

SEMICONDUCTING MATERIALS

Introduction

A semiconducting material has electrical conductivity considerably greater than that of an insulator but significantly lower than that of a conductor. The value of resistivity varies from 10^{-4} to 0.5 ohm metre.

Properties of a semiconductor.

1. The resistivity lies between 10^{-4} to 0.5 ohm metre.
2. At 0K, they behave as insulators.
3. The conductivity of a semiconductor increases both due to the temperature and impurities.
4. They have negative temperature coefficient of resistance.
5. In semiconductors both the electron and holes are charge carries and will take part in condition.

Types of Semiconductors

(i) Intrinsic semiconductor:

Semiconductor in a pure form is called intrinsic semiconductor. Here the charge carries are produced only due to thermal agitation. They are low electrical conductivity. They have low operating temperature.

(ii) Extrinsic semiconductor:

Semiconductor which are doped with impurity is called extrinsic semiconductor. Here the charge carries are produced only due to impurities and may also be produced due to thermal agitation. They are high electrical conductivity.

Density of electrons in the conduction band

The number of electrons per unit volume in the conduction band for the energy range E and E + d E is given by

$$d n = Z (E) F (E) d E \dots\dots (1)$$

$$\int d n = n = \int_{E_c}^{\infty} Z(E)F(E)dE\dots\dots(2)$$

Density of states in the conduction band between the energy range E and E + d E is given by,

$$Z(E) dE = \frac{4\pi}{h^3} (2m_e^*)^{3/2} E^{1/2} dE \dots (3)$$

$E - E_c$ is the kinetic energy of the conduction electron at higher energy levels.

Thus in equation (3), E is replaced by $(E - E_c)$

$$Z(E) dE = \frac{4\pi}{h^3} (2m_e^*)^{3/2} (E - E_c)^{1/2} dE \dots (4),$$

The probability of electrons occupation is given by

$$F(E) = \frac{1}{1 + e^{(E - E_F)/kT}} \dots (5),$$

Substituting the equations (4) & (5) in (2), we get,

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \int_{E_c}^{+\infty} \frac{(E - E_c)^{1/2}}{1 + e^{(E - E_F)/kT}} dE \dots (6),$$

Since $(E - E_F)$ is greater than kT , $e^{(E - E_F)/kT}$ is very large compared to '1'

i.e., $1 + e^{(E - E_F)/kT} \approx e^{(E - E_F)/kT}$, now the equation (6) becomes,

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \int_{E_c}^{\infty} \frac{(E - E_c)^{1/2} dE}{e^{(E - E_F)/kT}}, \quad n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \int_{E_c}^{+\infty} (E - E_c)^{1/2} e^{(E_F - E)/kT} dE$$

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} e^{E_F/kT} \int_{E_c}^{\infty} (E - E_c)^{1/2} e^{-E/kT} dE \dots (7),$$

To solve the integral in the equation (7), let us assume

$E - E_c = x$	When	when
$E = E_c + x$	$E = E_c$	$E = +\infty$
$dE = dx$	$E_c - E_c = x$	$+\infty - E_c = x$
	$\therefore x = 0$	$\therefore x = +\infty$

Substituting the above values in equation (7),

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} e^{E_F/kT} \int_0^{\infty} x^{1/2} e^{-(E_c + x)/kT} dx$$

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} e^{(E_F - E_c)/kT} \int_0^{\infty} x^{1/2} e^{-x/kT} dx \dots (8),$$

Using the gamma function, it is shown that

$$\int_0^{\infty} x^{1/2} e^{-x/kT} dx = \frac{(kT)^{3/2} \pi^{1/2}}{2} \dots (9),$$

Substituting the equation (9) in the equation (8), we have

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} e^{(E_F - E_c)/kT} \left[\frac{(kT)^{3/2} \pi^{1/2}}{2} \right] \text{ or } n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} e^{(E_F - E_c)/kT} \dots (10)$$

Density of holes in the valence band of an intrinsic semiconductor

Let dp be the number of holes per unit volume in the valence band between the energy E and $E + dE$.

$$dp = Z(E) (1-F(E)) dE \dots (1)$$

$1-F(E)$ is the probability of an unoccupied electron state, i.e., presence of a hole.

$$1-F(E) = 1 - \frac{1}{1 + e^{(E-E_F)/kT}} ; 1-F(E) = \frac{e^{(E-E_F)/kT}}{1 + e^{(E-E_F)/kT}} \dots (2)$$

Since E is very small when compared E_F , in the valence band $(E-E_F)$ is a negative quantity.

Therefore $e^{(E-E_F)}$ is neglected in the denominator.

$$\therefore 1-F(E) = e^{(E-E_F)/kT} \dots (3),$$

Density of states in the valence band,

$$Z(E)dE = \frac{4\pi}{h^3} (2m_h^*)^{3/2} E^{1/2} dE \dots (4)$$

Here, m_h^* is the effective mass of the hole in the valence band. $(E_v - E)$ is the kinetic energy of the hole at level below E_v . So the term $E^{1/2}$ is replaced by $(E_v - E)$ in equation (4).

$$\therefore Z(E)dE = \frac{4\pi}{h^3} (2m_h^*)^{3/2} (E_v - E)^{1/2} dE \dots (5)$$

Substituting the equations (3) & (5) in (1), we get $dp = \frac{4\pi}{h^3} (2m_h^*)^{3/2} (E_v - E)^{1/2} e^{(E-E_F)/kT} dE \dots (6)$

The number of holes in the valence band for the entire energy range is obtained by integrating the equation (6) between the limits $-\infty$ to E_v .

$$\int dp = p = \frac{4\pi}{h^3} (2m_h^*)^{3/2} e^{(-E_F/kT)} \int_{-\infty}^{E_v} (E_v - E)^{1/2} e^{(E/kT)} dE \dots (7),$$

