UNIT V

MAGNETIC, SUPERCONDUCTING AND SEMICONDUCTING MATERIALS

5.1 INTRODUCTION TO MAGNETIC MATERIALS

- Magnetism finds applications in the understanding of electricity, optics, atomic structure etc. So, it has an important place in physics. Naturally found magnets are weak. However, for strong magnetic fields electromagnets are made use of. The earth itself is a huge and powerful magnet.
- The magnetic materials can be classified as paramagnetic, diamagnetic, ferromagnetic, ferrimagnetic and antiferro-magnetic.
- First we will define a few magnetic parameters and derive the relationship between them.

5.2 MAGNETIC PARAMETERS

- **Magnetic Field Strength 'H' :** The magnitude of the force experienced by an unit north pole at any point in the field is called the strength of the magnetic field at that point. The unit of field is gauss or oersted (C.G.S. unit). In M.K.S. system the intensity of magnetic field is expressed in Newton/Ampere-metre or weber/meter^2.
- **Magnetic Induction or Flux Density 'B' :** It is defined as the number of hypothetical induction lines passing normally through unit area. It is measured in Tesla (T) or weber/meter^2.

  ∴ $B = \phi/A$ where ϕ is the normal flux and A the area of cross-section.

- **Intensity of Magnetisation 'M' :** It measures the degree of magnetisation of a magnetised specimen and is defined as the magnetic moment per unit volume.

$$M = \frac{\text{Magnetic moment } (\mu)}{\text{Volume } (V)}$$

- **Magnetic Susceptibility 'χ' :** It measures the ease with which the specimen can be magnetised. It is defined as the ratio of the intensity of magnetisation induced in it to the magnetising field strength

$$\chi = \frac{M}{H}$$

- **Magnetic Permeability 'μ' :** The measure of the degree to which the lines of magnetic force can penetrate the medium is called the absolute permeability of the medium. It is denoted by μ_o.

  It is also defined as the ratio of the magnetic induction B produced in a material to the magnetising or induced field H.

$$\mu = \frac{B}{H}$$

Also $\mu = \mu_o \mu_r$

where μ_o is the permeability of free space and is equal to $4\pi \times 10^{-7}$ Henry/meter or is equal to 1 (in C.G.S. units), μ_r is the relative permeability which is measured by the ratio of the number of lines of force per unit area in the medium to the number of lines per unit area if the medium were replaced by vacuum. For free space $\mu_r = 1$ and $B = \mu_o H$.

- **Bohr Magneton** [May 18] **:** The magnetic moment of an electron is caused by its orbital or spin orbital momentum.
- The physical constant which represents this magnetic moment is called the **Bohr Magneton** and is represented by symbol μ_B.
- In SI system it is given by $\mu_B = \frac{e\hbar}{2m}$ and $\mu_B = \frac{e\hbar}{2mC}$ in CGS system.
- The magnitude of Bohr magneton is equal to 9.274×10^{-24} J/T.

Derivation :

The period of an electron orbiting in orbit of radius r is given by

$$T = \frac{2\pi r}{v} \quad \text{... I}$$

where v = velocity of electron

Due to the orbital motion, the current developed is given by,

$$I = \frac{-ev}{2\pi r} \quad \text{... II}$$

$$\therefore \quad \mu = \frac{-e\,v}{2\pi r} \cdot \pi r^2$$

$$\mu = \frac{-erv}{2}$$

Divide and multiply by m, mass of electron

$$\mu = \frac{-e}{2\,m} \cdot mvr$$

From Bohr's second postulate

$$mvr = \frac{n\,h}{2\pi}$$

$$\therefore \quad \mu = \frac{-e}{2m} \cdot \frac{n\,h}{2\pi}$$

$$\mu = -n\frac{eh}{4\pi m} \qquad \ldots IV$$

The quantity $\frac{eh}{4\pi m}$ is called **Bohr Magneton** (μ_B)

$\therefore$ Bohr Magneton

$$\mu_B = \frac{e\,h}{4\pi M} \qquad \ldots V$$

or

$$\mu_B = \frac{e\,\hbar}{2m} \qquad \ldots VI$$

5.3 RELATIONSHIP BETWEEN μ AND χ

- Consider a magnetic material of cross-sectional area A and relative permeability μ_r to be placed in a uniform magnetic field of strength H.
- **Two Types of Lines of Induction Pass Through it :**

1. Due to the magnetic field.
2. Due to magnetisation by induction.

Hence, $\quad B = \mu_o H + \mu_o M \qquad \ldots (A)$

where μ_o is the permeability of free space.

But $\quad B = \mu_o \mu_r H \qquad \ldots (B)$

From (A) and (B)

$$\mu_o \mu_r H = \mu_o H + \mu_o M$$

i.e. $\quad (\mu_r - 1) H = M$

$$\mu_r - 1 = \frac{M}{H} = \chi$$ (χ being the susceptibility of the material).

5.4 TYPES OF MAGNETIC MATERIALS

- The most materials interact only slightly with an impressed magnetic field. A few substances, however, greatly alter any magnetic field in which they are placed.
- Consider a simple experiment to indicate the way in which material objects affect magnetic fields. An alternating potential difference is applied across the terminals of a toroidal coil so that current through it varies sinusoidally

$$i = i_o \sin 2\pi ft \qquad \ldots (5.1)$$

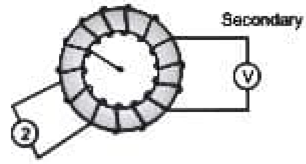

Fig. 5.1

- In Fig. 5.1 the voltage induced in the secondary coil can be used to determine the magnetic properties of the material inside the toroid.
- The flux inside such a coil is found to be

$$\phi = \frac{\mu_o N i a}{2} \ln\left(1 + \frac{a}{b}\right)$$

N is the total number of loops on the toroid. By Faraday's law, the induced e.m.f. in the secondary coil of N_2 loops wound on the toroid is

$$\epsilon_2 = -\frac{\mu_o N N_2 a}{2\pi} \ln\left(1 + \frac{a}{b}\right)\frac{di}{dt}$$

$$\epsilon_2 = -M_\delta \frac{di}{dt} \qquad \ldots (5.2)$$

where $M_\delta = \frac{\mu_o N N_2 a}{2\pi}$ is the mutual inductance.

