the energy produced in this effect is known as magnetostriction energy.

The deformation is different along different crystal directions and the change in dimension (increase or decrease) depends upon the nature of the material. For example in Ni the length decreases; and in permalloy the length increases. But both the increase (and) decrease is due to the mechanical stress generated by domain rotation.

HYSTERESIS

When a ferromagnetic material is made to undergo through a cycle of magnetization, the variation of B with respect to H can be represented by a closed hysteresis loop (or) curve. i.e., it refers to the lagging of magnetization behind the magnetizing field.



If a magnetizing field H is applied to a ferromagnetic material and if H is increased to H_{\max} the material acquires the magnetism. So the magnetic induction also increases, represented by 'oa' in the figure.

Now if the magnetic field is decreased from H_{\max} to zero, the magnetic induction will not fall rapidly to zero, but falls to 'b' rather than zero. This shows that even when the applied field is zero or removed, the material still acquires some magnetic induction (ob) which is so called Residual magnetism or Retentivity.

Now, to remove this residual magnetism, the magnetic field strength is reversed and increased to $-H_{\max}$ represented as 'oc' so called coercivity and hence we get the curve 'bcd'. Then

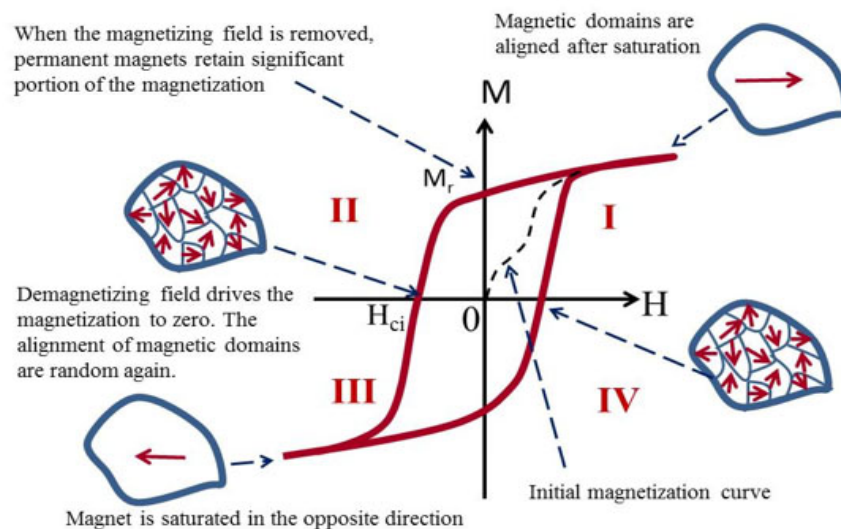
the reverse field ($-H$) is reduced to zero and the corresponding curve 'de' is obtained and by further increasing H to H_{\max} the curve 'efa' is obtained.

EXPLANATION OF HYSTERESIS ON THE BASIS OF DOMAINS

We know when the ferromagnetic material is subjected to external field, there is an increase in the value of the resultant magnetic moment due to two process, viz.,

1. The movement of domain walls
2. Rotation of domain walls

When a small external field is applied, the domains walls are displaced slightly in the easy direction of magnetization. This gives rise to small magnetization corresponding to the initial portion of the hysteresis curve (OA) as shown in figure.



Now, if the applied field is removed, then the domains returns to its original state, and is known as reversible domains.

When the field is increased, large number of domains contributes to the magnetization and thus the magnetization increases rapidly with H .

Now, even when the field is removed, because of the displacement of the domain wall to a very large distance, the domain boundaries do not come back to their original position. This process is indicated as AB in figure and these domains are called irreversible domains.

At point 'B' all the domains have got magnetized along the easy direction. Now, when the field is further increased, the domains starts rotating along the field direction and the anisotropic energy is stored in the hard direction, represented as BC in the figure.

Thus the specimen is said to attain the maximum magnetization. At this position, even after the removal of external field the material possess maximum magnetization, called residual magnetization or retentivity, represented by OD in figure.

Actually after the removal of the external field, the specimen will try to attain the original configuration by the movement of Bloch wall. But this movement is stopped due to the presence of impurities, lattice imperfections etc. Therefore to overcome this, a large amount of reverse magnetic field is applied to the specimen. The amount of energy spent to reduce the magnetization to zero is called as coercivity represented by 'OE' in the figure.

Hysteresis loss

It is the loss of energy in taking a ferromagnetic specimen through a complete cycle of magnetization and the area enclosed is called hysteresis loop.

Based on the area of the hysteresis loop, the magnetic materials are classified into soft and hard magnetic materials.

APPLICATIONS OF FERRITES

- (i) They are used to produce ultrasonics by magnetostriction principle.
- (ii) Ferrites are used in audio and video transformers.
- (iii) Ferrite rods are used in radio receivers to increase the sensitivity.
- (iv) Since the ferrites have low hysteresis loss and eddy current loss, they are used in two port devices such as gyrator, circulator and isolator.

Gyrator: It transmits the power freely in both directions with a phase shift of π radians.

Circulator: It provides sequential transmission of power between the ports.

Isolator: It is used to display differential attenuation.

- (i) They are also used for power limiting and harmonic generation.
- (ii) Ferrites are used in parametric amplifiers so that the input can be amplified with low noise figures.
- (iii) They are used in computers and data processing circuits.
- (iv) Ferrite cubes are used in switching circuits and in matrix storage devices of computers.
- (v) Ferrites are not metals, but their resistivity lies in the range of insulator or semiconductor. Thus, the power losses due to eddy currents are reduced in this type of materials and hence they are used in microwave frequency applications.
- (vi) Ferrites are used in storage devices such as magnetic tapes, floppy discs, hard discs, ferrite core memories and in bubble memories.

6.1 INTRODUCTION

Materials form an integral part of our life. Advancement in our day to day life leads to the discovery of many new Engineering Materials such as metallic glasses, nano-phase materials, non-linear materials, shape-memory alloys etc.

All these materials are composite materials which are prepared by grouping one type of material with the other, say for example, metals mixed with polymers, ceramics mixed with metals etc. Also, it was found that the resultant materials has some peculiar properties, which varies with respect to size, shape and the nature of mixture. *Because of their peculiar properties these materials are used in High-Tec applications such as magnetic alloys in CD's / DVDs, titanium alloys in supersonic planes, space shuttles, etc.* In this chapter some of the New Engineering Materials along with their properties and the wide range of applications it has in this Modern Engineering World were discussed.

6.2 METALLIC GLASSES (MET GLASSES)

We know metals are solids, which exhibits crystalline property, malleability, ductility etc.

Also we know glasses are solids in the amorphous form in which the atoms arrangement are not periodic and they are irregular. In general they are transparent and brittle in nature.

Metallic glasses are new type of materials which possess both the properties of metals and glasses as listed below in Table 6.1.

$$\text{i.e.} \quad \begin{array}{|c|c|c|} \hline \text{Properties of} & + & \text{Properties of} \\ \text{metals} & & \text{glass} \\ \hline \end{array} = \begin{array}{|c|} \hline \text{Properties of} \\ \text{metallic glasses} \\ \hline \end{array}$$

Table 6.1

S.No.	Properties of metals	Properties of glasses	Properties of metallic glasses
1.	Crystalline	Amorphous	Non-crystalline and amorphous alloys.
2.	Ductile	Brittle	Brittle and ductile.
3.	Not-transparent (opaque) Malleable	Transparent	Malleable and opaque

Definition : *Metallic glasses are the amorphous metallic solids which have high strength, good magnetic properties and better corrosion resistance and will possess both the properties of metals and glasses.*

Examples : Alloys of Fe, Ni, Al, Mn, Cu, Cr and Co mixed with metalloids such as Si, Ge, As, B, C, P and N.

6.3 CONCEPT BEHIND THE FORMATION OF METALLIC GLASSES

Generally liquids can be made into glassy state by increasing the rate of cooling.

In a similar manner the metals can also be made into glassy state by increasing the rate to cooling to a very high level [2×10^6 °C per second]. At that state the atoms will not be able to arrange orderly because of its rapid cooling rate.

Thus, the atoms will not be allowed to go to crystalline state, rather it goes to amorphous state and it will form a new type of material. These new type of materials which are made by rapid cooling technique (i.e., the temperature decreases suddenly with respect to time) are called *metallic glasses*.

NOTE : The cooling rate for the formation of metallic glasses varies from material to material.

Glass Transition temperature

The temperature at which the metals (alloys) in the molten form transforms into glasses i.e. liquids to solids is known as *glass transition temperature (T_g)*.

It was found that the glass transition temperature for metallic alloys varies from 20°C to 300°C.

The change of state from molten liquid to metallic glasses is shown in fig.6.1.

Case (1) : In fig.6.1, the curve ABDE shows the change of state from molten liquid to crystalline solid at the temperature called *melting point temperature (T_m)*.

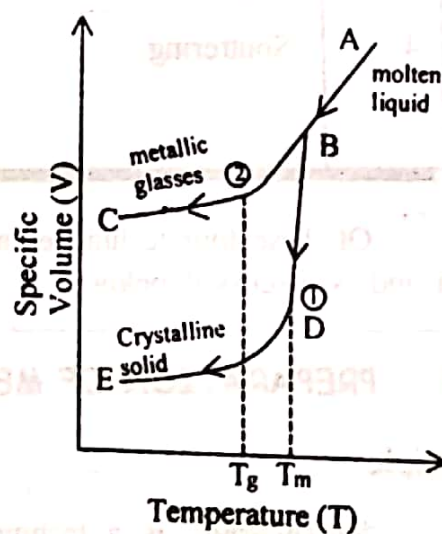


Fig. 6.1

This occurs due to normal rate of cooling, with the decrease in its specific volume. Thus it forms a normal crystalline material.

Case (2) : The curve ABC shows the change of state from a molten liquid to metallic glasses due to rapid cooling without decrease in its specific volume at the temperature called *glass transition temperature* (T_g). Thus it form materials with non-crystalline property.

6.4 TECHNIQUES FOR THE PREPARATION OF METALLIC GLASSES

There are several techniques available for the production of metallic glasses. The various techniques and the process involved in it are briefly listed in Table 6.2.

Table 6.2

S.No.	Technique	Process
1.	Melt spinning system (Quenching technique)	Molten alloy is made to impinge on a fast rotating roller to form metallic glasses.
2.	Twin roller system.	Molten alloy is passed through two rollers rotating in opposite directions to form metallic glasses.
3.	Melt extraction system	Fast moving roller sweeps off molten droplet into a strip to form metallic glasses
4.	Sputtering	The sputtering gas is ionized and the atoms are made to fly towards the substrate to form metallic glasses.

Of these four techniques melt spinning (quenching) technique is commonly used and is discussed below.

6.5 PREPARATION OF METALLIC GLASSES

Principle

"Quenching" is a technique used to form metallic glasses, *quenching means rapid cooling*. Actually atoms of any materials move freely in a liquid

state. Atoms can be arranged *regularly* when a liquid is *cooled slowly*. Instead, when a liquid is *quenched*, there will be an *irregular pattern*, which results in the formation of metallic glasses.

Technique

The process involved in the formation of metallic glasses is *melt spinning technique*. This technique is illustrated in Fig.(6.2).

Experimental setup

The setup consists of a refractory tube with fine nozzle at the bottom. The refractory tube is placed over the rotating roller made up of copper. An induction heater is wound over the refractory tube in order to heat the alloy inside the refractory tube as shown in fig.6.2.

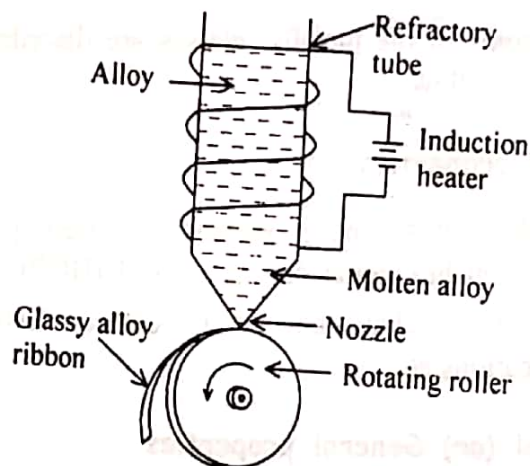


Fig. 6.2

Preparation

The alloy is put into the refractory tube and the induction heater is switched ON. This heats the alloy and hence the super heated molten alloy is ejected through the nozzle of the refractory tube onto the rotating roller and is made to cool suddenly. The ejection rate may be increased by increasing the gas pressure inside the refractory tube. *Thus due to rapid quenching a glassy alloy ribbon called metallic glass is formed over the rotating roller.*

NOTE : Metallic glasses of various thickness can be formed by increasing (or) decreasing the diameter and speed of the roller.