To solve the above integral in equation (7),

let us assume,

$E_v - E = x$	When	$E = -\infty$	when
$E = -x + E_v$	$E = \infty = x$		$E = E_v$
			$x = E_v - E_v$

$$\therefore dE = - dx$$

$$\therefore = \infty$$

$$\therefore x = 0$$

Substituting these values in equation (7), we have,

$$p = \frac{4\pi}{h^3} (2m_h^*)^{3/2} e^{(E_F - E_F)/kT} \int_0^{\infty} x^{1/2} e^{(-x/kT)} dx \dots (9),$$

Using the gamma function, it is shown that

$$\int_0^{\infty} x^{1/2} e^{(-x/kT)} dx = \frac{(kT)^{3/2} \pi^{1/2}}{2} \dots (10),$$

Substituting the equation (10) in the equation (9), we have

$$p = \frac{4\pi}{h^3} (2m_h^*)^{3/2} e^{(E_F - E_F)/kT} \left[\frac{(kT)^{3/2} \pi^{1/2}}{2} \right] \text{or..} p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} e^{(E_v - E_F)/kT} \dots (11).$$

Intrinsic carrier concentration

In an Intrinsic carrier concentration, number of electrons and holes are same.

Hence, $n = p = n_i$

Where n_i is the Intrinsic carrier concentration,

$$n_i^2 = n \times p$$

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} e^{(E_F - E_c)/kT} \left[\frac{(kT)^{3/2} \pi^{1/2}}{2} \right] \text{or..} n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} e^{(E_F - E_c)/kT} \dots (10)$$

$$p = \frac{4\pi}{h^3} (2m_h^*)^{3/2} e^{(E_F - E_F)/kT} \left[\frac{(kT)^{3/2} \pi^{1/2}}{2} \right] \text{or..} p = 2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} e^{(E_v - E_F)/kT}$$

$$n_i^2 = 2 \left[\frac{2\pi kT}{3/2} \right]^{3/2} (m_e^* m_h^*)^{3/4} e^{\frac{-E_g}{2kT}}$$

Fermi energy of an intrinsic semiconductor

Fermi energy level is the energy level which distinguishes the filled and empty states (or) it is the maximum energy level up to which the electrons are filled.

At 0K,

The Fermi energy of an intrinsic semiconductor is $E_F = \frac{E_c + E_v}{2}$ i.e., the Fermi energy level exactly lies between the lowest energy level of conduction band and highest energy level of valence band.

Elemental semiconductor and Compound semiconductor

Elemental semiconductors:

Semiconductor elements of fourth group, which are doped with pentavalent or trivalent impurities, in order to get n-type semiconductors, are called elemental semiconductors.

Compound semiconductors:

Semiconductors formed by combining fifth and third group or sixth and second group are called compound semiconductors.

Extrinsic semiconductor:

Semiconductor which are doped with impurity is called extrinsic semiconductor. Here the charge carriers are produced only due to impurities and may also be produced due to thermal agitation. They are high electrical conductivity.

Extrinsic semiconductors are further subdivided into

- (i) N- TYPE semiconductor
- (ii) P-TYPE semiconductor

Distinguish between P-type & N-type Semiconductors.

S.No.	N- TYPE	P-TYPE
1.	Pentavalent impurity is added	Trivalent impurity is added
2.	Electrons are majority charge carriers	Holes are minority charge carriers
3.	Impurity is called donor impurity	Impurity is called acceptor impurity
4.	Fermi level decreases with increase in temperature	Fermi level increases with increase in temperature

Fermi energy of an Extrinsic semiconductors at 0k.

Fermi energy level is the energy level which distinguishes the filled and empty states (or) it is the maximum energy level up to which the electrons are filled.

- (i) The Fermi energy of 'n'-type semiconductor is a $E_F = \frac{E_c + E_d}{2}$ i.e., the Fermi energy level exactly lies between minimum energy level of conduction band and donor energy level.
- (ii) The Fermi energy of 'p'-type semiconductor is a $E_F = \frac{E_c + E_d}{2}$ i.e., the Fermi energy level exactly lies between top of the valence band and acceptor energy level.

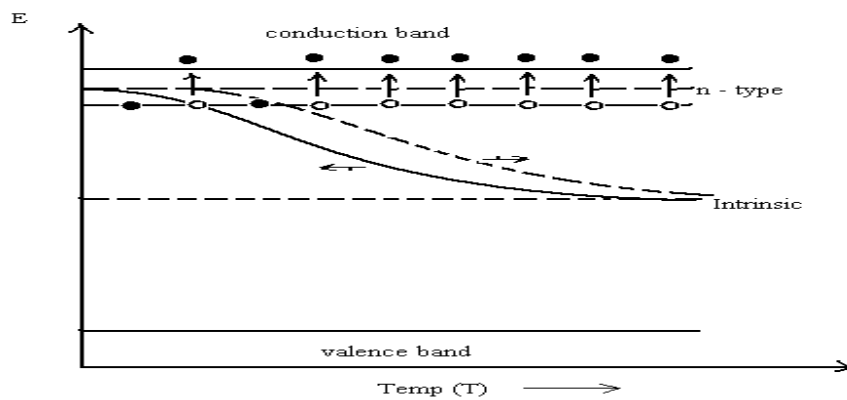
Donor energy level

A donor is an atom or group of atoms whose highest filled atomic orbital or molecular orbital is higher in energy than that of a reference orbital.

Acceptor energy level

An acceptor is an atom or group of atoms whose lowest unfilled atomic or molecular orbital is lower in energy than that of a reference orbital.

Variation of Fermi level with temperature in the case of n-type semiconductor.