- Since we known how the current in the toroid changes with time, we can rewrite (5.2) as

$$\epsilon_2 = -2\pi f M_\delta i_o \cos 2\pi ft \qquad \ldots (5.3)$$

- By using an appropriate voltmeter in the secondary coil, the maximum value of ϵ_2, namely, $2\pi f M_\delta i_o$ can be measured.
- In obtaining (5.3) it has been assumed that the space in the interior of the coil is empty.

$$\therefore \quad \mu = \frac{-e\,v}{2\pi r} \cdot \pi r^2$$

$$\mu = \frac{-erv}{2}$$

Divide and multiply by m, mass of electron

$$\mu = \frac{-e}{2\,m} \cdot mvr$$

From Bohr's second postulate

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The quantity $\frac{eh}{4\pi m}$ is called **Bohr Magneton** (μ_B)

$\therefore$ Bohr Magneton

$$\mu_B = \frac{e\,h}{4\pi M} \quad \ldots \text{V}$$

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But $B = \mu_o \mu_r H \quad \ldots \text{(B)}$

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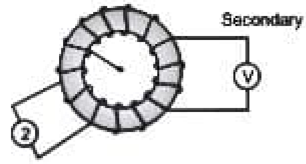

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- By using an appropriate voltmeter in the secondary coil, the maximum value of ϵ_2, namely, $2\pi f\, M_s\, i_o$ can be measured.
- In obtaining (5.3) it has been assumed that the space in the interior of the coil is empty.

- Experiments can be performed when the interior of the coil is completely filled with some material, and the effect on-the induced voltage ϵ_2 caused by changing the material within the coil can be found. It is found that the value of ϵ_2 does not change if the coil is filled with such very diverse substances as air, water, oil, wood, Al, Cu, plastic etc.
- Only a very special class of substances, change the induced voltage, by large amount. These are the so called ferromagnetic materials, and they are almost always pure or alloy composition containing iron, cobalt and nickel.
- In 1845 Faraday concluded that all substances were, to a greater or lesser extent affected by a magnet a few being attracted, but most are repelled. This gave rise to the grouping of different substances into
  - Ferromagnetic like iron, which are strongly attracted
  - Paramagnetic, feebly attracted and
  - Diamagnetic which are repelled by a magnet.

  Materials can also be classified on the following basis :

  (i) Sign of χ and its value.

  (ii) Value of permeability μ_a.

  (iii) Presence or absence of permanent magnetic dipoles.

5.4.1 Classification on the Basis of χ and μ_a

- **Paramagnetic :** Substances are those for which I varies linearly with H and χ has a small positive value. Also μ_a is slightly greater than 1. Examples are, platinum solutions of salts of iron, oxygen, manganese, palladium etc. For platinum μ = 1.00002 and $\chi = 1.71 \times 10^{-6}$. Also, χ not only decreases with increase of magnetising force but it also depends on the temperature. Curie discovered that the susceptibility of some paramagnetics varies inversely as the absolute temperature.
- **Diamagnetic :** Substances have $\mu < 1$ and χ is constant and has a negative value of the order of 10^{-4} to 10^{-6}. Example, bismuth, antimony, Zn, Ag, Cu, Sb, Au, Fb, water, alcohol, air hydrogen. When placed in a magnetic field they have a tendency to move away from the field.
- **Ferromagnetic :** Substances are those which can be magnetised to a great extent. They have an abnormally high value of χ e.g. steel, iron, cobalt, nickel and alloys of these substances. In these substances the magnetisation is not proportional to the magnetising force, hence χ and μ vary with the magnetising force considerably. Also χ varies with temperature. When a ferromagnetic substance is heated, its χ varies inversely as the absolute temperature. This is called as **Curies Law** and is expressed as χ T = Constant (T being absolute temperature). Thus, χ steadily decreases with increase in temperature, until a critical temperature is reached, at which ferromagnetism disappears and the substance becomes paramagnetic. This absolute temperature is called the **Curle Temperature**. The susceptibility of a ferromagnetic substance above its Curie point is inversely proportional to the amount its temperature is above the Curie temperature.

  i.e. $\chi \propto \frac{1}{(T - T_c)}$, T_c being Curie temperature.

  This law is called the **Curie - Weiss Law**.

  T_c for cobalt is about 1100°C, for nickel 4000°C and for iron 770°C.

  Ferromagnetics have non linear variation of μ_a with H i.e. $B \neq \mu_o H$ and hysteresis effect is exhibited.

5.4.2 Classification on the Basic of Presence or Absence of Permanent Magnetic Dipoles

[May 18]

- The magnetic materials can also be classified on-the basis of the presence or absence of permanent magnetic dipoles in them. The materials which lack permanent magnetic dipoles are called **Diamagnetic**. The magnetisation of such materials occurs when the applied field induces a magnetic moment in the individual atoms. Due to the external magnetic field causing changes in the electron orbits. In the absence of the external field, the net magnetic moment of the orbit is zero.
- If permanent dipoles are present in the atoms of a material, it could be **Paramagnetic**, **Ferromagnetic**, **Antiferromagnetic** or **Ferrlmagnetic**. The differentiation is done on the basis of interaction between individual dipoles.
  - The substance is diamagnetic if dipole interaction is zero and orientation of individual dipole moment is random. Point the magnetic moments will align with an applied magnetic field.
  - For ferromagnetics, dipoles interact to line up parallel to each other, to give a large resultant magnetisation. This is known as ordered magnetism because of the stronger interatomic interactions.

> When magnetic moments of equal magnitude are present and neighbouring moments are aligned antiparallel, the substance is antiferromagnetic. In these substances, the magnetisation vanishes.