6.9 SHAPE MEMORY ALLOYS (SMA)

As the name itself indicates that shape memory alloys are materials (alloys), which remember its original shape during heat treatment i.e., it was found that these alloys will have its original shape in its memory and hence while on heating/cooling, it returns to its original shape. Thus, these materials are also called as *smart (or) intelligent materials*.

Definition : *Shape memory alloys (SMA) are the alloys which changes its shape from its original shape to new shape and while heating/cooling it will return to its original shape.*

Transformation temperature

In SMA, the shape recovery process occurs not at a single temperature, rather it occurs over a range of temperatures (may be few degrees).

Thus, the range of temperature at which the SMA switches from new shape to its original shape is called **transformation temperature (or) memory transfer temperature**.

Below the transformation temperature the SMA can be bent into various shapes. Above the transformation temperature the SMA returns to its original shape. This change in shape was mainly caused due to the change in crystal structure (phase) within the materials, due to the rearrangement of atoms within itself.

6.10 PHASES (STRUCTURES) OF SMA

In general the SMA has two phases (crystal structures) viz.,

- (i) Martensite and
- (ii) Austenite

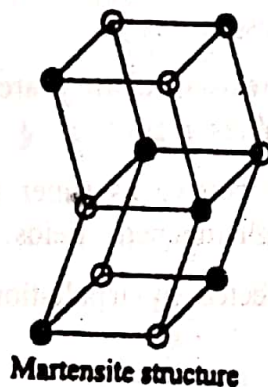


Fig. 6.4

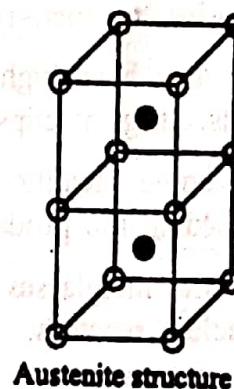


Fig. 6.5



The interactive animation of this concept can be viewed in the CD.

(i) Martensite

Martensite is an interstitial super solution of carbon in α -iron and it crystallizes into twinned structure as shown in fig.6.4. The SMA will have this structure generally at lower temperatures and it is soft in this phase.

NOTE : In martensite structure itself the SMA will have two forms viz., Twinned martensite, before loading and Deformed martensite after loading.

(ii) Austenite

Austenite is the solid solution of carbon and other alloying elements in γ -iron and it crystallizes into cubic structure as shown in Fig.6.5. The SMA will attain this structure at higher temperatures and it is hard in this phase.

6.11 PROCESSING OF SMA**Shape memory effect**

It is very clear that at lower temperature the SMA will be in martensite structure and when it is heated then it will change its shape to Austenite structure and while cooling it will again return to martensite form. This effect is called shape memory effect.

Let us consider a shape memory alloy, for which the temperature is decreased. Due to decrease in temperature, phase transformation take place from austenite to twinned martensite as shown in fig.6.6 (Process 1) i.e., a micro-constituent transformation takes place from the platelet structure (Austenite) to needle like structure (martensite).

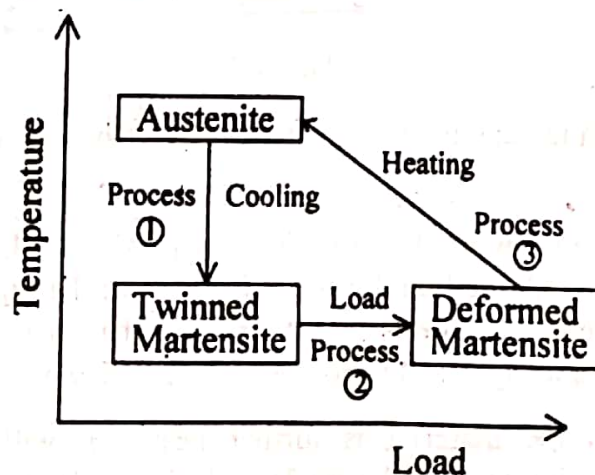


Fig. 6.6

During this state the twinned martensite phase will have same size as that of austenite phase as shown in fig.6.7 (Macroscopic view). Hence macroscopically if we see, no change in size (or) shape is visible between the Austenite phase and twinned Martensite phase of the SMA.

NOTE : It is found that the transformation from austenite to martensite takes place not only at a single temperature, but over a range of temperatures.

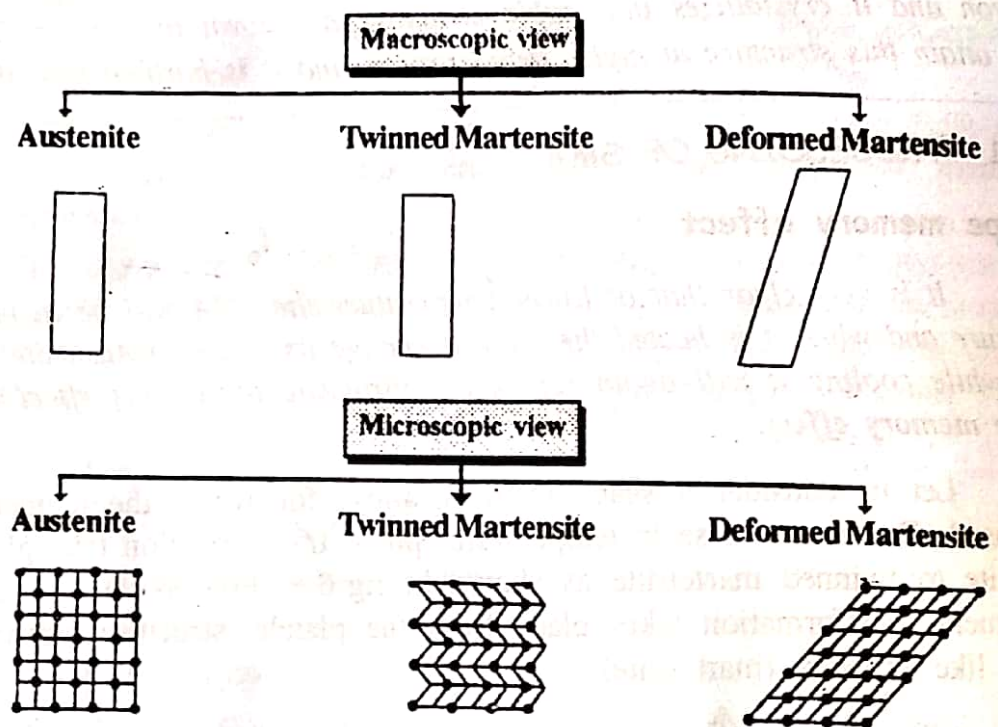


Fig. 6.7

Both austenite and twinned martensite is stable in a particular range of temperature.

Now when the twinned martensite is applied a load, it goes to deformed martensite phase as indicated in fig.6.6. (Process-2). During the transformation from twinned martensite to deformed martensite the change in shape and size occur both microscopically and macroscopically as shown in fig.6.7.

Now when the material is further heated it will go from deformed martensite to Austenite form (Process-3) and the cycle continues as shown in fig.6.6.

6.12 CHARACTERISTICS OF SMA

- (i) The transformation occurs not only at a single temperature rather they occur over a range of temperatures.
- (ii) **Pseudo-elasticity** : Pseudo-elasticity occur in some type of SMA in which the change in its shape will occur even without change in its temperature.

Say for example if we look into the stress-strain curve, [fig.6.8] the SMA can change its shape from Austenite to Martensite during the transition temperature from T_1 to T_3 . At a constant temperature T_2 , when the stress is slightly increased, a large strain is observed in the material and the phase transition takes place from Austenite to Martensite, which is indicated as line AB. Now when the stress is decreased the material again goes to Austenite phase, as indicated by the line CD. Thus it can be noticed that the shape is recovered only due to stress and not due to temperature. This behaviour is called *pseudo-elastic behaviour* and the effect is called *pseudo-elastic effect*.

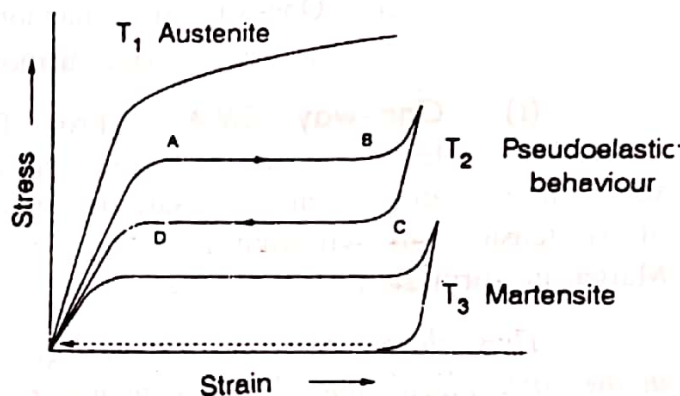


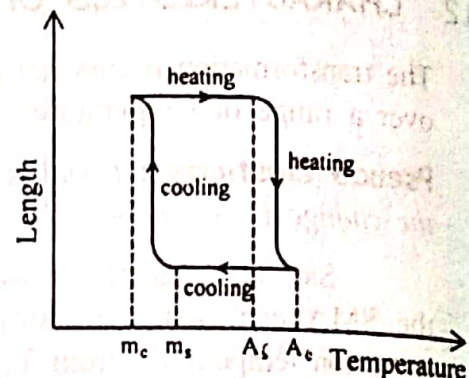
Fig. 6.8

- (iii) **Super-elasticity** : The shape memory alloys which have change in its shape at constant temperature are called *super-elastic SMAs* and that effect is known as *super-elasticity*.

Here, at a single temperature, when the load is applied the SMA will have a new shape (deformed Martensite) and if the load is removed it will regain its original shape (Twinned Martensite), similar to pressing a *rubber* (or) a *spring*.

- (iv) **Hysterisis** : For an SMA, during cooling process, a martensite starts (m_s) and ends (m_e) and during heating process, austenite starts (A_s) and ends (A_e).

It is found that they do not overlap with each other and the transformation process exhibits the form of hysteresis curve as shown in fig.(6.9)



- (v) Crystallographically the thermo-elastic martensites are reversible.

Fig. 6.9

6.13 TYPES OF SMA

There are two types of SMA viz.,

- (i) One-way shape memory alloy (SMA)
- (ii) Two-way shape memory alloy (SMA)

(i) **One-way SMA** : From fig.6.9, we can see that when the material is cooled below the Martensite ends (m_e) temperature, then there exist some minor change in energy inside the material, but the individual atomic units of Martensite will self-align in such a way that the material will remain in Martensite form alone.

Thus, though there is some change in its temperature, the SMA remains in the same phase, and this type of material is called one way shape memory alloy.

NOTE : We can also note if load is applied to SMA, it will remain either in twinned Martensite form (or) deformed Martensite form i.e., Macroscopically we can say that it remains in Martensite phase alone, which can also be taken as an example for one way SMA.

(ii) **Two-way SMA** : From fig.6.9, we can note that if the temperature is increased then the Martensite becomes Austenite and if the temperature is decreased it reverses its state.

Thus the type of materials which produces spontaneous and reversible deformation just upon heating and cooling even without load are called two way shape memory alloys.

6.14 PROPERTIES OF NI-TI ALLOY.

Nickel-Titanium [Ni-Ti] is a type a shape memory alloy which has high shape memory strain.

It has the following properties, viz.

- (i) Ni-Ti alloy has high shape memory strain [8.5.%].
- (ii) The density of Ni-Ti is 6.45 gm/cm^3 .
- (iii) It is more flexible.
- (iv) It has high melting point [1300°C].
- (v) The transformation temperature varies between -200°C and 110°C .
- (vi) It has high thermal stability.
- (vii) It has high corrosion resistance.
- (viii) The thermal conductivity ranges from 8.5 [Martensite] to 18 [Austenite] $\text{W}^\circ\text{C/cm}$.
- (ix) It has very high yield strength of about 70 to 140 Mps in Martensite form, and about 200 to 700 Mps in Austenite form.