Concentration of Holes in the Valence Band of n-type Semiconductor :

In n-type semiconductor, donor energy level (E_d) is just below the conduction band and N_d denotes the number of donor atoms per unit volume. Density of electrons per unit volume in the conduction band is given by

$$n = 2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} e^{(E_f - E_c)/kT} \dots\dots\dots(1)$$

Density of ionized donors = $N_d F(E_d)$

$$= \frac{N_d}{1 + e^{(E_d - E_f)/kT}} = \frac{1}{1 + e^{(E_d - E_f)/kT}} \dots\dots\dots(2)$$

Since $E_d - E_f$ is very large when compared to kT , $e^{(E_d - E_f)/kT}$ is a large quantity and thus ‘1’ from the denominator of R.H.S. of the equation (2) is neglected.

Now, the equation (2) is modified as, $N_d e^{(E_f - E_d)/kT} \dots\dots\dots(3)$

At equilibrium,

Density of holes in valence band = Density of ionized donors.

$$2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} e^{(E_f - E_c)/kT} = N_d e^{(E_d - E_f)/kT} \dots\dots\dots(4)$$

Taking log on both sides of the equation (4), we have

$$\log_e \left[2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \right] + \frac{E_f - E_c}{kT} = \log_e N_d + \frac{E_d - E_f}{kT} \dots\dots\dots(5)$$

Rearranging the expression (5), we have

$$\frac{E_f - E_c - E_d - E_f}{kT} = + \log_e N_d - \log_e \left[2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2} \right] \dots\dots\dots(6)$$

$$E_f = \frac{E_d + E_c}{2} + \frac{kT}{2} \log_2 \left[\frac{N_d}{2 \left(\frac{2\pi m_e^* kT}{h^2} \right)^{3/2}} \right] \dots\dots\dots(7)$$

Substituting the expression of E_f from (7) in (1), we get

$$n = 2 \left(\frac{2 \pi m_e^* kT}{h^2} \right)^{3/2} \exp \left\{ \frac{E_d - E_c}{2} + \frac{kT}{2} \log_e \frac{N_d}{2 \left[\frac{2 \pi m_e^* kT}{h^2} \right] - E_c} \right\}$$

$$n = 2 \left(\frac{2 \pi m_c^* kT}{h^2} \right)^{3/2} \exp \frac{E_c + E_d - 2E_c}{2kT} + \frac{1}{2} \log_e \left[\frac{N_d}{2 \left(\frac{2 \pi m_c^* kT}{h^2} \right)^{3/2}} \right] \dots\dots\dots(8)$$

$$n = 2 \left(\frac{2 \pi m_c^* kT}{h^2} \right)^{3/2} \frac{\left(\frac{N_d}{2} \right)^{1/2}}{\left(\frac{2 \pi m_c^* kT}{h^2} \right)^{3/4}} e^{(E_d - E_c) / 2kT}$$

$$n = (2 N_d)^{1/2} \left(\frac{2 \pi m_c^* kT}{h^2} \right)^{3/4} e^{(E_d - E_c) / 2kT} \dots\dots\dots(9)$$

$$n = (2 N_d)^{1/2} \left(\frac{2 \pi m_e^* kT}{h^2} \right)^{3/4} e^{-\Delta E / 2kT} \dots\dots\dots(10)$$

Where $\Delta E = E_c - E_d$

Fermi energy of a P – type semiconductor

In p-Type semiconductor, acceptor energy level (E_a) is just above the valence band and N_a denotes the number of acceptor atoms per unit volume. Density of holes per unit volume in the valence band is given by

$$p = 2 \left(\frac{2 \pi m_h^* kT}{h^2} \right)^{3/2} e^{(E_v - E_F) / kT} \dots\dots\dots (1)$$

$$\text{Density of ionized acceptors} = N_a F(E_a) = \frac{N_a}{1 + e^{(E_a - E_F) / kT}} = \frac{1}{1 + e^{(E_a - E_F) / kT}} \dots\dots\dots(2)$$

Since $E_a - E_F$ is very large when compared to kT , $e^{(E_v - E_F) / kT}$ is a large quantity and thus ‘1’ from the denominator of R.H.S. of the equation (2) is neglected.

Now, equation (2) is modified as, $N_a e^{(E_F - E_a) / kT} \dots\dots\dots(3)$

At equilibrium,

Density of holes in valence band = Density of ionized acceptors.

$$2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} e^{(E_v - E_F)/kT} = N_a e^{(E_F - E_a)/kT} \dots (4)$$

Taking log on both sides of the equation (4), we have

$$\log_e \left[2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \right] + \frac{E_v - E_F}{kT} = \log_e N_a + \frac{E_F - E_a}{kT} \dots (5)$$

Rearranging the expression (5), we have

$$\frac{E_F - E_a - E_v + E_F}{kT} = -\log_e N_a + \log_e \left[2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2} \right] \dots (6)$$

$$E_F = \frac{E_a + E_v}{2} - \frac{kT}{2} \log_e \left[\frac{N_a}{2 \left(\frac{2\pi m_h^* kT}{h^2} \right)^{3/2}} \right] \dots (7)$$

When T = 0 K, Then $E_F = \frac{E_a + E_v}{2}$, the Fermi level lies at the middle of the acceptor energy level and the top most energy level of the valence band.

Hall effect

When a conductor (metal or semiconductor) carrying a current (I) is placed perpendicular to a magnetic field (B), a potential difference (electric field) is developed inside the conductor in a direction perpendicular to both current and magnetic field.

Expression of Hall coefficient.

Statement: When a conductor (metal or semiconductor) carrying a current (I) is placed perpendicular to a magnetic field (B), a potential difference (electric field) is developed inside the conductor in a direction perpendicular to both current and magnetic field.