> When unequal magnetic moments are present-and are aligned antiparallel to each otter, the substance is ferrimagnetic. In these substances a net magnetisation exists.

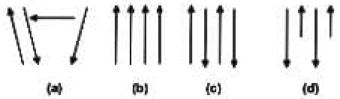


Fig. 5.2 : Paramagentic, ferromagnetic, antiferromagnetic and ferrimagnetic arrangement of spins

- Diamagnetism is a universal property of all materials. However, diamagnetic properties are weaker than paramagnetic ones and still weaker than ferromagnetic properties. The presence of a permanent magnetic moment in atoms is a necessary condition for the existence of ferromagnetic properties.
- The peculiarities of ferromagnetism are due to the formation of vast regions or domains. In the domains the magnetic moments of a large number of atoms are arranged parallel to one another giving magnetic saturation.

5.4.3 Ferrites [Dec. 18, May 19]

- The ferrites are a type of ceramic compound composed of (Fe_2O_3) combined chemically with one or more additional metallic elements. They are basically ferrimagnetic i.e. they can be magnetised or attracted by a magnet and are electrical insulator.
- The ferrites have a spiral crystal structure and the chemical formula for the ferrites are given as $X\,Y_2\,Z_4$ in which X is a divalent negative ion. Y is Fe and Z is mostly the divalent oxygen atom.
- The most common ferrite is Fe_3O_4 whose chemical formula can be written as $Fe^{2+}\,Fe_2^{3+}\,O_4^{2-}$. The other divalent metallic ions used are Co^{2+}, Mn^{2+}, Zn^{2+}, Cd^{2+} etc.
- The ferrites have wide applications in electrical engineering. The most common application of ferrites are
  > Hard ferrites are used in permanent magnets.
  > They are also used in transformer core.
  > As ferromagnetic insulators in electrical circuits.
  > In type recorder head for recording.
  > The main disadvantage is that they have low electrical resistivity.

5.4.4 Garnets [Dec. 18, May 19]

- Garnets are the group of silicate materials that are being used as gemstone and abrasive. The different types of garnets have similar properties and crystal forms but have different chemical composition.
- The garnets are found in colors like red, orange, yellow, green, etc of which the red color is most common.
- The garnets are nesosilicate having the formula $X_3Y_2\,(SiO_4)_3$ where the X site is occupied by divalent cations Ca^{2+}, Mg^{2+}, Mn^{2+} and Y by trivalent cations like Al^{3+}, Fe^{3+}, Cr^{3+}.
- The garnets are crystalline in cubic system having three axis that are of equal length and perpendicular to each other.
- The garnets do not show cleavage so under pressure when they fracture irregular pieces are formed.

5.5 HYSTERESIS LOOP (B – H CURVE) [Dec. 17]

- Consider an unmagnetised bar of a ferromagnetic substance. Subject it to a magnetising field as follows :
- To start with, gradually increase the magnetising field H and find the corresponding value of I (the intensity of magnetisation) or of B (the magnetic induction).
- A graph of B verses H gives a curve OAC as shown in Fig. 5.3. If we increase the magnetising force beyond the point C, B remains constant and the substance is said to be **Saturated**.

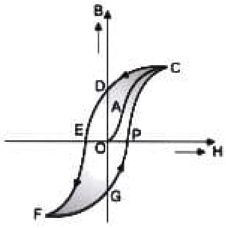


Fig. 5.3 : Cycle of magnetisation H-I curve for a ferromagnetic material

- After reaching the point C, gradually decrease, the H and obtain the value of B (as H decreases). It is found that the curve obtained does not coincide with that obtained with increasing value of H. It takes the form CD.

- Thus when the magnetising force is zero, the intensity of magnetisation (or the induction B) instead of being zero has a value = OD.
- This value of intensity of magnetisation for which H = 0 is called **Residual Magnetism** or **Retentivity** or **Remanence**.
- If the direction of H is reversed, the curve DEF is obtained. On decreasing H to zero and then increasing in its original direction the curve FGPC is obtained.
- Thus in all cases I (the intensity of magnetisation) or B (the induction) appears to lag behind the magnetising force.
- This lagging of B (or I) behind the magnetising force is called **Hysteresis**. The loop so obtained is called the **Hysteresis Loop**. The cycle of operation is called **Hysteresis Cycle**. The magnetising force represented by OE or OG represents the force required to remove the residual magnetism of the bar. Therefore it gives the **Coercive Force** for the material.
- The shape of the hysteresis loop between B and H is similar to the one between I and H. The areas of loops are different in both the cases.
- In B - H curve the intercept on the B-axis is called **Remanent** induction. In this curve the value of the applied field to make B = 0 is not coercivity because

$$B = H + 4\pi I \text{ (Using the relation in CGS system)}$$

When $$B = 0$$

$$H = -4\pi I$$

As I is not zero the specimen is magnetised.

- The hysteresis loop obtained depends entirely on the absence of mechanical vibrations. The mechanical vibrations tend to destroy the retentivity and this results in the partial or complete coincidence of the two sides of the hysteresis loop. The shape of hysteresis loop is a characteristic of the magnetic material.
- Fig. 5.4 shows the shapes B and A in the case of steel and soft iron respectively. From the curves it is seen that soft iron has greater retentivity than steel but less coercivity or in other words, steel retains magnetism ... ft iron loses it.

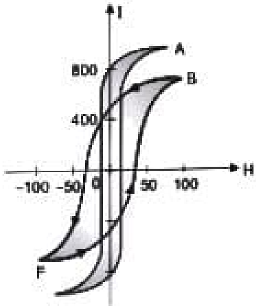


Fig. 5.4 : Hysteresis curve : A – soft Iron, B – Hard steel

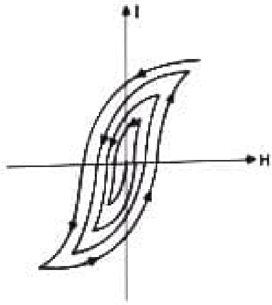


Fig. 5.5 : Demagnetisation

Demagnetisation :

- In order to demagnetise a substance, it must be taken through a cycle of magnetisation with gradually decreasing magnetising force (Fig. 5.5). To achieve this, insert the bar in a coil through which an alternating current of gradually diminishing value is passed.
- Demagnetisation can also be achieved if the substance is heated above the critical temperature.