6.15 APPLICATIONS OF SMA

Shape memory alloys have vast applications in our day-to-day life, as follows:

1. Eye glass frames : We know that the recently manufactured eye glass frames can be bent back and forth, and can retain its original shape within fraction of time. All these materials are made up of Ni-Ti alloys, which can withstand to maximum deformation.

2. Toys : We might have seen toys such as butterflies, snakes etc. which are movable and flexible. These materials are made using SMAs.

3. Helicopter blades : The life time of helicopter blades depends on vibrations and their return to its original shape. Hence shape memory alloys are used in helicopter blades.

4. Blood-clot filter : Here, the SMA is cooled and sent into vein. Due to body temperature its changes its shape and acts as a blood clot filter, by which it controls the blood flow rate.

5. Fire safety valves : The SMA is mainly used to control and

prevent the fire and toxic gases (or) liquids to a large extent. For example, if an SMA is placed in a fire safety valve, when fire occurs, then due to change in temperature the SMA changes its shape and shuts off the fire. Similar principle has been used in the area of leakage in toxic gases (or) liquids.

6. Coffee makers : The Ni-Ti spring is used to release the hot milk and the ingredients at certain temperature and to close it after particular time, thereby we can get coffee automatically.

7. Cryofit hydraulic couplings : SMA is used for *cryofit hydraulic couplings* i.e., to join the ends of the tubes. Here, the SMA material is pasted inbetween the two tubes to be joint at a particular temperature when the temperature change the SMA expands and thus the two ends are joined.

8. Circuit edge connector : Using SMA the circuit can be connected and disconnected, depending on the variation in temperature. Hence SMA is used as a *circuit edge connector*.

9. Cracks : They are used in controlling and preventing cracks.

10. They are used in relays and activators.

11. They are used for steering the small tubes inserted into the human body.

12. They are used to correct the irregularities in teeth.

13. Ni-Ti SMA are also used in artificial hip-joints, bone-plates, pins for healing bones-fractures and also in connecting broken bones.

6.16 ADVANTAGES AND DISADVANTAGES OF SMA

Advantages

- (i) SMA is very compact in nature.
- (ii) It is safe and smart.
- (iii) They are flexible.
- (iv) They are Non -Corrosive.

Disadvantages

- (i) Cost is high.
- (ii) Efficiency is low.
- (iii) Transformation occurs over a range of temperatures.
- (iv) Structural arrangements may some time get deformed.

6.17 NANO-PHASE MATERIALS

Basics of nano-materials

We know all materials are composed of atoms with different sizes which have movement with one another. There exist a special class of materials in which the atoms do not move away from each other and its size will be in the order of 1 to 100 nano-meters. These new materials are called **nano-materials** and the developed technology is called **nano-technology**. Using the highly sophisticated latest technology the nano-materials can also be formed from metals, ceramics, polymers and even from liquids.

Definition

Nano-phase materials are the materials in which the atoms / grain size is in the order of 1 to 100 nano-metres and these atoms will not move away from each other.

Examples : ZnO, Cu-Fe alloys, Ni, Pd, Pt etc.

6.18 SYNTHESIS OF NANO-PHASE MATERIALS

Nanophase materials can be synthesised in any of the two ways viz.,

(i) **Top down approach**, in which bulk materials are broken into nanosizes as shown in Fig.6.10. and

(ii) **Bottom up approach**, in which nano materials are made by building atom by atom as shown in fig.6.11



fig.6.10

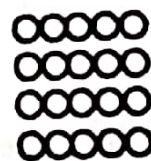


fig.6.11

Various techniques are adopted for the synthesis of nano-phase materials viz.,

- (i) Plasma-arching
- (ii) Chemical vapour deposition
- (iii) Sol-gel technique
- (iv) Electro-deposition
- (v) Mechanical crushing (or) Ball milling
- (vi) Laser synthesis
- (vii) Inert gas condensation etc.

Using the above techniques it is possible to produce nano-phase materials in the form of nano-particles, nano-powders, nano-crystals, nano-films, nano-wires, nano-tubes, nano-dots etc.

Of the above methods let us discuss the first five methods in detail.

6.19 PLASMA - ARCHING

This method is used to produce Nano-particles.

Principle

Nano Particles are produced by generating plasma using Radio frequency (RF) heating Coils.

Instrumentation

It consists of an evacuated chamber, wound by high voltage RF Coils as shown in fig 6.12. The starting metal is placed in a metal container kept inside the evacuated chamber. A colder collector rod is used to collect the nano-particles.

Processing

- (i) The starting metal from which the nano particle has to be produced is placed in the metal container.
- (ii) The RF coil is switched ON and in turn it produces heat radiation.

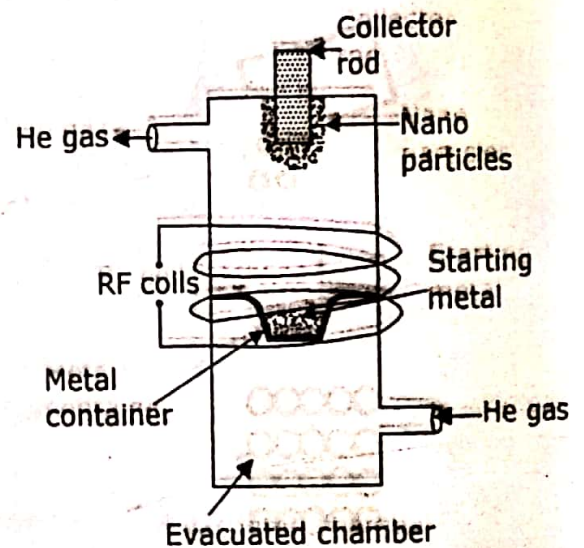


Fig.6.12

- (iii) The starting metal is heated to a very high temperature above its evaporation point.
- (iv) Now, the Helium gas is allowed to pass through the molten metal (plasma).
- (v) At this juncture the metal vapour nucleates on the Helium gas atom and it diffuses up towards the colder collector rod.
- (vi) Thus the nano-particles are slowly deposited over the collector rod and hence nano-particles are produced.

6.20 CHEMICAL VAPOUR DEPOSITION

This method is used to prepare nano-powder.

In this technique, initially the material is heated to form a gas and is allowed to deposit on a solid surface under vacuum condition, which forms nano-powders on the surface of the solid.

This method can also be used to grow surfaces, i.e., suppose if an object has to be coated with nano-powders, then the object has to be introduced inside the chemical vapour deposition area so that the nano-powders can be deposited all over the object.

Examples :

- (i) Nano-powders of oxides and carbides.
- (ii) Pure metal nano-powders.

6.21 SOL-GEL TECHNIQUE

This technique is used to generate nano-particles and nano-powders.

In general, sol-gel [wet chemical (or) chemical solution deposition] technique is based on the hydrolysis of liquid precursors and formation of colloidal solutions (sols).

Based on the different combinations of precursors and on their mechanical and physio-chemical properties [Eg: Wetability], various sol-gels can be formed.

Nano-particles can be generated using sol-gels by the process of precipitation, gelation, hydrothermal treatment, hydro-dynamic cavitation. etc.

Of these hydro-dynamic cavitation technique is often used, in which *nano-particles can be generated through creation and release of gas bubbles inside the sol-gel solution.*

Here, the sol-gel solution is taken in a drying chamber and thoroughly mixed by applying enormous pressure, high temperature and further exposing it to cavitation disturbances.

This process creates hydrodynamic bubbles in the sol-gel. These bubbles will undergo nucleation, growth and then it quenches to form nano-particles.

NOTE : The size of the nano-particles can be controlled by adjusting the pressure and solution retention time inside the chamber.

6.22 ELECTRO-DEPOSITION

This technique is deployed generally in electroplating and in the production of nano-films.

In this technique two electrodes [E1 and E2] are immersed inside the electrolyte [aqueous solutions of salts, acids etc.] as shown in fig.6.13 Now when the current is passed through the electrodes, certain mass of substance is liberated from one electrode say for example from electrode-E1 and is deposited on the surface of the other electrode say E2 and hence forms a thin nano-film on the surface of the electrode E2.

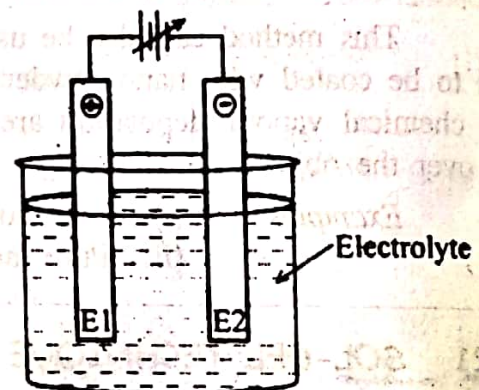


fig.6.13

The thickness of the nano-film can be adjusted by controlling the current and the time of deposition.

- Examples :**
- (i) Nano films of Cu, Platinum etc.
 - (ii) Nano films of Ni, Gold etc.

NOTE : It is possible to even deposit a single layer of atoms just by controlling the current and other parameters.

6.23 MECHANICAL CRUSHING, (OR) BALL MILLING

This method is preferred mainly in the preparation of metal oxide nano crystals.

In this method small balls are allowed to rotate inside a drum and is made to fall on a solid with high gravitational force, which crushes the solid into nano-crystals.

- Examples :*
- i) Ni and Al based nano-crystals.
 - ii) Iron nitriles nano-crystals made using ammonia gas.

6.24 PROPERTIES OF NANO-PARTICLES

As the *size of the nanoparticle is very very less*, these materials exhibits peculiar physical, electronic, magnetic, mechanical and chemical properties. Some of them are discussed below.

(i) Physical properties

- (a) Since the size of the particle is very less, the particles are very close to each other and hence the *interparticle spacing is very less* in nano-materials.
- (b) Because of its very less size, these nano-materials cannot be further divided into smaller particles and it *does not have any dislocation in it*. Thus we can say that they have *high strength and super hardness*.
- (c) The melting point of nano-materials will be very less.

(ii) Electronic properties

- (a) The *energy bands in these materials* will be very narrow.
- (b) The *ionization potential is found to be higher* for nano-materials.
- (c) When the nano-materials are prepared from bulk materials, they *have more localized molecular bonds*.
- (d) Nano-materials are *capable of storing hydrogen atoms*.

(iii) Magnetic properties

- (a) In nano-materials a large number of atoms will be present at the surface. These atoms will have less co-ordination number and hence *possess local magnetic moment* within themselves.
- (b) Due to large magnetic moment these nano-materials *exhibits spontaneous magnetisation* at smaller sizes.
- (c) Ferro-magnetic and anti-ferro magnetic *multi-layer nano-materials* has *GMR (Giant Magneto Resistance) effect*.
- (d) The nano-materials shows variation in their magnetic property, when they change from bulk state to cluster (nano-particle) state. Some of the examples are listed in Table 6.3.

Table 6.3

S.No.	Material	Bulk state	Nano-Phase state
1.	Iron, Ni, Cobalt	Ferro-magnetic	Super para-magnetic
2.	Sodium, Potassium	Para-magnetic	Ferro-magnetic
3.	Chromium	Anti-ferromagnetic	Frustrated para-magnetic

(iv) Mechanical Properties

- (a) The hardness of nano-phase materials varies from material to material. This may be due to the phase transformation, stress relief, density and grain boundaries.
- (b) They *exhibit super plastic behaviour*.

6.25 APPLICATIONS OF NANO-PARTICLES

Though nano-particles are very small, they are the important materials to built the future world. They have applications almost in all Engineering fields as follows.

(i) Mechanical Engineering

- (a) Since they are stronger, lighter etc., they are used to make hard metals.

- (b) Smart magnetic fluids are used in vacuum seals, magnetic separators etc.
- (c) They are also used in Giant Magneto Resistance (GMR) spin valves.
- (d) Nano-MEMS (Micro-Electro Mechanical Systems) are used in ICs, optical switches, pressure sensors, mass sensors etc.