Hall Effect in an n-type semiconductor:

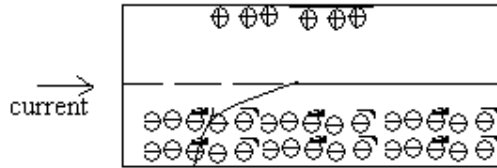
Let us consider an n-type semiconducting material in the form of rectangular slab. In such a material, current flows in X-direction and magnetic field B is applied in Z-direction. As a result,

Hall voltage is developed along Y-direction as shown. The current flow is entirely due to the flow of electrons moving from right to left along X-direction as shown. When a magnetic field (B) is applied in Z-direction, the electrons moving with velocity v will experience a downward force.

Downward force experienced by the electrons = Bev ,

Where e is the charge of an electron; ... (1)

This downward force deflects the electrons in downward direction.



This causes the bottom face to be more negative with respect to the top face. Therefore, a potential difference is developed between top and bottom of the specimen. This potential difference causes an electric field E_H called Hall field in negative Y-direction. This electric field develops a force which is acting in the upward direction on each electron.

Upward force acting on each electron = eE_H (2),

At equilibrium, the downward force Bev will balance the upward force eE_H

$$\therefore Bev = eE_H \text{ or } E_H = Bv \dots\dots (3).$$

The current density (J_x) acting along the X-direction is related to the velocity v as

$$J_x = -nev,$$

$$v = \frac{-J_x}{ne} \dots\dots(4)$$

Substituting the equation (4) in the equation (3), we have

$$E_H = \frac{-BJ_x}{ne} \dots(5); E_H = R_H J_x B \dots\dots(6) \text{ or, } R_H = \frac{E_H}{J_x B}$$

$$\text{Where } R_H = -\frac{1}{ne} \text{ (for, electrons)}$$

R_H is a constant and it is known as Hall coefficient.

Hall Coefficient in terms of Hall Voltage:

If 't' is the thickness of the sample and V_H the voltage developed, then

$$V_H = E_H t \dots\dots(7)$$

Where E_H is Hall field.

Substituting the equation (6) in the equation (7), we have

$$V_H = R_H J_x B t \dots\dots (8),$$

Area of the sample (A) = Breadth (b) × Thickness (t) = bt.

$$\text{Current density, } J_x = \frac{I_x}{\text{Area.of.the.sample.(A)}} = \frac{I_x}{bt} \dots(9)$$

Substituting the equation (9) in the equation (8), we have $V_H = \frac{R_H I_x B t}{bt}$ or $V_H = \frac{R_H I_x B}{b}$

$$\text{Hall coefficient } R_H = \frac{V_H b}{I_x B} \dots\dots(11)$$

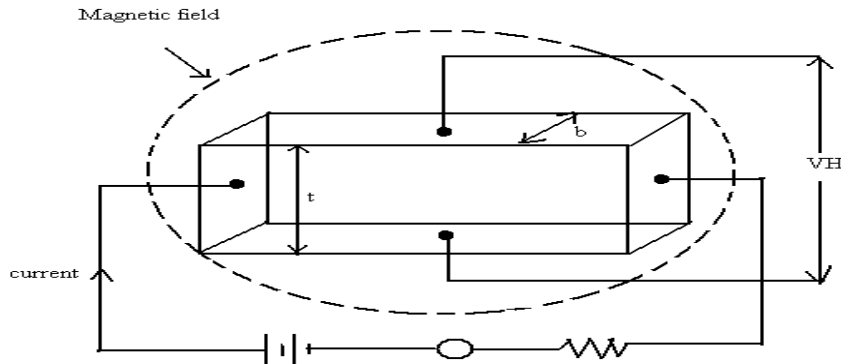
Hall voltage.

- Hall voltage is the voltage developed across a conductor or semiconductor, when an electric and magnetic fields are applied perpendicular to each other in the specimen

Experimental setup for the measurement of the Hall voltage

Determination of Hall Coefficient:

The experimental set up for the measurement of Hall-Coefficient is shown.



A Semi conducting material is taken in the form of a rectangular slab of thickness ‘t’ and breadth ‘b’ current I_x is passed through this sample along X-axis by connecting it to a battery.

This sample is placed in between two poles of an electromagnet such that the magnetic field is applied along Z-axis. Due to Hall Effect, Hall voltage (V_H) is developed in the sample.

This voltage is measured by fixing two probes at the centers of the bottom and top faces of the sample. By measuring Hall voltage, Hall coefficient is determined from the formula,

$$R_H = \frac{V_H b}{I_x B}$$

From Hall coefficient, carrier concentration and mobility can be determined.

Application of Hall effect.

1. The sign of charge carriers (electrons or holes) are determined.

2. The carrier density (concentration) is determined

$$n = - \frac{1}{R_H e}$$

$$p = \frac{1}{R_H e}$$

3. Mobility of charge carriers are measured.

Mobility of electron $\mu_n = R_H e$

Mobility of hole $\mu_h = R_H h$

4) Electrical conductivity of the material is determined

5) Magnetic flux density is measured from known Hall coefficient and measured Hall voltage.

UNIT- III. MAGNETIC MATERIALS AND SUPER CONDUCTORS

Introduction

Magnetism arises in the materials mainly due to orbital and spinning motion of electrons. Magnetic materials are of great use in equipments such as transformers, alternators, motors, electromagnets and magnetic tapes. The materials Ferrites and Metallic glasses find special applications in the memory of computer cores, magnetic shielding and recording devices.