5.6 INTRODUCTION TO CONDUCTING MATERIALS

- Solids differ from each other in their physical properties like electrical, optical, mechanical etc. It is desired to understand these physical properties for scientific and engineering application of the material. One of the most important properties from engineering point of view is electrical property. So in this part, we will mainly concentrate on electrical properties.
- With respect to electrical properties, metals are good **Conductors** whereas other solids can be classified as either **Semiconductors** or **Insulators**.
  - In conductors, the electrons are free to move within the specimen. These free electrons are contributed by the atoms within the specimen.

- As the electron moves away from the atom, the atom becomes positive ion. These **Positive Ions** or **Lattice Points** are fixed at a particular point and vibrate back and forth from its mean position. Higher the temperature, more will be the amplitude of vibration.
- Under the influence of electric field, the electrons move freely. But their velocity is reduced with collisions with lattice points. The conducting properties of material is governed by these free electrons and conductivity is reciprocal of resistivity.
- At room temperature, the conductivity of conductors ranges from 10^6 to 10^8 mho/m. The conductivity range of semiconductors and insulators is from 10^{-6} to 10^4 mho/m and from 10^{-16} mho/m to 10^{-7} mho/m respectively.

5.6.1 Free Electron Theory of Metals

- The free electron theory of metals was first proposed by Drude and later improved by Lorentz and hence the theory is called the Drude-Lorentz theory. Following are the basic assumptions made in the theory :
  - All metals contain a fixed number of valence electrons forming an **Electron Gas**, which are free to move throughout the volume of the metal.
  - The electron velocities in metals obey the classical **Maxwell-Boltzmann Distribution** of velocities.
  - The positive ions which can vibrate about their mean position, cannot move from one lattice site to another. The repulsive force between the negatively **Charged Electron** is ignored and the electric field due to the positive ions is assumed to be uniform.
  - The electrons move from one point to another randomly with **Random Velocity** which is temperature dependent. At room temperature, this velocity is about 4×10^5 m/s.
  - The **Kinetic Energy** of the electron is given by 3 kT/2, where k is Boltzmann's constant and T is absolute temperature.
  - In absence of external electric field, the electrons move in **Random Directions**, making collisions from time to time with positive ions, which are fixed in lattice. This makes net current zero.
  - When an electric field is applied, free electrons move towards positive terminal of the supply. Thus, the electrons will experience two motions – random motion due to temperature and drift motion due to applied voltage. As a result the electron will move in **Opposite Direction to the Electric Field** while maintaining their random motion.
  - While drifting towards positive of the supply, the electrons colloid with positive ions. During each collision the electron loses all its drift velocity and starts from rest once again. The average distance covered by an electron between collisions is known as **Mean Free Path** 'λ' and time taken to cover this distance is termed as relaxation time 'τ'.
  - As the temperature increases, the vibration of the ion core increases, this increases the probability of electron-core collision. As a result, **Resistivity Increases with Increase in Temperature.**
- By replacing the classical statistics by Fermi-Dirac statistics, Sommerfeld calculated the conductivity along the line of Lorentz's theory. At equilibrium the free electrons have different velocities. In the absence of electric field, the velocities are in all directions and the velocity vectors cancel each other and net velocity vector is zero.
- The velocity of the electron present in the Fermi level is called Fermi velocity. When the electric field is applied along X-axis, the electron starts **Drifting with Velocity** v_x and the force experienced by the electron is eE. The forces on the electrons are governed by the equation,

$$ma = eE \quad \text{... (5.4)}$$

$$\therefore \quad m\frac{dv_x}{dt} = eE$$

$$\therefore \quad dv_x = \frac{eE}{m}dt$$

$$\therefore \quad v_x = \frac{dx}{dt} = \frac{eE}{m}t + k \quad \text{... (5.5)}$$

where k is constant of integration.

At $t = 0, v_x = 0$.

$$\therefore \quad k = 0$$

Substituting in equation (5.5),

$$v_x = \frac{eE}{m}t \quad \text{... (5.6)}$$

The average drift velocity is given by,

$$\bar{v}_x = \frac{eE}{m}\tau \quad \text{... (5.7)}$$

where, τ = relaxation time

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

where, λ = mean free path

Thus, the average drift velocity is proportional to the applied electric field as $\frac{e\tau}{m}$ is constant. The constant $\frac{e\tau}{m}$ is called **Drift Mobility** μ.

$$\therefore \quad \bar{v}_x = \mu E$$

$$\therefore \quad \mu = \frac{\bar{v}_x}{E} \quad \text{... (5.8)}$$

Therefore, the drift velocity is defined as the increase in the average electron velocity per unit of electric field.

The electrical current density is given by

$$J = ne\bar{v}_x \quad \text{... (5.9)}$$

where n is the number of electrons per unit volume.

From equation (5.7),

$$J = ne\frac{eE}{m}\tau$$

$$J = \left(\frac{ne^2\tau}{m}\right)E \quad \text{... (5.10)}$$

The Ohm's law is given by

$$J = \sigma E \quad \text{... (5.11)}$$

Comparing (5.10) and (5.11), we get electrical conductivity.

$$\sigma = n\frac{e^2\tau}{m} \quad \text{... (5.12)}$$

The mobility is given by

$$\mu = \frac{\bar{v}_x}{E} = \frac{eE\tau}{mE} = \frac{e\tau}{m} \text{ using equation (5.7)} \quad \text{... (5.13)}$$

$$\therefore \quad \sigma = ne\mu \quad \text{... (5.14)}$$

The expression is same as that obtained on the basis of classical theory. As charge is constant, the conductivity depends on charges per unit volume n and their mobility μ.