(II) Electrical, Electronics and Communication Engineering

- (a) Orderly assembled nano-materials are used as quantum electronic devices and photonic crystals.
- (b) Some of the nano-materials are used as sensing elements. Especially the molecular nano-materials are used to design the robots, assemblers etc.
- (c) They are used in energy storage devices such as hydrogen storage devices, magnetic refrigeration and in ionic batteries.
- (d) Dispersed nano-materials are used in magnetic recording devices, rocket propellant, solar cells, fuel cells, etc.
- (e) Recently nano-robots were designed, which are used to remove the damaged cancer cells and also to modify the neuron network in human body.

(III) Computer Science Engineering and IT

- (a) Nano-materials are used to make CD's and semiconductor laser.
- (b) These materials are used to store the informations in smaller chips.
- (c) They are used in mobiles, lap-tops etc.
- (d) Further they are used in chemical/optical computers.
- (e) Nano-dimensional photonic crystals and quantum electronic devices plays a vital role in the recently developed computers.

(IV) Bio-medical and Chemical Engineering

- (a) Consolidated state nano-particles are used as catalyst, electrodes in solar and fuel cells.
- (b) Bio-sensitive nano-particles are used in the production of DNA-chips, bio-sensors etc.

- (c) Nano-structured ceramic materials are used in synthetic bones.
- (d) Few nano-materials are also used in adsorbents, self-cleaning glass, fuel additives, drugs, ferrofluids, paints etc.
- (e) Nano-metallic colloids are used as film precursors.

NOTE : In marine engineering recently the underwater nano-sensors are used to detect the movement of ships and in future it was planned to design nano material based submarines.

6.26 METALLIC NANO-CLUSTERS (OPTIONAL)

Clusters

Clusters are new type of nano materials, whose size and the properties lies between bulk materials and their atomic and molecular constituents.

For better understanding about clusters, the differences between an atom, molecule, cluster and bulk materials is shown in Table 6.4.

Table 6.4

Differences between atom, molecule, cluster and bulk materials.

S.No.	Property	Atom/molecule	Cluster	Bulk material
1.	Size	Few Å	Å to nm	Microns
2.	Number of units	For atom - 1 unit For molecule - Many units	2 to several thousand units	Infinite
3.	Electronic structure	Quantized (Discrete)	Quantized (Discrete)	Continuous
4.	Geometric structure	Defined	Defined	Depends on its crystal structure
5.	Examples	Na, NaCl etc.	$C_{60}(NaCl)_n$	Au, Ag etc.

Types

Depending on the type of constituent units, the clusters are classified into two types viz.,

- (i) Atomic clusters, which are formed from atoms
- (ii) Molecular clusters, which are formed from molecules.

The clusters formed from atoms, molecules and bulk materials are as shown in fig.6.14.

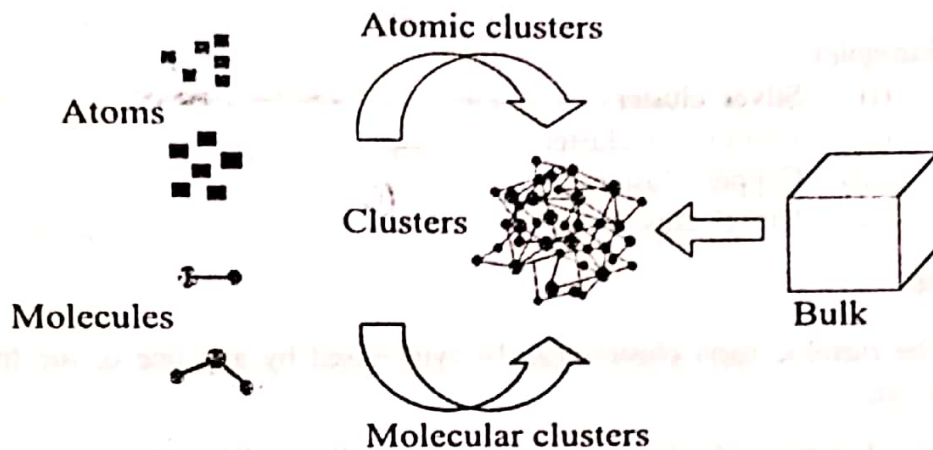


Fig. 6.14

The clusters can also be classified based on the types of bonding between the atoms / molecules as shown in Table 6.5.

Table 6.5

S.No.	Type	Bonding	Nature of Bonding	Examples
1.	Ionic clusters	Ionic bonding	Very strong	$(\text{NaCl})_n$, $(\text{CsI})_n$
2.	Co-valent clusters	Covalent bonding	Strong	C_{60} , Si_n
3.	Metallic clusters	Metallic bonding	Moderate	Na_n , Au_n , Fe_n , Ag_n
4.	Molecular clusters	Hydrogen bonding	Weak	$(\text{H}_2\text{O})_n$
5.	vander Walls clusters	vander Walls, and polarization effects	Very weak	Ar_n , Xe_n

Metallic nano clusters

The clusters formed by alkali metals, alkaline earth metals and transition metals are called **metallic nano clusters**. The metallic clusters formed from single metallic element (or) from more than one metal are called **intermetallic nano clusters**.

Examples :

- (i) Silver cluster
- (ii) Aluminium cluster
- (iii) Copper cluster
- (iv) Nickel cluster, etc.

Synthesis

The metallic nano clusters can be synthesised by any one of the following techniques. viz.,

- (i) **Laser synthesis** – In which the metallic sodium is heated to a very high temperature of about 400°C and the hot sodium vapour is allowed to expand into a low vacuum He- atmospheres, where it is suddenly cooled and condensed to form nano cluster.

NOTE : A detail discussion of the laser synthesis is made in Carbon-nanotubes.

- (ii) Pulsed arc method
- (iii) Ion sputtering technique etc.

Properties

- (i) Nano-clusters have great hardness and yield strength.
- (ii) The energy of the clusters varies with respect to the constituent of the atoms.
- (iii) The ratio of number of atoms on the surface to the number of atoms inside the material is nearly equal to 1.
- (iv) The ratio of the surface energy to total energy is more or less equal to 1.

- (v) The metallic clusters absorb light to produce different colours. Also the wave length shift will change the optical absorption spectrum.
- (vi) The ionization potential and electron affinity vary with respect to the size of the cluster.
- (vii) At certain sizes the electron affinity of clusters become similar to that of a bulk material.

6.27 CARBON NANOTUBES [CNTs]

Introduction

The discovery of carbon leads to form stable, ordered structures other than graphite and diamond, which have stimulated the researchers worldwide to search for other new forms of carbon. The search was given new impetus when it was shown that C_{60} could be produced in a simple arc-evaporation apparatus. This C_{60} is very much useful in the production of carbon nano tubes, so called CNT.

The CNT have remarkable electronic properties and many other unique characteristics. For these reasons they have attracted huge academic and industrial interest.

Definition

Carbon nanotubes (CNT) are molecular-scale tubes of graphitic carbon with outstanding properties. They are among the stiffest and strongest fibres researched till date, with remarkable electronic properties and applications.

Types

Carbon nano-tubes are of two types. viz

- (i) (a) Single walled nano-tubes (SWNTs)
- (b) Multi walled nano-tubes (MWNTs)
- (ii) Single walled nano-horns (SWNHs).

6.28 STRUCTURE OF CARBON NANOTUBES

The nano-tubes possess atleast two layers, often many more, and ranged in outer diameter from about 3 nm to 30 nm. The bonding in carbon nanotubes is sp^2 hybridization, with each atom joined to three neighbours as in graphite. The tubes can therefore be considered as rolled-up graphene sheets (graphene is an individual graphite layer). There are three distinct ways (fig.6.15) in which a graphene sheet can be rolled into a tube, viz.,

- (i) Arm chair structure
- (ii) Zig-zag structure
- and (iii) Chiral structure.

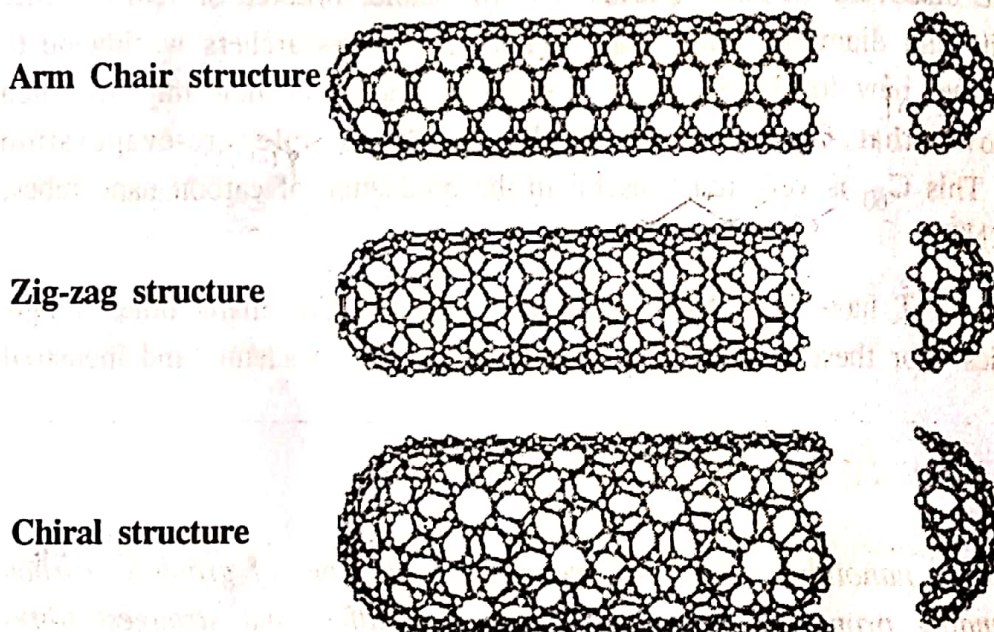


Fig.6.15

Here the armchair structure and zig-zag structure have a high degree of symmetry. The terms "armchair" and "zig-zag" refer to the arrangement of hexagons around the circumference. The "chiral" term means that it can exist in two mirror-related forms.

The internal arrangements of atoms in the structure of a nanotube is shown in fig.6.16. The structure is specified by a vector, (n,m) , which defines how the graphene sheet is rolled up. The carbon nanotube can be produced with various values of 'n' and 'm'.

For example, to produce a nanotube with the indices (7, 6), the sheet has to be rolled up in such a way that the atom labelled (0, 0) has to be superimposed on the one labelled (7, 6). It can be seen from the figure that $m = 0$ for all zig-zag tubes, while $n = m$ for all armchair tubes.

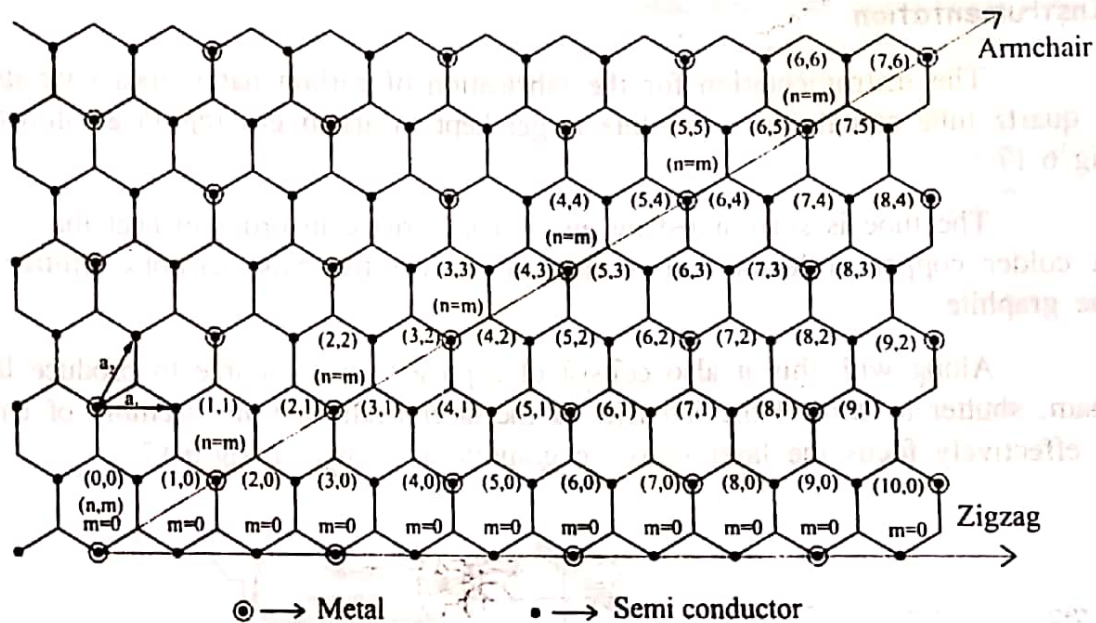


Fig. 6.16

6.29 FABRICATION OF CARBON NANOTUBES

Carbon nanotubes can be fabricated by anyone of the following methods viz.,

- (i) Pulsed Laser deposition (or) Laser Synthesis.
- (ii) Carbon Arc method and
- (iii) Chemical vapour deposition

Let us discuss the above methods in detail.