Basic Definitions

Bohr magneton

The magnetic moment contributed by an electron with angular momentum quantum number $n=1$ is known as bohr magneton

Bohr magneton is the elementary electromagnetic moment of value.

$$\mu_B = \frac{eh}{4\pi m} = 9.274 \times 10^{-24}$$

Magnetic susceptibility

It is defined as the intensity of magnetization produced in the substance per unit magnetic field strength.

Magnetic permeability

Magnetic permeability of a substance measures degree to which the magnetic field can Penetrate through the substance

Classification of Magnetic materials

The different types of magnetic materials are

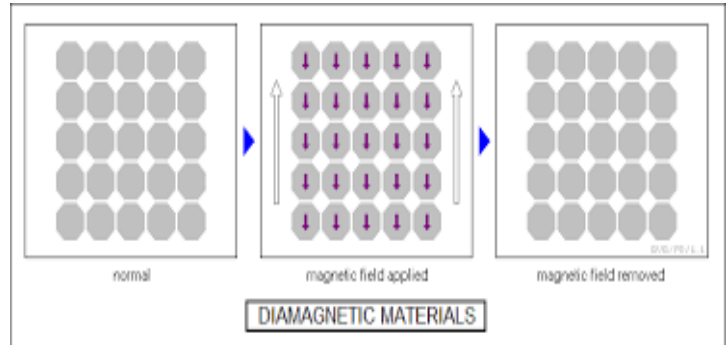
- (i) Diamagnetic materials
- (ii) Paramagnetic materials
- (iii) Ferromagnetic materials

(iv) Antiferromagnetic materials

(V) Ferrimagnetic materials

Diamagnetic materials

- Diamagnetic materials do not have permanent dipoles.
- In an external magnetic field H , the orbital motion of electrons undergoes changes and the atoms acquire induced magnetic moment in the direction opposite to the field.
- Its susceptibility is negative χ and independent on temperature

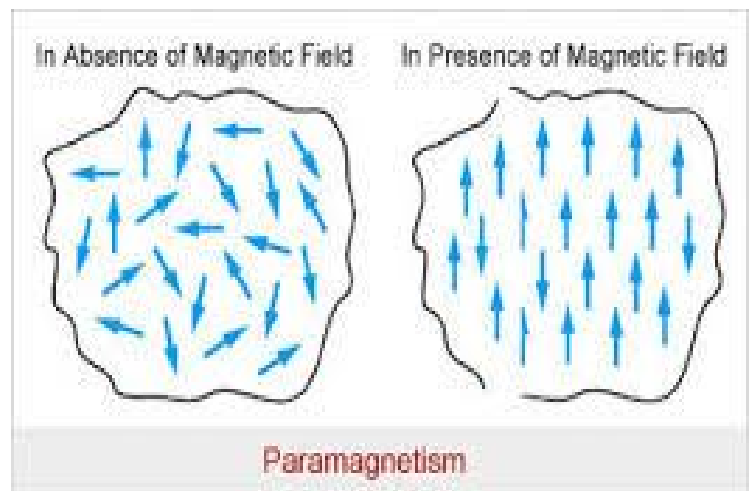


$$\kappa = \frac{M}{H} = -1$$

The induced dipoles and magnetization vanishes as soon as the field is removed. Diamagnetism is a universal property of all the substances. But other magnetic property dominates it.

Paramagnetism

- Paramagnetic materials have permanent dipoles.
- The dipoles are randomly oriented. Therefore, the net magnetic moment is zero. In the external magnetic field H , the dipoles are tending to align in the direction of the field.
- The material becomes magnetized. Its susceptibility χ is positive and inversely proportional to the temperature T .



$$\chi = \frac{C}{T} > 1 \quad (\text{Curie-Weiss law})$$

Where C – Curie’s constant.

Ferromagnetism

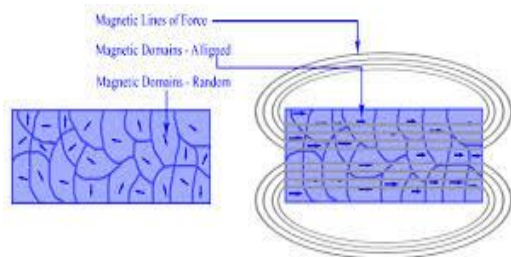
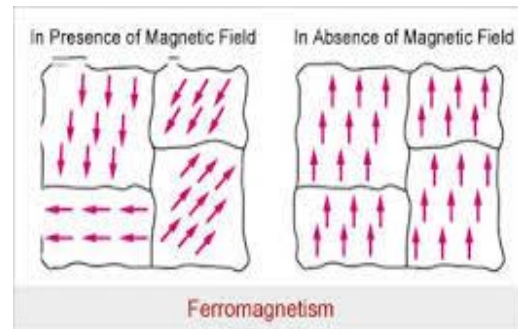


Fig. Ferromagnetism (a) Unmagnetized Material (b) Magnetized Material



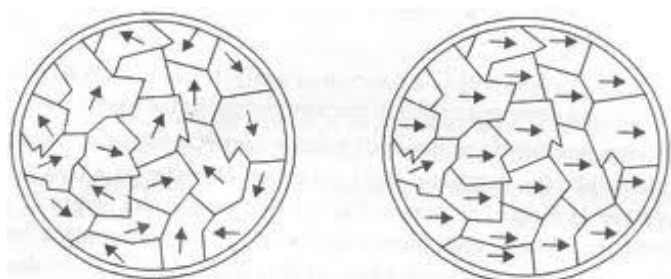
- Ferromagnetic materials have permanent dipoles.
- The dipoles are parallel to each other within the domain.
- The net magnetic moment of the domain is zero due to intermolecular field.
- The spin magnetic moments of unpaired electrons are responsible for it. They have spontaneous magnetization.
- Its susceptibility is very large and depends on temperature.

$$\chi = \frac{C}{T - \theta} \gg 1$$

When the temperature T increases its susceptibility χ decreases and shows paramagnetic behaviour above the paramagnetic Curie temperature θ .