- Both the classical and the quantum theories led to the same expressions, there is an essential difference in their approaches. According to the classical theory all free electrons contribute to the electrical conduction whereas according to the quantum theory only those electrons near the Fermi level take part in the electrical conduction.
- The quantum free electron theory is successful in explaining many properties of metals like specific heat, electrical and thermal conductivities, magnetic susceptibility etc. The main drawback of this theory of that it has failed to explain why some solids are semiconductors while some others are insulators and why divalent metals have lower conductivities than monovalent metals and why some metals exhibit positive Hall coefficient.

5.6.2 Drawbacks of Classical Free Electron Theory

- The free electron theory, successfully established Ohm's law, showed that the resistivity is directly proportional to temperature and the Wiedemann-Franz relation was proved. However, the theory has many drawbacks.

The main drawbacks are :

- The specific heat capacity value based on classical theory shows that it is independent of temperature. But as per quantum theory, it directly depends on temperature i.e. it increases with the increase in temperature.
- As per classical theory, the paramagnetic susceptibility is inversely proportional to temperature. But experimental results show that it is almost independent of temperature.
- The classical theory failed to explain occurrence of long mean free paths (10^8 or 10^9 times interatomic spacing).
- Classification of solids i.e. metals, semimetals, semiconductors and insulators cannot be done by classical theory.
- The positive values of Hall coefficient of metals could not be explained by classical theory.
- Classical theory also failed to explain photoelectric effect, Compton effect and black body radiation.

SOLVED PROBLEMS

Problem 5.1 : *Find the relaxation time of conduction electrons in a metal having resistivity 1.54×10^{-8} Ωm and electron density 6.8×10^{28} m^3.*

Data : $\rho = 1.54 \times 10^{-8}$ Ωm

$n = 6.8 \times 10^{28} / m^3$

Formula : $\rho = \frac{1}{\sigma}$

and $\sigma = \frac{n e^2 \tau}{m}$

$\therefore$ $\rho = \frac{m}{n e^2 \tau}$

Or $\tau = \frac{m}{n e^2 \rho}$

Solution : $\tau = \frac{9.1 \times 10^{-31}}{6.8 \times 10^{28} \times (1.6 \times 10^{-19})^2 \times 1.54 \times 10^{-8}}$

$\tau = \boxed{3.39 \times 10^{-14} \text{ sec.}}$

***Problem 5.2 :** Calculate the drift velocity of the free electrons in copper for an electrical field strength of 0.5 V/m (with a mobility of 3.5×10^{-3} $m^2 V^{-1} s^{-1}$).*

Data : $E = 0.5$ V/m

$\mu = 3.5 \times 10^{-3}$ $m^2 V^{-1} s^{-1}$

Formula : $v = \mu E$

Solution : $v = 3.5 \times 10^{-3} \times 0.5$

$v = 0.00175$ m/s $= \boxed{1.75 \times 10^{-3} \text{ m/s}}$

***Problem 5.3 :** Find the electrical conductivity of copper.*

***Given :** Atomic weight of copper = 63.5*

density of copper = 8.94×10^3 kg/m³

and relaxation time of electron = 2.48×10^{-14} s.

Data : At. wt. = 63.5

Density of copper = 8.94×10^3 kg/m³.

$\tau = 2.48 \times 10^{-14}$ s

Formula : $\sigma = \frac{n e^2 \tau}{m}$

Solution : Concentration of copper atoms

$= \frac{\text{Avogadro number}}{\text{Atomic weight}} \times \text{Density}$

$= \frac{6.02 \times 10^{26}}{63.5} \times 8.94 \times 10^3$

$= 8.475 \times 10^{28}$ / m³

$\therefore$ Electron density,

$n = 8.475 \times 10^{28}$ / m³

$\therefore$ $\sigma = \frac{8.475 \times 10^{28} \times (1.6 \times 10^{-19})^2 \times 2.48 \times 10^{-14}}{9.1 \times 10^{-31}}$

$\sigma = \boxed{5.91 \times 10^7 \text{ mho/m}}$

***Problem 5.4 :** A wire has a resistivity of 1.60×10^{-8} Ωm. If the charge density is 8.4×10^{28} /m³, Calculate (i) relaxation time, (ii) mobility and (iii) the average drift velocity when an electric field of 2 V/cm is applied.*

Data : $\rho = 1.60 \times 10^{-8}$ Ωm

$n = 8.4 \times 10^{28}$ / m³

$E = 2$ V/cm $= 2 \times 10^2$ V/m

Formulae : (i) $\sigma = \frac{n e^2 \tau}{m}$

$\therefore$ $\tau = \frac{m}{n e^2 \rho}$

(ii) $\mu = \frac{e\tau}{m}$

(iii) $v = \mu E$

Solution :

(i) $\tau = \frac{9.1 \times 10^{-31}}{8.4 \times 10^{28} \times (1.6 \times 10^{-19})^2 \times 1.6 \times 10^{-8}}$

$\tau = \boxed{2.64 \times 10^{-14} \text{ sec}}$

(ii) $\mu = \frac{1.6 \times 10^{-19} \times 2.64 \times 10^{-14}}{9.1 \times 10^{-31}}$

$\mu = \boxed{4.65 \times 10^{-3} \text{ m}^2 V^{-1} s^{-1}}$

(iii) $v = 4.65 \times 10^{-3} \times 2 \times 10^2$

$v = \boxed{0.93 \text{ m/sec}}$

5.7 RESISTIVITY AND ITS TEMPERATURE DEPENDENCE

- Resistivity of material is an intrinsic property of the material. It is defined as the measure of a materials resistance to the flow of an electric current. The resistivity is reciprocal of conductivity. It is found that the resistivity of a material depends on the temperature.
- The resistivity of metallic conductors with in a limited range to temperature is given by formula.

$$\rho_T = \rho_o (1 + \alpha (T - T_o)) \quad \dots (5.15)$$

where ρ_T = resistivity at temperature at T

ρ_o = resistivity at temperature at T_o

α = temperature coefficient of resistivity

- Thus the resistivity, of a metallic conductor increases with increasing temperature.