6.30 PULSED LASER DEPOSITION

Pulsed Laser deposition (or) Laser synthesis is the latest technique adopted for the preparation of carbon nano-tubes.

Principle

The technique of laser heat treatment is used in the preparation of carbon nano-tubes. In general ruby laser, Nd-YAG laser and CO_2 laser are used for this purpose.

Instrumentation

The instrumentation for the fabrication of carbon nano-tubes consists of a quartz tube containing a graphite target kept in argon gas region as shown in fig 6.17.

The tube is surrounded by an electric furnace in order to heat the target. A colder copper collector rod is used to collect the nano carbons emitted by the graphite.

Along with this it also consist of a pulsed laser source to produce laser beam, shutter to control the intensity of the laser beam and an assembly of lenses to effectively focus the laser onto the graphite as shown in fig.6.17.

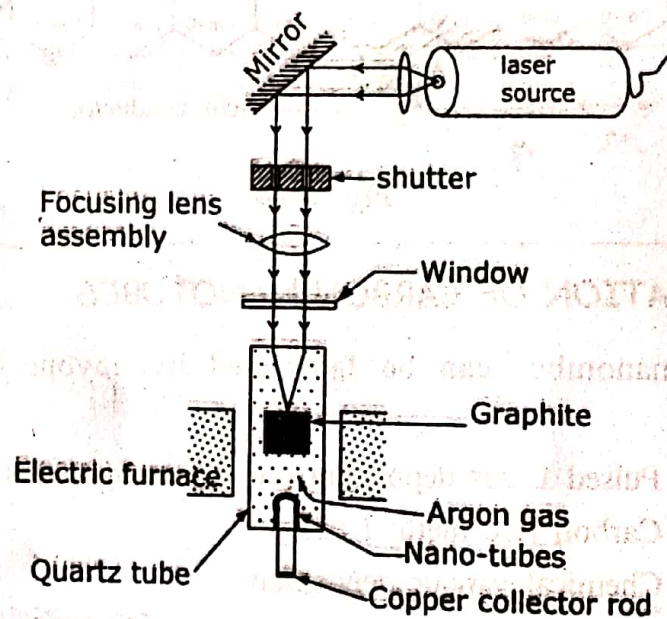


Fig.6.17

Synthesis

Initially the graphite is heated upto 1200°C with the help of the electric furnace. An intense laser beam can be used to evaporate carbon from the graphite and thus, now the Laser source is switched ON.

The light reflected by the plane mirror is made to pass through the shutter. The intensity of the laser beam is controlled by the shutter and the controlled laser beam is allowed to fall on the focussing lens assembly. This lens assembly focusses the light effectively onto the window and is made to incident on the graphite.

Due to laser heating the graphite gets heated and evaporate carbon atoms. The argon gas present inside the quartz tube is used to sweep the carbon atoms towards the colder copper collector rod.

Thus, due to the movement of carbon atoms from a higher temperature region to lower temperature region it gets condensed and hence carbon nano-tubes over the collector rod.

The Cobalt and Nickel present in the graphite act as catalytic nucleation sites for the formation of carbon nano tubes.

6.31 CARBON-ARC METHOD

Carbon arc method is similar to that of electro-deposition-technique and is used to produce both the single walled nano-tubes [SWNTs] and multiwalled nano-tubes [MWNTs].

Instrumentation

It consists of positive carbon electrode (E_1) and negative carbon electrode (E_2) as shown in fig. 6.18. Liquid helium of 500 torr pressure is made to flow through the electrodes to deposit the carbon from E_1 to E_2 .

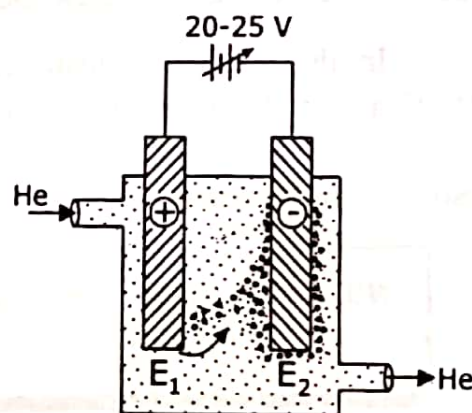


Fig.6.18

Fabrication

The battery is switched ON and a potential of about 20 to 25 volt is applied across the carbon electrodes. This potential leads to the emission of carbon atoms from the positive electrode. Now, with the help of high pressure Helium, the carbon atoms are deposited over the negative electrode.

Now when the potential is continuously applied, the length of the positive electrode start decreasing and the carbon deposit over the negative electrode starts increasing, which results in the formation of carbon nano-tubes, layer by layer, so called Multi Walled Carbon Nano-Tubes [MWNTs], as shown in fig 6.19

MULTI WALLED CARBON NANO TUBES

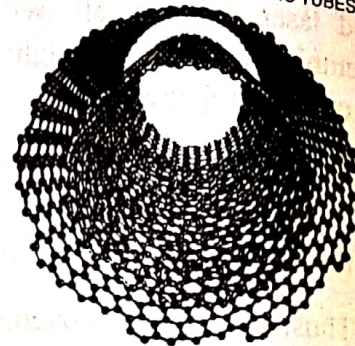


Fig.6.19

NOTE : The single walled carbon nano-tube [SWNT] can also be produced by the above technique just by using cobalt, Nickel (or) Iron as a catalyst in the central region of the positive electrode.

6.32 CHEMICAL VAPOUR DEPOSITION TECHNIQUE

In this method a hydro-carbon gas such as methane is heated upto 1100°C and is decomposed. As the gas decomposes, it produces carbon atoms. These carbon atoms (chemical vapours) are made to deposit over a cooler substrate, which contains iron as a catalyst to form carbon nano-tubes.

NOTE : Using this technique we can fabricate carbon nanotubes continuously.

6.33 PROPERTIES OF CARBON NANO-TUBES

- (i) The strength of the sp^2 carbon-carbon bonds gives high hardness for carbon nanotubes.
- (ii) The Young's modulus of the nanotubes is approximately 5 times greater than the steel.
- (iii) The tensile strength is around 50 times higher than steel.

- (iv) The electronic properties of carbon nanotubes are also extraordinary. Especially the Caison nanotubes can be obtained in the form of metallic or semiconducting, based on its structural content.
- (v) Nanotubes have higher conductivities than that of copper.

6.34 APPLICATIONS OF CARBON NANOTUBES

- (i) The carbon nanotubes are very light in weight, but they are very strong, hence they are used in aerospace.
- (ii) They are used in constructing nanoscale electronic devices.
- (iii) Carbon nano-tubes (CNTs) are used in battery electrodes, fuel cells, reinforcing fibers etc.
- (iv) CNTs are used in the development of flat panel displays for computer monitors and televisions.
- (v) Plastic Composite CNTs are used as a light weight shielding materials for protecting electromagnetic radiation.
- (vi) Light weight CNTs are also used in military and communication systems, for protecting computers and electronic devices.
- (vii) Semiconducting CNTs are used as switching devices.
- (viii) Semiconducting CNTs are also used as chemical sensors to detect various gases.
- (ix) Nano-tubes can also serve as catalysts for some chemical reactions.
- (x) The unique properties of carbon nanotubes will undoubtedly lead to many more applications in future to produce nano-computers, plastic composites etc.

questions	opt1	opt2	opt3	opt4	answer
How does a semiconductor behave at absolute zero?	Conductor	Insulator	Semiconductor	Protection device	Insulator
How is the resistance of semiconductor classified?	High resistance	Positive temperature coefficient	Negative temperature coefficient	Low resistance	Negative temperature coefficient
Which of the following is known as indirect band gap semiconductor?	Germanium	Nickel	Platinum	Carbon	Germanium
What are the charge carriers in semiconductors?	Electrons and holes	Electrons	Holes	Charges	Electrons and holes
How are charge carriers produced in intrinsic semiconductors?	By pure atoms	By electrons	By impure atoms	By holes	By impure atoms
Majority carriers in P-type semiconductor are _____.	electrons	neutrons	holes	neutrinos	holes
Minority carriers produced by thermal agitation or vibration in a semiconductor are _____.		holes in N-type & free electrons in P-type	holes in N-type & free electrons in P-type	free electrons in N-type & holes in P-type	holes in N-type & free electrons in P-type
The cause of a potential barrier in a P - N diode is the _____.		concentration of positive ions	depletion of negative ions	concentration of positive ions	concentration of positive ions
A Zener diode is always used _____.	with forward bias	with reverse bias	as a rectifier	as a switch	with reverse bias
How does a semiconductor behave at absolute zero?	Conductor	Insulator	Semiconductor	Protection device	Insulator
How is the resistance of semiconductor classified?	High resistance	Positive temperature coefficient	Negative temperature coefficient	Low resistance	Negative temperature coefficient
Which of the following is known as indirect band gap semiconductor?	Germanium	Nickel	Platinum	Carbon	Germanium
What are the charge carriers in semiconductors?	Electrons and holes	Electrons	Holes	Charges	Electrons and holes
How are charge carriers produced in intrinsic semiconductors?	By pure atoms	By electrons	atoms	By holes	atoms
The probability that an electron in a metal occupies the Fermi level _____.	1	0.5	0.75	0.5	0.5
n-type semiconductors are _____.	Negatively charged	Produced when illuminated	Produced when illuminated	None of the above	Produced when illuminated
If the energy gap of a semiconductor is 1.1 eV it would be _____.	Opaque to the visible light	Transparent to the visible light	Transparent to the visible light	Transparent to the visible light	Opaque to the visible light
In an intrinsic semiconductor, the mobility of electrons is _____.	Less than the mobility of holes	Zero	Greater than the mobility of holes	1	Greater than the mobility of holes
The electron and hole concentrations in an intrinsic semiconductor are _____.	$n = p$	$n + p = n_i$	$n = p$	$n - p = n_i$	$n = p$
If the temperature of an extrinsic semiconductor is increased so that the intrinsic carrier concentration is doubled, then _____.		The majority carrier concentration is doubled	The minority carrier concentration is doubled	Both majority and minority carrier concentrations are doubled	Both majority and minority carrier concentrations are doubled
At room temperature, the current in an intrinsic semiconductor is _____.	Holes	Electrons	Holes and electrons	phonons	Holes and electrons
The mobility is given by _____.	$\mu = V/E$	$\mu = V^2/E$	$\mu = V/E^2$	$\mu = V^2/E^2$	$\mu = V/E$
A good ohmic contact on a p-type semiconductor chip is formed by _____.	Gold as an impurity	High concentration of gold	High concentration of gold	None of the above	High concentration of gold
The width of the depletion region is _____.	Directly proportional to the square root of the doping concentration	Inversely proportional to the square root of the doping concentration	Independent of the doping concentration	Directly proportional to the square root of the doping concentration	Inversely proportional to the square root of the doping concentration
The Fermi energy in a p-n junction at thermal equilibrium is _____.	Proportional to the distance from the valence band	Directly proportional to the distance from the valence band	Invariant with the distance from the valence band	Proportional to the distance from the valence band	Invariant with the distance from the valence band
Germanium has _____ protons.	30	32	34	36	32
One eV equals to _____.	1.6×10^{-19} J	2.6×10^{-19} J	1.4×10^{-19} J	1.2×10^{-19} J	1.6×10^{-19} J
An electron volt is a unit of _____.	momentum	potential difference	energy	charge	energy
Which one has four valence electrons?	conductor	semiconductor	insulator	semi-insulator	semiconductor
The temperature coefficient of resistance of semiconductors is _____.	positive	negative	zero	infinite	negative
A negatively charged body has _____.	excess of electrons	excess of electrons	deficit of electrons	deficit of protons	excess of electrons
The value of temperature coefficient is dependent upon _____.	length	nature and temperature	volume	cross-sectional area	nature and temperature
Semiconductor in pure form is called _____.	semiconductor	intrinsic	extrinsic	doped	intrinsic
_____ and _____ are the two carrier transport mechanisms in a semiconductor.	covalent bonding and recombination	forward and reverse drift	drift and diffusion	free and charged drift and diffusion	drift and diffusion
Semiconductor in impure form is called _____.	semiconductor	intrinsic	extrinsic	bad	extrinsic
_____ is associated with random motion due to the thermal agitation in the movement of holes and electrons in a silicon crystal?	Diffusion	Drift	Recombination	Doping	Diffusion
Silicon that has been doped with trivalent impurity is called _____.	N-type	P-type	intrinsic	extrinsic	P-type
Silicon that has been doped with pentavalent impurity is called _____.	N-type	P-type	intrinsic	extrinsic	N-type
What is the another name for a pn crystal?	lattice	diode	junction diode	pn junction	junction diode
An acceptor atom is also called _____.	Minority carrier	Majority carrier	trivalent atom	pentavalent atom	trivalent atom
Which is a donor atom?	Pentavalent atom	trivalent atom	Aluminium	Boron	Pentavalent
What is the barrier potential of germanium at 25 degree Celsius?	0.3 V	0.4 V	0.5 V	0.6 V	0.3 V
What is the barrier potential of silicon at 25 degree Celsius?	0.4 V	0.5 V	0.6 V	0.7 V	0.7 V
When temperature increases, barrier potential _____.	remains the same	decreases	increases	depends on material	decreases
The most important application of Schottky diodes is in _____.	Digital computers	Voltage regulator	Power supplies	amplifier circuits	Digital computers
Typical leakage current in a pn junction is in the order of _____.	micrometer	millimeter	nanometer	picometer	micrometer
The resistance of a forward biased pn junction is in the order of _____.	ohm	milliohm	microhm	kiloohm	ohm
Doping materials are called impurities because they _____.	decrease number of charge carriers	change the chemical nature	make semiconductor	alter the crystal structure	alter the crystal structure
The method of adding impurities to a pure semiconductor is known as _____.	etching	doping	annealing	doping	doping
The merging of a free electron and a hole is called _____.	covalent bonding	lifetime	recombination	thermal energy	recombination
A donor atom has how many valence electrons?	1	2	4	5	5