Ferromagnetic domain theory

- It states that a ferromagnetic material consist of large number of small



regions of spontaneous magnetization called domains.

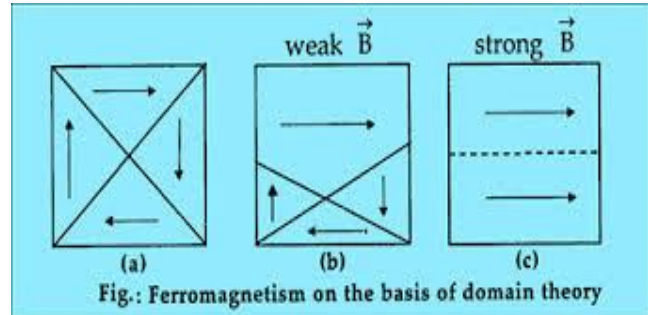
- Within each domain, the magnetic moments are aligned parallel to one another.
- The direction of magnetization varies from domain to domain and thus net macroscopic magnetization is zero in a virgin specimen.

When we apply an increasing external magnetic field, initially, the areas of the domains which are parallel to the field are increased. In the final saturation stage, the other domains are rotated parallel to the field.

Process of domain magnetization:

1. By the motion of domain walls:

When small magnetic field is applied the domain with magnetization direction parallel or near by parallel to the field ,grow at the expense of others as show below picture



2. By rotation of domains :

As the magnetic field increased to large value further domain growth becomes impossible through domain wall movement

Types of energy involved in the process:

1. Exchange energy
2. Magnetstatic energy
3. Crystal anisotropy energy

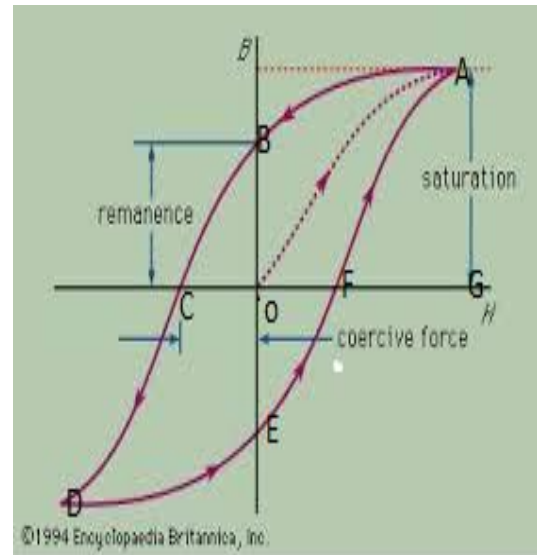
The hysteresis on the basis of domain theory of ferromagnetism

Hysteresis is the lagging of magnetic induction B behind the applied magnetic field H .

Hysteresis loop

A B-H curve is drawn by taking magnetization H in the x-axis and magnetic induction B of the ferromagnetic material in the y-axis.

1. H is increased then B increased and reached saturation at A.
2. H is decreased then B decreased and reached retentivity at B.
3. H is increased in the reverse direction then B decreased and reached zero at C known as coercivity.
4. H is further increased then B increased in the reverse direction and reached saturation at D.
5. H is decreased then B decreased and reached retentivity at E.
6. H is increased in the reverse direction then B decreased and reached zero at F.
7. H is increased further then B reached saturation again at A.



The obtained loop ABCDEA as in the figure is called **Hysteresis loop**.

The area occupied by the loop indicates the **Hysteresis energy loss** during the magnetization cycle of ferromagnetic material.

- **Retentivity or residual magnetism** is the amount of magnetic induction retained at B in the material after the removal of the applied magnetic field ($H = 0$).
- **Coercivity or coercive force** is the required amount of magnetizing field H in the reverse direction to remove the residual magnetism completely from the material ($B=0$).

Types of Magnetic materials

There are two types of magnetic materials. They are

- (i) Soft magnetic materials
- (ii) Hard magnetic materials

Soft and hard magnetic materials

Soft magnetic materials	Hard magnetic materials
They are easily magnetized and demagnetized.	They cannot be easily magnetized
They have large permeability and susceptibility	They have low permeability
Hysteresis loss is low	Hysteresis loss is high.
Low retentivity	High retentivity
Low coercitivity	High coercitivity
Low eddy current loss	High eddy current loss

Energy Product

The Energy product is defined as the product of retentivity and coercivity. The energy product gives the maximum amount of energy stored in the specimen. The value of energy product should be very large for manufacturing permanent magnets. Hard magnetic materials are having large energy product.

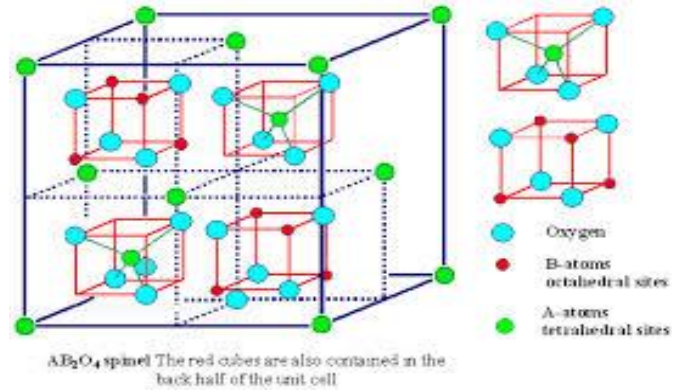
Anti ferromagnetism

Antiferromagnetic materials containing two types of dipoles in the adjacent sites. The electron spin of neighboring dipoles are aligned antiparallel. So net magnetization is zero at 0 K. Its susceptibility initially increases slightly with temperature T and decreases beyond the Neel temperature T_N .