In terms of charge density n, the resistivity is given by,

$$\rho = \frac{m}{ne^2\tau} \quad \text{... (5.16)}$$

where, n = charge density

τ = the average time between collision.

- In metals the charge density 'n' does not changes with temperature. However the increase in temperature can increase the collision of electrons. This reduce τ and implies that increase in temperature increase the resistivity.
- However in insulators and semiconductors the charge density 'n' increases with the increasing temperature. Thus an increase in temperature decreases the resistivity.
- The resistivity of semiconductor is given by,

$$\rho = \frac{1}{n_i e (\mu_e + \mu_h)} \quad \text{... (5.17)}$$

where n_i = charge density in intrinsic semiconductors.

- In intrinsic semiconductors the carrier concentration n_i increases with temperature as

$$n_i^2 = A_o T^3 e^{-Eg/KT} \quad \text{... (5.18)}$$

where, A_o = Constant independent of temperature

E_g = Energy gap

T = Absolute temperature

Thus the resistivity of the semiconductor decreases with increase in the temperature.

5.8 MICROSCOPIC OHM'S LAW [May 18]

- When electric current in a material is proportional to the voltage across it, the material is said to be **Ohmic**, or to obey **Ohm's Law**. A microscopic view suggest that this proportionality comes from the fact that an applied electric field superimposes a small drift velocity on the free electrons in a metal.
- For ordinary currents, this drift velocity is of the order of millimeters per second in contrast to the speeds of electrons them selves which are of the order of 10^6 m/s. Even by the electron speeds are small, the speed of transmission of electric signal along a wire is very high.
- The current density can be expressed as

$$I = nevA$$

or
$$J = \frac{I}{A} = nev \quad \text{... (5.19)}$$

But,
$$I = \frac{V}{R}$$

$$\therefore \quad J = \frac{V}{RA}$$

as
$$R = \frac{\rho L}{A}$$

$$\therefore \quad J = \frac{V}{\frac{\rho L}{A} \cdot A}$$

$$J = \frac{EL}{\rho L} \quad \text{...} \left(\because E = \frac{V}{L}\right)$$

$$J = \frac{E}{\rho}$$

$$\therefore \quad J = \sigma E \quad \text{... (5.20)}$$

This is microscopic Ohm's Law.

5.9 INTRODUCTION TO SUPERCONDUCTIVITY [Dec. 17]

- It is a known fact that the resistivity of pure metals decreases with decreasing temperature. When the temperature falls below a certain value (the exact value depending on the substance), the resistivity vanishes entirely.

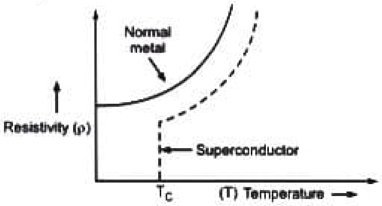


Fig. 5.6 : Variation of resistance with temperature

- In metals, both the thermal vibrations of atoms and the presence of impurities or imperfections scatter the moving conduction electrons. This gives rise to electrical resistivity. The variation of resistivity for a pure metal and superconductor is shown in Fig. 5.6.
- At the beginning of the twentieth century, in 1908, H. Kamerling Onnes, a Dutch Physicist, successfully liquified helium. As helium boils at 8.2 K, it therefore became possible to study the properties of materials at low temperature.

- In 1911, he observed that the electrical resistivity of pure mercury dropped suddenly to zero at about the boiling point of helium. He concluded that mercury had passed into a new state, which he called the **Superconducting State** due to its remarkable electrical properties.
- The temperature at which the material changes its state from a state of normal resistivity to a superconducting state, is called the **Transition or Critical Temperature T_c**.
- A conductor having zero (or almost zero) electrical resistance is called a **Superconductor** and this phenomenon is called as **Superconductivity**.

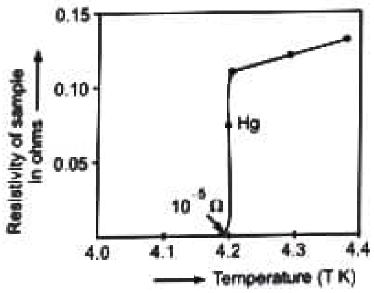


Fig. 5.7: Resistance of mercury as a function of temperature showing a transition from normal state to superconducting state at a critical temperature of 4.2 K

- The superconducting transition is found to be very sharp for a pure metal and it is broad for an impure metal. The zero magnetic induction in a superconductor is responsible for levitation effects.
- In a famous levitation experiment, a horizontal bar magnet was suspended from a chain. It was lowered over a sheet of lead, which had been cooled to the superconducting state. As the magnet came nearer to the superconducting state, the magnet remained floating horizontally over the lead sheet.
- The field of the approaching magnet induces a current on the surface of the superconductor. As the resistance is zero in the superconductor, the current persisted and the field due to the current repelled the bar magnet.
- This persistence of currents is found uniquely in superconductors. Certain experiments on the study of decay of these supercurrents in a solenoid found decay time to be greater than 10^5 years.

5.10 PROPERTIES OF SUPERCONDUCTORS

Following are the properties of superconductors:

5.10.1 Zero Electrical Resistance

- A superconductor is characterized by zero electrical resistance. The temperature below which the resistance of the material vanishes is called as the **Transition Temperature** or **Critical Temperature**. It is referred as T_c.
- As it is not possible to test experimentally whether the resistance is zero, the specimen is connected in a circuit as shown in Fig. 5.8.