questions

What does conductivity of metals depend upon?
What happens to the free electrons when electric field is applied?
Which of the following theories cannot be explained by classical theory?
Which of the following theories can be adopted to rectify the drawbacks of classical theory?
Calculate the drift velocity of the free electrons with mobility of $3.5 \times 10^{-3} \text{ m}^2/\text{Vs}$ in copper for an electric field strength of 0.5 V/m .
Electrons in the outer shell are called _____ electrons.
Which of the following has least number of valence electrons?
A good conductor has how many electrons?
What principle states that each electron in an atom must have a different set of quantum numbers?
The temperature coefficient of resistance of conductors is _____.
The temperature coefficient of resistance of conductor _____ with an increase in temperature.
A positively charged body has _____.
Electrons flow assumes charges flow from _____.
Which of the following has negative temperature coefficient?
Which orbit controls the electrical property of the atom?
Which of the following statements correctly describes a metal within band theory?
Which is the correct ordering of the band gaps energy?
The energy required to break a covalent bond in a semiconductor _____.
Fermi level for a metal is _____.
The probability of occupation of an energy level E , when $E - E_F = kT$, is given by _____.
The Fermi level is _____.
Mobility of electron is _____.
Fermi level represents the energy level with probability of its occupation of _____.
At absolute zero temperature, the probability of finding an electron at an energy level E is zero when _____.
Substances which allow electric current to pass through them are called _____.
The probability that an electron in a metal occupies the Fermi level, at any temperature ($>0 \text{ K}$) is:
The mobility is given by:
Fermi energy level for n type extrinsic semiconductors lies _____.
Fermi energy level for intrinsic semiconductors lies _____.
Not an example for intrinsic semiconductor _____.
In intrinsic semiconductor, number of electrons _____ number of holes.
In p type semiconductors, number of holes _____ number of electrons.
Mobility of holes is _____ mobility of electrons in intrinsic semiconductors.
Electronic current in the wire is the flow of _____ electrons.
The highest energy band of an atom which can be filled with electrons is _____.
An energy band in which electrons can move freely _____.
Which type of material usually has one valence electron?
Which of the following is considered as best conductor?
The eight electrons which are tightly held by the atom are called _____.
The amount of time between creation and disappearance of a free electron is _____.
Density of states is defined as the number of available electron states per unit volume in an energy interval _____.
Phonon is the quantum of _____ wave.
The effective mass of an electron _____.
Einstein's theory of lattice vibration is based on the quantum theory of _____.
A phonon interacts with _____.
_____ is defined as the number of available energy states per unit volume in an energy interval.
When the effective mass of an electron is positive then the curve of $E(k)$ will be _____.
Classical free electron theory was proposed by _____.
In the Kronig-Penney model, if there exists no potential barrier, then _____.
The density of allowed states between E and $E + dE$ is proportional to _____.
The average time taken by a free electron between any two successive collisions is known as _____.
In an electric field, the electron moves away from the field with a constant velocity, known as _____.

opt1
The nature of the material
They move randomly and collide with each other
Electron theory
Quantum theory
 3.5 m/s
outer shell
conductor
8
Inclusion principle
positive
increases
excess of neutrons
positive to negative
Nickel
first orbit
A material possessing moderate band gap
Diamond > silicon > copper
is equal to 1 eV
Highest energy level occupied by electrons at 0
 0.75
an average value of all available energy levels
Average flow of electrons per unit field.
 0%
 $E = EF$
Conductors
 0
 $\mu_{\text{uo}} = V / E$
At middle of the band gap
At middle of the band gap
Si
Equal
Greater than
Equal
Free
energy level
valence band
conductors
Gold
valence electrons
recombination
 $E = dE$
electromagnetic
positive
Schrodinger
another photon
 $E = dE$
Concave up
Bloch
there exists a periodic dependence of E on k
 $E^* (1/2)$
mean free path
mean free path

opt2
Number of free electrons
They move in the direction of the field
Lorentz theory
Quantum theory
 $1.75 \times 10^{13} \text{ m/s}$
inner shell
semiconductor
4
exclusion principle
negative
decreases
excess of electrons
positive to positive
Carbon
fourth orbit
A material possesses a large band gap
Diamond < silicon < copper
is equal to the width of the forbidden gap
Highest energy level occupied by electrons at 0
 0.63
an energy level at the top of the valence band.
Average applied field per unit drift velocity.
 25%
 $E = EF$
Insulation
 1
 $\mu_{\text{uo}} = V / E$
Close to conduction band
Close to conduction band
Al
Greater than
Greater than
valence
valence band
conduction band
insulation
Germanium
bound electrons
propagation
 $E^* dE$
polarization
infinity
Dirac
boson
 dE
parabola
De-Broglie
 E is not a continuous function of k
 $E^* (1/2)$
drift velocity
collision time
collision time

opt3
Resistance of the metal
They remain stable
Photo-electric effect
Band theory
 11.5 m/s
Semiconductor
insulator
2
electron principle
zero
remains same
deficit of electrons
negative to positive
Brass
Mishell
A material with zero band gap
Diamond < silicon < copper
is greater in Ge than in Si
Average value of all available energy levels
highest energy level occupied by electrons at 0
 0.5
the highest occupied energy level at 0
Average drift velocity per unit field.
 300%
 $2E = E + F$
semi conductors
 0.75
 $\mu_{\text{uo}} = V / E$
Close to valence band
Close to valence band
Ge
Less than
Less than
bound
conduction band
conduction band
superconductors
Germanium
bound electrons
propagation
 $E^* dE$
polarization
infinity
Dirac
boson
 dE
parabola
De-Broglie
 E is not a continuous function of k
 $E^* (1/2)$
drift velocity
drift velocity

opt4
Number of electrons
They move in the direction opposite to that of the field
Classical free electron theory
Electron theory
 $1.75 \times 10^{13} \text{ m/s}$
valence
semi-insulator
1
quantum principle
infinite
becomes negative
deficit of protons
negative to negative
Constant
valence orbit
A material with infinite band gap
Diamond < silicon < copper
is the same in Ge and Si
highest energy level occupied by electrons at 0
 0.27
the highest occupied energy level at 0
Reciprocal of conductivity per unit charge.
 300%
 $2E = E + F$
superconductors
 0.5
 $\mu_{\text{uo}} = V / E$
Close to forbidden band
Close to forbidden band
Si
Can not define
Can not define
free
valence band
conduction band
conductors
Mica
covalent electrons
bonding
 $E^* dE$
magnetization
positive, negative and infinity
Heisenberg
muon
 $2E/dE$
hyperbola
Schrodinger
all values of E are not allowed
 $E^* (1/2)$
relaxation time
relaxation time

answer
Number of free electrons
They move in the direction of th
Photo-electric effect
Quantum theory
 $1.75 \times 10^{13} \text{ m/s}$
valence
conductor
1
exclusion principle
positive
decreases
deficit of electrons
negative to positive
Carbon
valence orbit
A material possesses a large ba
Diamond < silicon < copper
is equal to the width of the forbi
highest energy level occupied by
 0.27
the highest occupied energy leve
Average drift velocity per unit fie
 30%
 $E = EF$
Conductors
 0.5
 $\mu_{\text{uo}} = V / E$
Close to conduction band
Close to valence band
Si
Less than
Equal
Can not define
free
valence band
conduction band
conductors
Gold
bound electrons
lifetime
 $E^* dE$
elastic
positive, negative and infinity
Planck
another photon
 $2E/dE$
Concave up
Dirude
there exists no forbidden energy
 $E^* (1/2)$
collision time
drift velocity