- The dipole alignment is antiparallel
- The susceptibility is very small and is antiparallel
- Initially, the susceptibility increases slightly as the temperature increases. Beyond a particular temperature known as Neel temperature, the susceptibility decreases with temperature.
- Example : Ferrous oxide, Manganese oxide.

The structure and application of Ferrites

- They are compounds of iron oxides with oxides of other metals.
- Magnetic moment of sub-lattices are antiparallel of different magnitude. Mechanically it has pure iron character.
- They have high permeability and retentivity.
- They have low hysteresis and eddy current losses. Its susceptibility is very large and positive



C

$$\chi = \frac{C}{T \pm \theta}$$

Where C – Curie constant and θ - paramagnetic Curie's temperature

Applications of ferrites

1. Soft magnetic ferrites are used to make cores for transformer.
2. Soft Ferrite rods are used to produce ultrasonic sound by magnetostriction principle.
3. Soft Ferrite rods are used to increase the sensitivity and selectivity of the radio receiver.
4. To make ferrite coated magnetic film, magnetic discs, magnetic tapes and microwave drivers.
5. Hard magnetic ferrites are used to make permanent magnet.

SUPER CONDUCTORS

Introduction

The electrical resistivity of many metals and alloys drops suddenly to zero when the materials are cooled to a sufficiently low temperature called critical or transition temperature. This phenomenon is known as superconductivity.

Superconductivity was first observed in 1911 by a Dutch Physicist, H.K. Onnes in the course of his experiment on measuring the electrical conductivity of metals at low temperature. He observed that when purified mercury was cooled to 4.2 K its resistivity suddenly dropped to zero. Superconductivity occurs in metallic elements and also in alloys and semiconductors.

Transition temperature

The temperature at which a normal conductor loses its resistivity and becomes a super conductor is known as transition temperature.

Meissner effect

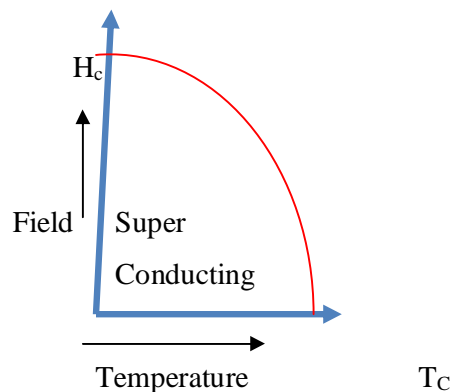
When a super conducting material is kept in an external magnetic field under the condition when $T \leq T_c$ and $H \leq H_c$, the magnetic flux lines are completely excluded from the material and the phenomenon is known as Meissner effect.

Critical magnetic field in superconductor.

When a super conductor is kept in magnetic field, the super conductor becomes normal conductor. The magnetic field required to destroy the super conducting property is called critical field (H_c). It is given by

$$H_c = H_o \left[1 - \frac{T^2}{T_c^2} \right]$$

Where H_o Critical field at 0K
 T_c Transition temperature.



Persistent Current

The steady current which flows through a superconducting ring without any decrease in its strength as long as the material is in the superconducting state even after the removal of the magnetic field is called persistent current.

Types of Super conductors:

There are two types of Superconductors. They are,

- Type I superconductors
- Type II superconductors

When a super conductor is kept in a external magnetic, if the super conductors becomes normal conductor suddenly at critical magnetic field. It is called as type I super conductors.

When a super conductor is kept in a external magnetic, if the super conductors becomes normal conductor gradually with respect to various critical fields, it is called as type II super conductors.

Type I and Type II superconductors

S.No	Type I (soft) superconductor	Type II (Hard) superconductor
1.	The Type I super conductor becomes a normal conductor abruptly at critical magnetic field.	Type II super conductor loses its super conducting property gradually, due to increase in magnetic field.
2.	Here we have only critical field (H_c)	Here we have two critical fields (i.e.) Lower critical fields (H_{c1}) and Upper critical fields (H_{c2}).
3.	No mixed state exists	Mixed (or) vortex state is present.
4.	Highest known critical field is 0.1 Tesla	The critical field is greater than Type I (i.e) Upto 30 Teslas.
5.	Examples:Pb, Zn, Al, Ga, Hg,	Examples:Niobium, Vanadium.

BCS Theory

- The BCS theory relies on the assumption that superconductivity arises when the attractive Cooper pair interaction dominates over the repulsive Coulomb force.
- A Cooper pair is a weak electron-electron bound pair mediated by a phonon interaction. Although somewhat ambiguous, one can visualize this pairing by the following explanation. Imagine an electron moving within a material.
- The Coulomb attraction between the electron and the positively charged cores of ions in the material will leave a net positive charge in the vicinity.
- A “paired “electron is one with opposite momentum and spin that is attracted to this force.

The BCS Theory is, in its simplest form, actually contradictory to our crude macroscopic view expressed earlier. As discussed earlier, superconductivity arises because electrons do not interact destructively with atoms in the crystal lattice of the material.

The BCS Theory says that electrons do actually interact with the atoms, but constructively. The BCS Theory makes a crucial assumption at the beginning: that an attractive force exists between electrons. In typical Type I superconductors, this force is due to Coulomb attraction between the electron and the crystal lattice.

- An electron in the lattice will cause a slight increase in positive charges around it. This increase in positive charge will, in turn, attract another electron. These two electrons are known as a Cooper pair.
- Cooper pairs are formed by Coulomb interactions with the crystal lattice.
- As the Cooper pair flows, the leading electron causes this increase of charge, and the trailing electron is attracted by it. This is illustrated below.