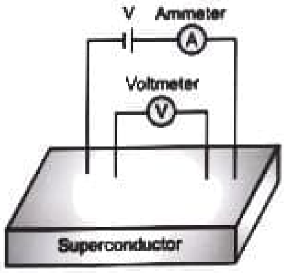


Fig. 5.8

- When the material is in normal conducting state, a voltage drop is measured across its ends. As the material is cooled below its transition temperature T_c, the voltage drop disappears as its resistance drops to zero (R = V/I).
- A more sensitive method devised by K. Onnes consists in measuring the decrease of current in a closed ring of superconducting wire.

Table 5.1 : A List of Some Superconductors along with their Critical Temperature

Sr. No.	Material	T_c in K
1.	Copper, silver, gold	Non-superconducting
2.	Rhodium	240×10^{-6}
3.	Aluminium	1.1
4.	Tin	3.72
5.	Mercury	4.15
6.	Lead	7.2
7.	Niobium	9.3
8.	Niobium-titanium alloys	9-11
9.	Lead molybdenum sulphide	14
10.	Niobium-tin	18.3
11.	Vanadium-gallium	15.4
12.	Niobium-germanium	23.3

- It has been observed that traces of paramagnetic elements in the specimen can lower the transition temperature. Hence, it becomes necessary to remove these traces completely. Non-magnetic impurities have no marked effect on the transition temperature.

5.10.2 Critical Field: Effect of External Magnetic Field

- K. Onnes discovered in 1913 that, when a superconductor is placed in an increasing magnetic field, it loses superconductivity at a certain value H_c of the field. The magnetic field strength at which superconductivity gets destroyed is called the **Critical Magnetic Field** H_c. This value is a characteristic of the metal and depends on its orientation in the magnetic field and the temperature.
- The relation between superconductivity and magnetic field plays an important role in the study of properties of superconductors. Obviously, the value of H_c varies with temperature. Fig. 5.9 shows the variation of H_c with temperature for a typical superconductor.

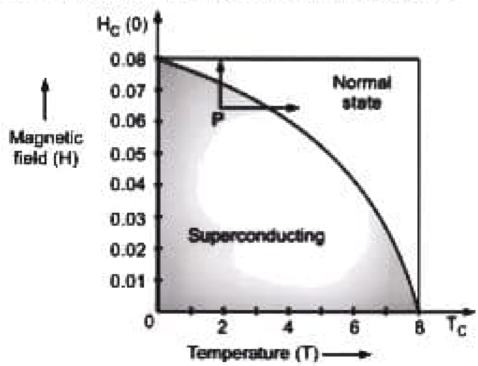


Fig. 5.9

- From Fig. 5.9, consider point P, where the temperature and the magnetic field are within the shaded region, the metal is in the superconducting state. On increasing either the temperature or the field, it can be driven into the normal state. Hence, it can be seen that a superconductor has two possible states: (i) The superconducting one which is resistanceless and perfectly diamagnetic and (ii) A normal state which is the same as a normal metal.
- At any temperature $T < T_c$, the material remains superconducting until a corresponding critical magnetic field is applied. When the magnetic field exceeds the critical value, the material goes into the normal state. The critical field required to destroy the superconducting state decreases progressively with increase in temperature.
- For example, a magnetic field of 0.04 T will destroy the superconductivity of mercury at $T \approx 0$ K, whereas a field of 0.02 T is sufficient to destroy its superconductivity at $T \approx 3$ K.
- The variation of critical field with temperature is given by the relation

$$H_c(T) = H_c(0)\left[1 - \left(\frac{T}{T_c}\right)\right]^2$$

where $H_c(0)$ is the critical magnetic field at 0 K.

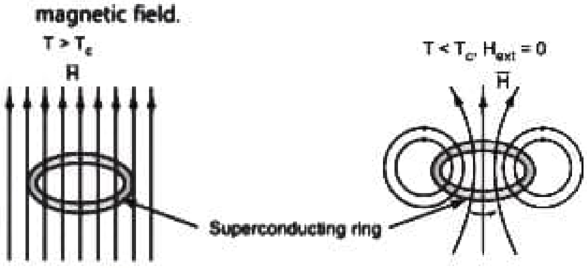
5.10.3 Persistent Currents

- Consider a superconducting ring placed in a magnetic field. When cooled to below the critical temperature, it becomes superconducting. The external field induces a current in the ring. When switched off, the current will continue to keep flowing, on its own accord, around the loop, as long as the loop is held below the critical temperature.
- Such a steady current flowing with undiminished strength is called **Persistent Current**. This current does not need external power to maintain it as there does not exist I^2R losses. If the superconducting ring has a finite resistance R, the current circulating in the ring would decrease according to the relation,

$$I(t) = I(0)\ e^{-Rt/L}$$

where L is the inductance of the ring.

- Calculations show that once the current flow is initiated, it persists for more than 10^5 years. Persistent current is one of the most important properties of a superconductor.
- Superconductor coils with persistent currents produce magnetic fields. They can therefore be used as magnets which do not require a power supply to maintain its magnetic field.



(a) Superconducting ring is cooled in the presence of a magnetic field **(b) At $T < T_c$, the magnetic field is switched off. Persistent current is induced in the ring**

Fig. 5.10

5.10.4 Critical Current Density (J_c)

- The magnetic field which destroys superconductivity, need not be due to an externally applied field, but it may be the field produced as a result of current flow in the superconductor ring itself. If the field produced by itself exceeds H_c, the superconductivity of the ring is destroyed.
- Thus, if a superconducting material carries a current and if the magnetic field produced by it is equal to H_c, then superconductivity disappears. The maximum current density J at which superconductivity vanishes is called the **Critical Current Density** J_c. For $J < J_c$, the current can sustain itself while for $J > J_c$, the current cannot sustain itself. A superconducting ring of radius R loses its superconductivity when the current is,

$$I_c = 2\pi RH_c$$

∴ The critical current density,

$$J_c = \frac{\text{Critical current}}{\text{Area of the ring}}$$

$$J_c = \frac{2\pi RH_c}{\pi R^2} = \frac{2H_c}{R}$$

This sets a limit to the maximum current a superconductor can carry without disturbing its superconducting state.