questions	opt1	opt2	opt3	opt4	answer
Any material that can be _____ by an applied external magnetic field is called magnetic material.	electricified	oxidised	magnetised	reduced	magnetized
Magnetism arises from _____ of the magnetic material	resistance	magnetic dipole moment	electric moment	none of the above	magnetic dipole moment
_____ is the unit of magnetic induction B.	Whm ⁻²	Whm ⁻¹	Teola	Whm	Teola
Magnetic induction B is _____	μH	μH	$\mu\text{-H}$	$2\mu\text{-H}$	μH
The formula for intensity of magnetization is _____	$M=I/V$	$I=M/V$	$\mu=I/\mu\cdot M$	$I=V/M$	$I=M/V$
Relative permeability is given by _____	$\mu=\mu/\mu_0$	$\mu=\mu\cdot\mu_0$	$\mu=I/\mu\cdot\mu_0$	$2\mu\text{-H}$	$\mu=\mu/\mu_0$
The formula for magnetic susceptibility is _____	I/H	$I+H$	I/H	$I-H$	I/H
Relation between μ and c is _____	$\mu=1/c$	$\mu=1\cdot c$	$\mu=c$	$\mu=1+c$	$\mu=1+c$
Diamagnetic materials have _____ number of electrons.	even	odd	many	less	even
The net magnetic moment of diamagnetic materials in the absence of external field is _____	4	0	1000	1	0
_____ material repel magnetic lines of force.	superconducting	diamagnetic	paramagnetic	superconducting & diamagnetic	superconducting & diamagnetic
Permanent dipoles are absent in _____ materials.	paramagnetic	diamagnetic	ferromagnetic	ferrites	diamagnetic
Magnetic lines of force are attracted by _____ magnetic material.	para and ferro	dia and para	dia and ferro	ferrites	para and ferro
The susceptibility of diamagnetic materials is temperature _____	dependent	independent	resistant	gradient	independent
IT is less than curie temperature, paramagnetic materials are converted into _____ magnetic material	para	ferri	dia	para	dia
IT is greater than curie temperature, ferromagnetic is converted into _____ magnetic material	para	ferri	ferri	anti-ferro	para
The susceptibility for diamagnetic materials is _____ value	high negative	high positive	low positive	low negative	low negative
The susceptibility is high positive value for _____ material.	diamagnetic	paramaterial	ferromagnetic	ferrites	ferromagnetic
Ferromagnetic material exhibit _____ magnetization	spontaneous	random	stimulated	saturated	spontaneous
Diamagnetic materials align _____ to applied field.	antiparallel	perpendicular	opposite	parallel	perpendicular
_____ are very weak magnet	diamagnets	paramagnets	ferrimagnets	diamagnets	diamagnets
Para and ferromagnetic materials align themselves _____ to the external field.	perpendicular	normal	parallel	inclined	parallel
_____ magnetic materials have their dipoles aligned antiparallel	ferri	antiferro	ferro	dia	antiferro
Above Neel temperature, antiferromagnetic material becomes _____	ferromagnetic	ferrimagnetic	paramagnetic	diamagnetic	paramagnetic
_____ magnetic materials have unequal magnetic moments aligned antiparallel to one another.	ferri	antiferro	ferro	para	ferri
Ferrimagnetic materials are also called _____	cuprites	magnetite	ferrites	ferrites	ferrites
In ferrites _____ sites are octahedral	A	B	D	B	D
In ferrites _____ sites are tetrahedral.	B	C	A	D	C
There are _____ octahedral and _____ tetrahedral sites.	4,8	8,12	16,8	8,16	16,8
The number of ferrous, ferric and oxygen ions in ferrites are _____	4,8,12	8,16,32	32,8,16	12,24,36	8,16,32
If divalent and trivalent ions are in B site then the ferrite is said to have _____ spinel structure	inverse	regular	negative	positive	inverse
If two Fe ³⁺ ions are in B site and one Fe ²⁺ ion is on A site then the ferrite has _____ spinel structure	inverse	regular	negative	positive	regular
The mixture is preheated in a furnace at _____ °C while preparing ferrites.	100 to 200	1100 to 1400	900 to 1100	1000 to 1200	900 to 1100
A single crystal of ferromagnetic material is divided into large number of small regions called _____	same	tunnel	domain	grain	domain
The orientation of moments in one domain is in _____ direction	different	different	random	opposite	same
The net magnetization of ferromagnetic material is _____	minimum	maximum	zero	one	maximum
The energy required to align atomic magnets into single domain is _____ energy.	exchange	anisotropy	bloch	magnetostatic	exchange
During magnetostriction _____ waves are produced.	UV	IR	electrical	ultrasonic	ultrasonic
Lagging of magnetic induction behind magnetic field is called _____	exchange	hysteresis	magnetisation	retentivity	hysteresis
The negative field applied to remove the retained magnetism is called _____	retentivity	coercivity	resistivity	coercivity	coercivity
The use of SQUIDS is in _____	earthquake prediction	capacitors	resistance	ship	earthquake prediction
The AC Josephson Effect is _____	$v=2\phi h$	$v=2\phi h$	$v=2\phi v h$	$v=2\phi v h$	$v=2\phi v h$
The Meissner Effect is _____	$M/H=-1$	$M/H=-2$	$M/H=-3$	$M/H=-1$	$M/H=-1$
_____ are called soft super conductors	type-I superconductor	type-II superconductor	magnetic material	ferro-magnetic material	type-I superconductor
_____ are called hard superconductors	type-I superconductor	type-II superconductor	magnetic material	ferro-magnetic material	type-II superconductor
The hysteresis loss depends on _____	loop area	loop width	loop breadth	loop height	loop area
The materials with great hysteresis loss are called _____ magnetic materials.	soft	hard	flexible	ferro	hard
Soft magnetic materials are used to make _____ magnets.	permanent	weak	temporary	strong	temporary
Retentivity and Coercivity are _____ for hard magnetic materials.	large	small	medium	same	large
Susceptibility and Permeability are high for _____ magnetic material.	dia	para	soft	para	soft
_____ is the principle of magnetic recording and storage.	magnetostriction	electro magnetic induction	absorption	pico electric effect	electro magnetic induction
_____ materials are used in storage devices.	ferromagnetic	ferrimagnetic	ferro and ferri	anti ferro	ferro and ferri
Which of the memory cannot be edited?	RAM	ROM	DRAM	SRAM	ROM
_____ is also called a diskette.	DVD	CD	VCD	floppy disk	floppy disk
Write protect notch is used to prevent _____ on the disk by others.	writing	edting	deleting	saving	writing
The maximum capacity of floppy disk is _____	720 KB	1.2MB	160 KB	1.44MB	160 KB
Diamagnetic property of a superconductor is also called _____	Tydall effect	Raman effect	Meissner effect	Hall effect	Meissner effect
The interaction between cooper pairs is strong only when two electrons have _____ moments and spin .	equal	opposite	parallel	equal and opposite	equal and opposite
In superconductivity the conductivity of a material becomes _____	zero	one	finite	infinite	infinite
The temperature at which conductivity of a material becomes infinite is called _____ temperature.	Critical	Absolute	Mean	Crystallization	Critical
The superconducting state is perfectly _____ in nature.	Diamagnetic	Paramagnetic	Ferromagnetic	Ferromagnetic	Diamagnetic
In superconductivity the electrical resistance of material becomes _____	zero	finite	infinite	zero	zero
Which of the following conductor has highest critical temperature?	Aluminium	Zinc	Molybdenium	Tin	Tin
The energy required to break a cooper pair is _____ the energy gap of superconductor.	one half	equal to	twice	thrice	equal to
In superconductors, the Fermi energy level is _____	Below the ground state	Midway between the ground state and first excited state	Above first excited state	At first excited state	Midway between the ground state and first excited state
The minimum amount of current passed through the body of superconductor in order to destroy the superconductivity is called _____ current.	induced	critical	eddy	hall	critical
The binding energy for a cooper pair is _____	10^{-2} eV	10^{-4} eV	10^{-6} eV	10^{-8} eV	10^{-4} eV
There are three important lengths which enter the theory of superconductivity except _____	London penetration length	Intrinsic coherence length	Normal electron mean free length	Mean path length	Mean path length
The magnetic lines of force cannot penetrate the body of a superconductor, a phenomenon is known as Superconductivity was first observed by _____	Isotopic effect	BCS theory	Meissner effect	London theory	Meissner effect
The first successful theory on superconductivity was due to _____	Ohm	Ampere	H.K. Onnes	Schrieffer	H.K. Onnes
The current in a superconductor produces _____	Schrieffer	Onnes	Ampere and Schrieffer	Bardeen Cooper and Schrieffer	Bardeen Cooper and Schrieffer
At the critical temperature, the resistance of a super conductor _____	zero, voltage drop across it increase rapidly	a small voltage drop across it decrease rapidly	a large voltage drop across it remains constant	a strong electric field around it increase slowly	zero, voltage drop across it decrease rapidly
Superconductivity is exhibited by _____	hydrogen at 4.2 K	mercury at 4.0 K	mercury at 4.2 K	potassium at 4.2 K	mercury at 4.2 K
Superconductivity is observed for _____	infrared frequencies	d.c. and low frequency	a.c. and high frequency	frequencies having no effect	d.c. and low frequency
The superconductivity is due to _____	the crystal structure having no atomic vibration at 0°K	all electrons interact in the super-conducting state	the electrons jump into nucleus at 0°K	the electrons jump into nucleus at 4.2°K	having no atomic vibration at 0°K
The value of critical field below the transition temperature will _____	increase	decrease	remain unchanged	unaltered	increase
Superconductors are becoming popular for use in _____	memories	generating very strong magnetic field	generating electrostatic field	generating regions free from magnetic field	generating very strong magnetic field
Mercury as an electric contact material is _____	a liquid	a metal	a metal liquid	a gas	a metal liquid
The structure sensitive property of a super conductor is _____	critical magnetic field	transition temperature	critical current density	critical temperature	critical current density
At transition temperature the value of critical field is _____	zero	negative real value	positive real value	complex value	zero
_____ has zero temperature co-efficient of resistance.	Aluminium	Carbon	Porcelain	Manganin	Manganin
Super conductivity can be destroyed by _____	adding impurities	reducing temperatures	application of magnetic field	application of electric field	application of magnetic field
Superconducting metal in super conducting state has relative permeability of _____	zero	one	negative	more than one	zero
What happens to current sent through a superconducting wire?	It gains a slight voltage boost.	It's transmitted without loss of energy.	It experiences a sharp voltage drop.	It's transmitted with loss of energy.	It's transmitted without loss of energy.
In what year did Onnes discover it?	1911	1921	1931	1941	1911
Approximately how cold do conventional superconductors have to get before they enter the superconducting state?	0 K	39 K	130 K	120 K	39 K
Which of the following do NOT currently use superconductors?	MRI machines	alkaline batteries	proton accelerators	photon accelerators	alkaline batteries
Two essential and independent properties of a superconducting material are _____.	Zero resistivity, diamagnetic	high resistivity, diamagnetic	Zero resistivity, paramagnetic	high resistivity, paramagnetic	Zero resistivity, diamagnetic
Meissner's effect is related to _____ properties of superconductors.	optical	thermal	electrical	electrical	magnetic
The converse of hardness is known as _____	malleability	softness	toughness	brittle	softness
An HRC fuse is _____	a wire of Platinum	ceramic body with carbon rod	ceramic body with metal and caps	heavy cross section of copper and aluminium	ceramic body with metal and caps
The coils of D.C. motor starter are wound with wire of _____	Aluminium	Carbon	Porcelain	Manganin	Manganin
An ideal conducting material has _____	zero conductivity	small conductivity	large conductivity	infinite conductivity	infinite conductivity
Superconductors are _____	amorphous thin films of Be, Bi and Fi.	monovalent metals	ferromagneti and antiferromagnetic metals	ferrimagnetic metals	amorphous thin films of Be, Bi and Fi.
Soft superconductor follow _____	Silsbee's rule alone	Meissner effect alone	Silsbee's rule and Meissner effect	high critical field and transition temperature	Meissner effect
Hard superconductors observe _____	breakdown by Silsbee's rule	incomplete Meissner effect	low losses	all the above	all the above
A high Q coil has _____	large bandwidth	high losses	low losses	flat response	low losses