High T_c Superconductors

High temperature superconductors are the one which has the transition temperature above 77 K. Here crossing 77 K is very important, because cooling can be made by liquid nitrogen instead of liquid helium, which is costly than nitrogen.

Example:

- (i) $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ [YBCO] [$T_c=90\text{K}$]
- (ii) $\text{Tl}_2\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$ [TBCO] [$T_c=120\text{K}$]

High T_c super conductor

- High-temperature superconductors (abbreviated high- T_c or HTS) are materials that have a [superconducting](#) transition temperature (T_c) above 30 K (-243.2°C).
- "High-temperature" has three common definitions in the context of superconductivity: Technological applications benefit from both the higher critical temperature being above the boiling point of liquid nitrogen and also the higher critical magnetic field (and critical current density) at which superconductivity is destroyed.
- In magnet applications the high critical magnetic field may be more valuable than the high T_c itself. Some cuprates have an upper critical field around 100 teslas. However, cuprate materials are brittle ceramics which are expensive to

High temperature superconductors have transition temperature T_c above 24 K.

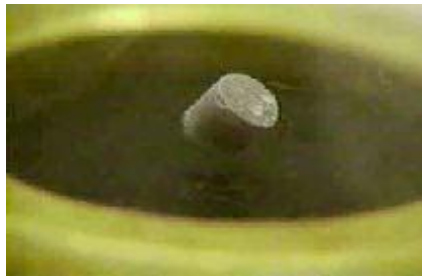
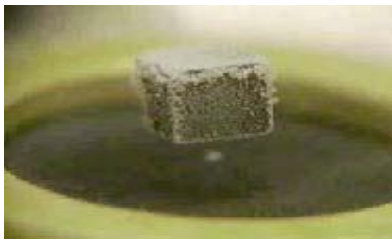
Eg: $\text{YBa}_2\text{Cu}_3\text{O}_7$ $T_c = 95 \text{ K}$.

Properties of high temperature superconductors

1. They obey **Resonating Valence Bond RVB theory**
2. They are oxides of copper in combination with other elements
3. Their superconducting property is direction dependent.

Magnetic Levitation

- Magnetic fields are actively excluded from superconductors (Meissner effect). If a small magnet is brought near a superconductor, it will be repelled because induced super currents will produce mirror images of each pole.
- If a small permanent magnet is placed above a superconductor, it can be levitated by this repulsive force. The black ceramic material in the illustrations is a sample of the yttrium based superconductor.
- By tapping with a sharp instrument, the suspended magnet can be caused to oscillate or rotate. This motion is found to be damped, and will come to rest in a few seconds.



- Magnetically levitated (MAGLEV) trains are considered as a future application of HTS development. To understand why, we must look briefly at the history of the railroads. The development of trains and rails began in the early 1800s. The modern conventional train is no faster (~110 mph) than those of the late 1890s.
- So conventional trains have reached the end phase of their development. France, Germany, and Japan have developed "high-speed" or "bullet" trains capable of speeds of 150-180 mph. This improvement in speed is based upon improved rails and controls.

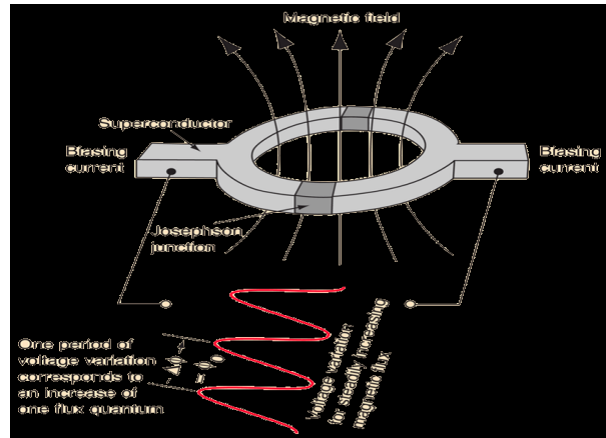
However, this technology has also reached the end phase of its development. One limiting factor for these trains is the expensive and time-consuming maintenance of the rails. So it is the mechanical friction between train wheels and metal tracks that limit this technology. This leads us to the development of the magnetically levitated (no friction) trains. We briefly describe the history of this development.

Two basically different concepts of magnetic suspension have evolved.

1. The attractive electromagnetic suspension (EMS) uses electromagnets on the train body which are attracted to the iron rails. The vehicle magnets wrap around the iron guideways and the attractive upward force lifts the train.
2. The electrodynamic suspension (EDS) levitates the train by repulsive forces from the induced currents in the conductive guideways.

SQUIDS

- The superconducting quantum interference device (SQUID) consists of two superconductors separated by thin insulating layers to form two parallel Josephson junctions.
- The device may be configured as a magnetometer to detect incredibly small magnetic fields -- small enough to measure the magnetic fields in living organisms.
- Squids have been used to measure the magnetic fields in mouse brains to test whether there might be enough magnetism to attribute their navigational ability to an internal compass.
- The great sensitivity of the SQUID devices is associated with measuring changes in magnetic field associated with one flux quantum. One of the discoveries associated with Josephson junctions was that flux is quantized in units.
- If a constant biasing current is maintained in the SQUID device, the measured voltage oscillates with the changes in phase at the two junctions, which depends upon the change in the magnetic flux. Counting the oscillations allows you to evaluate the flux change which has occurred.



Application of superconductors.

Engineering applications:

- (i) It is used in magnetic levitation, cryotrons, Josephson devices, SQUIDS etc.
- (ii) It is used in computers transmission lines etc.

Medical applications:

- (i) Super conductors are used in NMR (Nuclear Magnetic Resonance) imaging equipments.
- (ii) Super conducting solenoids are used in magneto hydrodynamic power generation to maintain plasma in the body.