questions	opt1	opt2	opt3	opt4	answer
The frequency range of electronic polarization is _____	10 ¹² Hz	10 ¹³ Hz	10 ¹⁴ Hz	10 ¹⁵ Hz	10 ¹⁵ Hz
The frequency range of ionic polarization is _____	10 ¹² Hz	10 ¹³ Hz	10 ¹⁴ Hz	10 ¹⁵ Hz	10 ¹⁴ Hz
The frequency range of orientation polarization is _____	10 ¹² Hz	10 ¹³ Hz	10 ¹⁴ Hz	10 ¹⁵ Hz	10 ¹² Hz
The frequency range of space-charge polarization is _____	10 ¹² Hz	10 ¹³ Hz	10 ¹⁴ Hz	10 ⁵ Hz	10 ⁵ Hz
The example of electronic polarization is _____	inert gases	ionic crystal	CHCl	HCl	inert gases
The example of ionic polarization is _____	inert gases	ionic crystal	CHCl	HCl	ionic crystal
The power loss of space-charge polarization is _____	low	high	higher	highest	highest
The dielectric loss can occur both in the _____	direct and alternating vol	alternating voltage and capac	resistance and capacitor	resistance and frequency	direct and alternating voltage
The temperature of Avalanche Breakdown is _____	low	very low	high	very high	low
_____ breakdown occurs at high temperature	thermal	discharge	defect	electrolytic	thermal
The relaxation time of electronic polarization is _____	very slow	slow	very fast	fast	very fast
The relaxation time of ionic polarization is _____	very slow	slow	very fast	fast	slow
The relaxation time of orientation polarization is _____	very slow	slow	slower	slowest	slower
The relaxation time of space-charge polarization is _____	very slow	slow	fast	slowest	slowest
_____ molecules have permanent dipole moment even in the absence of an applied field	non-polar	polar	dielectric	dipole moment	polar
_____ molecules do not have permanent dipole moment.	non-polar	polar	dielectric	dipole moment	non-polar
The properties of dielectric materials is _____	large insulation resistance	low insulation resistance	very low insulation resistance	very large insulation re	large insulation resistance
The induced dipole moment (μ) is _____	charge \times displacement	charge \times voltage	voltage \times displacement	voltage \times current	charge \times displacement
w is called as _____	angular frequency	dipole moment	mass	current	angular frequency
_____ polarization occurs due to the accumulation of charges at the electrodes when field is applied	electronic	orientation	ionic	space-charge	space-charge
_____ type of polarization occurs at audio and radio frequency ranges	electronic	orientation	ionic	space-charge	orientation
_____ type of polarization occurs at optical frequency range	electronic	orientation	ionic	space-charge	electronic
_____ type of polarization occurs at electric power	electronic	orientation	ionic	space-charge	space-charge
The another name of the internal field is _____	Clausius-Mosotti	Lorentz field	Electric field	Magnetic field	lorentz field
The example of ferro electric material is _____	Rochelle salt	NaCl	HCl	CH	Rochelle salt
The ferro-electrics are used in _____	SONAR	LASER	MASER	Capacitor	SONAR
The dielectric strength is _____	dielectric voltage/thickness	thickness of dielectric/ diele	dielectric current/ thickness of	thickness of dielectric/ c	dielectric voltage/thickness of dielectric
For solids the dielectric constant is -----	Less than one	greater than one	equal to one	equal to zero	greater than one
Example for polar molecule is -----	CHCl3	CCl4	H2	CO2	CHCl3
The following molecules will not have centre of symmetry.	Polar	non polar	symmetric molecules	insulating	Polar
Electronic polarisation is ----- of temperature	dependent	irrespective	independent	symmetry	independent
Polar molecules have ----- dipole moments.	induced	permanent	temporary	unstable	permanent
Polarisation which occurs due to diffusion of ions is known as-----	Ionic polarisation	orientation polarisation	space charge polarisation	electronic polarisation	space charge polarisation
The relaxation times are ----- for different kinds of polarisations	same	different	remains constant	fixed value	different
The materials which have negative temperature co-efficient of resistance is known as-----	Dielectrics	insulators	conductors	resistors	Dielectrics
Dielectric constant for water at 0 ° C is -----	87.8	88.7	787.8	71.8	87.8
Mono atomic gases exhibit ----- type of polarisation.	Ionic	Space charge	electronic	orientation	electronic
Dielectric loss occurs in -----	only in direct voltage	only in alternating voltage	Both in alternating & direct vol	only in DC	Both in alternating & direct voltages
Power loss varies with -----	Frequency	amplitude	volume	time	Frequency
Ferroelectrics are ----- crystals	isotropic	Anisotropic	isomorphic	symmetric	Anisotropic
which of the following material have spontaneous polarisation?	ferromagnetic	paramagnetic	ferroelectric	ferrite	ferroelectric
The dielectric constant reaches a maximum value at -----	curie temperature	neel temperature	absolute temperature	fixed temperature	curie temperature
The materials which are used to produce ultrasonics is -----	ferro magnetic	antiferromagnetic	ferro electric	ferrite	ferro electric
The domain structure of ferro electric is similar to ----- material.	ferro magnetic	dia magnetic	para magnetic	anti ferromagnetic	ferro magnetic
The principle used in microwave ovens are-----.	Heating	dielectric heating	charging	annealing	dielectric heating
Dielectrics follows ----- effect	piezo electric	inverse piezo electric	magnetostriction	magnetostatic	inverse piezo electric
Dielectrics are ----- materials .	non metallic	metallic	semiconducting	conducting	non metallic
Dielectrics are also called as ----- .	conductors	semiconductors	insulators	resistors	insulators
The ratio between absolute permittivity to the permittivity of free space is known as	dielectric	dielectric constant	relative permeability	relative permittivity	dielectric constant
When a dielectric material is placed between a parallel plate capacitor its capacitance-----	decreases	increases	remains constant	same	increases
All insulating materials are ----- dielectrics	passive	active	liquid	fluid	passive
The material which restricts the flow of electrical energy is known as-----	dielectrics	active dielectrics	passive dielectrics	insulators	passive dielectrics
The following molecules will have center of symmetry.	Polar	non polar	symmetric molecules	insulating	non polar
The polarisation of polar molecules is highly ----- dependent.	temperature	pressure	volume	shape	temperature
The following molecules are not having absorption or emission in the infrared range.	polar molecules	non polar molecules	infrared molecules	visible	polar molecules
The displacement of charged particles under the action of ----- field is known as dielectric polarisation.	magnetic	electric	spontaneous	saturated	electric
Electronic polarisation is proportional to ----- of the atom.	volume	pressure	specific heat	temperature	volume
Orientation polarisability is ----- to temperature of the material.	directly proportional	inversely proportional	square	square root	inversely proportional

Question	opt1	opt2	opt3	opt4
Shape memory alloys have	high energy efficiency	low energy efficiency	zero efficiency	infinity
The density of Ni-Ti is	7 gm/cm ³	6 gm/cm ³	6.45 gm/cm ³	8 gm/cm ³
Melting point of Ni-Ti is	300 °C	200 °C	1800 °C	1300 °C
One nanometer is _____	1/10 ⁹ of meter	1/10 ⁸ of meter	1/10 ⁹ of meter	1/10 ¹¹ of meter
The process involved in the formation of metallic glass is _____	melt spinning technique	air quenching technique	alloy spinning technique	melt extraction technique
Cooling rate of metal-metal metallic glasses are _____	hundred degree/second	thousand degree/second	million deg/second	ten deg/second
Materials returning to original shape by having memory is _____	shape memory	plastic memory	magnetic shape memory	characteristics memory
Bandwidth of SMA's are	high	low	limited	close bandwidth
Nanometers are of _____ size.	10 ⁻¹⁰ m	10 ⁻⁸ m	10 ⁻⁹ m	10 ⁻⁹ m
A stable liquid phase containing particles in the 1-1000nm range are called	cluster	fullerene	nanorods	colloids
Phenomena that occurs on length between 1 and 100 nanometers are	nanodots	nanowires	nanoscale	nanotubes.
A form of carbon having large molecule consisting empty cage of 60 carbon atoms are	colloids	fullerene	nanofabrication	nanosstructure
Radius of clusters	1-100 nm	1-100 nm	1-1000 nm	1-5000 nm
Vapour-liquid-solid (VLS) growth of nanowires are	liquid growth	vapour phase growth	hybrid growth	solid phase growth
Atomic layer deposition (ALD) for thin film deposition is	vapour phase growth	liquid phase growth	solid phase growth	hybrid growth
Nanorods and nanowires are electroplated by _____	solution liquid solid growth (sls)	atomic layer deposition(ald)	molecular beam epitaxy (mbe)	Plasma assisted growth
_____ involves the ionization of gas atoms by electrons	vacuum arc deposition	magnetron sputtering	dc glow discharge	plasma arcing
_____ type of magnets are used in vacuum arc deposition	permanent magnet	solenoid magnet	horse magnet	bar magnet
Deposition rates produced by magnetrons are	high	low	~2Mn/mm	none of these
_____ type of gases are used in pulsed laser deposition	argon gas	neon gas	inert gas	argon and neon gas
Pressure of ultrahigh vacuum (cvd) are	10 ⁻⁷ pa	10 ⁻³ pa	10 ⁻⁶ pa	10 ⁻¹⁶ pa
A process in which the precursors are transported by means of a liquid/gas aerosol is	atomic layer(alkvd)	aerosol assisted (aacvd)	rapid thermal (rtcvd)	plasma enhanced (pecvd)
Hot wire-cvd (hwcvd) is also known as:	aerosol cvd	catalytic -cvd	atmospheric pressure cvd	low pressure cvd
The temperature range of carbon nanotubes in cvd method is _____	1000-1500 °c	1500-3000°c	above 1200°c	above 3000°c
_____ increases the growth rate in CVD chamber	arsine	phosphine	disilane	silane
Sols are also known as _____ solutions	flurene	colldal	liquid	plasma
The light scattering in synthesis is happened by _____ effect	tyndal	scatter	SMA effect	quartz
If the liquid phase of the gels are removed in the synthesis process _____ are obtained	aerogel	aerogel	xerogel	solgel
Sol-Gel method produce metals at ultra-low temperature of around _____	600-1000°F	150-600 °F	900 °F	1100 °F
High quality ball mills can grind mixture particles upto	0.001mm	0.0001mm	0.01mm	0.1mm
The nanomaterials used in the petroleum industry as catalyst are _____	permutite	zeolite	ambersite	naptha
The distance between grapheme layers of graphite are	5.2Å	5.18 Å	5.0 Å	3.3 Å
Single-walled nanotubes(SWNT) have a diameter of	2.0 nm	1.0nm	0.1nm	2.1 nm
In SWNT, if m=0 then the nanotubes are called	chiral	armchair	zig-zag	vector
The amount of current passed between two graphites in arc method is	100 Amps	50 Amps	150 Amps	no current
The nanosized catalyst metals are	Fe	Co	Fe and Ni	Fe
The deposition rate of pulsed laser deposition is	1nm/pulse	0.1 nm/pulse	2 nm/pulse	5 nm/pulse
The strength of carbon nanotubes are	93 (Gpa)	65(Gpa)	63(Gpa)	95(Gpa)
The electric current density of metallic nanotubes are	4×10 ⁹ A/cm ²	4×10 ⁹ A/m ²	8 ×10 ⁹ A/cm ²	8 ×10 ⁹ A/m ²
The temperature stability of carbon nanotubes in vacuum are	3600 °C	2800 °C	4000 °C	750 °C
The temperature stability of carbon nanotubes in air is	3600 °C	2800 °C	4000 °C	750 °C
Solar cells are formed by the mixture of carbon nanotubes and	fullerences	colloids	borons	both collids and borons
The pressure of helium atmosphere in arc method is	500 torr	300 torr	200 torr	400 torr
The buds, which are bounded covalently outside the sidewalls of carbon nanotubes are called	torus	nanobuds	microbuds	carbonbuds
The metting temperature of Ni-Ti alloys are	1500°C	1300°C	1200 °C	>1500 °C
The process which uses heating lamps and other methods to heat the water substrate is known as	RTCVd	ALCVD	MOCVD	AACVD
The flow of H gas in CVD method is	300ml/min	200 ml/min	150 ml/min	10 ml/min
Example for clusters	semiconductors	ceramic oxides	insulators	both ceramic oxides and ins
Diameter of human hair is	~20 µm	~15 µm	~10 µm	~25 µm
At particular temperature, when stress is applied to SMA, it deforms then it is known as	austenite	martensite	shape memory	both austenite and martensite
The process in which the molten alloy is passed through two rollers rotating in opposite directions are known as	roll spinning	twin roller	melt extraction	melt retraction
_____ is a technique used to form metallic glasses by rapid cooling	tyndal	quenching	melting	both quenching and melting
In metallic glasses, the thickness of the ribbon can be varied by increasing (or) decreasing the _____	width	speed	flow	both width and speed
Metallic glasses have good _____ properties	mechanical	electrical	magnetic	mechanical, electrical and m
The linear array of dots formed by self assembly is known as	nanodots	nanoscales	nanowires	nanotechnology
In which year, the active nanostructures are discovered	2005	2010	2000	1975
_____ technique is used to form metallic glasses.	Quenching	Cooling	Annealing	Calcination
Density of Ni-Ti alloy is-----	6.45 gm/cm ³	6.45 gm/cm	4.65gm/cm ³	8.3gm/cm ³
The melting point of nanoparticles is -----	high	less	very less	very high

answer
low energy efficiency
6.45 gm/cm³
1300 °C
1/10⁹ of meter
melt spinning technique
million deg/second
shape memory
limited
10⁻⁹ m
colloids
nanoscale
fullerene
1-10 nm
hybrid growth
vapour phase growth
solution liquid solid growth (sls)
dc glow discharge
solenoid magnet
high
inert gas
10⁻⁶ ps
aerosol assisted (aacvd)
catalytic -cvd
500-1200°C
diborane
colloidal
tyndal
xerogel
150-600 °F
0.0001 mm
zeolite
3.3 Å
1 nm
zig-zag
50 Amps
all of these
0.1 nm/pulse
63(GPa)
4×10⁹ A/cm²
2800 °C
750 °C
fullerenes
400 torr
nanobuds
1300°C
RTCVD
200 ml/min
both ceramic oxides and insulators
~10 µm
martensite
twin roller
quenching
speed
mechanical, electrical and magnetic
nanowires
2005
Quenching
6.45 gm/cm³
very less