- As the temperature is raised, the maximum current that a superconductor can carry decreases as the temperature is raised and falls to zero at the transition temperature T_c. This maximum current leads to a maximum applied magnetic field.

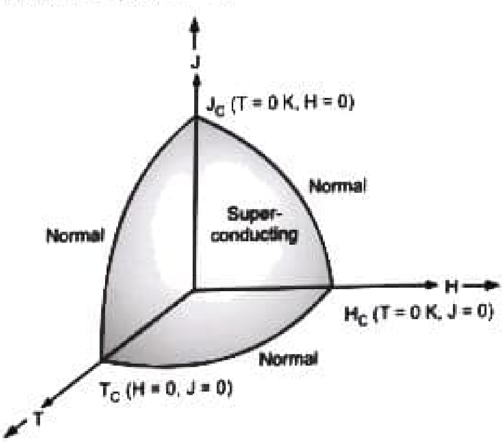


Fig. 5.11

- As critical current falls with the temperature, the critical magnetic field will also decrease as the transition temperature is approached. The variation of critical current density J_c and critical magnetic field H_c with temperature is shown in Fig. 5.11.
- Fig. 5.11 shows the combined effects of temperature, current density and magnetic field on a superconductor. The boundary separates superconducting and normal states. Within the boundary, the state is superconducting.

In the superconducting state,

$$T < T_c$$
$$H < H_c$$
$$\text{and } J < J_c$$

5.11 MEISSNER EFFECT [Dec. 17, 18, May 19]

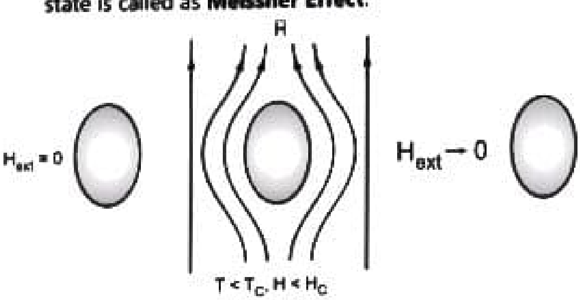
- Meissner and Ochsenfeld discovered in 1933 that a superconductor completely expels any magnetic field lines that were initially penetrating it in its normal state. This property is independent of the path by which the superconducting state is reached.

Path 1

- The sample is in superconducting state and is brought to the magnetic field. It is found that the magnetic flux is totally expelled from the sample.

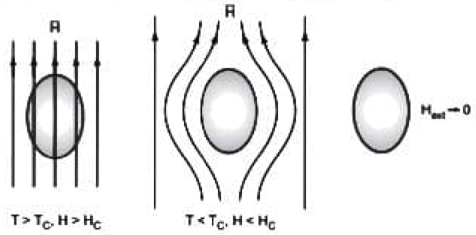
Path 2

- The magnetic field is applied first to the sample in the normal state. Then the material be cooled to below T_c in the presence of the magnetic field. Meissner and Ochsenfeld found that the magnetic flux is totally expelled from the sample as it becomes superconducting. This expulsion of magnetic flux during the transition from normal to superconducting state is called as **Meissner Effect**.



(a) Superconductor is initially outside the magnetic field **(b) When the superconductor is transported into the magnetic field, it pushes the field lines aside** **(c) When the magnetic field is switched off**

Fig. 5.12



(a) Superconductor in a magnetic field at $T > T_c$, magnetic field penetrates the body in normal state

(b) On cooling the superconductor in the presence of magnetic field, it expels the flux lines within the specimen at $T = T_c$. This is Meissner effect

(c) When the field is switched off, field is not trapped within the superconductor. Superconductivity is thus characterized by perfect diamagnetism

Fig. 5.13

Explanation of Meissner Effect

- When a superconducting sample is placed in a magnetic field, it induces currents which circulate on the surface of the specimen in a manner that it creates a magnetic field everywhere equal and opposite to the applied magnetic field.

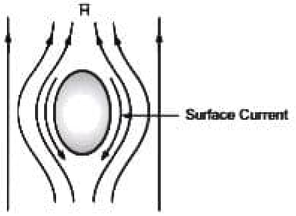
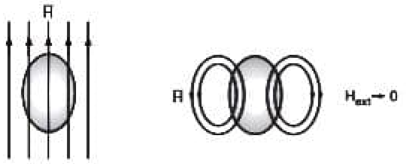


Fig. 5.14 : Meissner effect

- Meissner effect cannot be explained by the assumption that a superconductor is a resistanceless conductor. A superconductor is not just a perfect conductor but has an additional property. A material in the superconducting state does not permit any magnetic flux to exist within the body of the material.
- When a perfect conductor is cooled in a magnetic field until its resistance becomes zero, the magnetic field in the material is frozen or trapped in the material. It cannot change subsequently, irrespective of the applied field. Therefore, a conductor does not exhibit diamagnetic behaviour even slightly.



(a) Conductor held in magnetic field is cooled to the state of zero electrical resistance

(b) When magnetic field H_{ext} is switched off, magnetic field is trapped in the ideal conductor

Fig. 5.15

- The magnetic induction inside the specimen is given by,

$$B = \mu_0 (H + M) \quad \text{(Normal state } T > T_c\text{)}$$

where, H – external applied field

M – magnetisation produced within the specimen

For $T < T_c$, $B = 0$

$$\therefore \mu_0 (H + M) = 0 \quad \text{(Superconducting state)}$$

$$\Rightarrow H = -M$$

The susceptibility of the material,

$$\chi = \frac{M}{H} = -1 \quad \text{(Perfect diamagnetism)}$$

- Thus, the superconducting state is characterized by perfect diamagnetism. Meissner effect conclusively proves whether a particular material has become a superconductor or not. Because of Meissner effect, superconducting materials strongly repel external magnets, it leads to both **Levitation Effect** and **Suspension Effect**.

5.12 TYPES OF SUPERCONDUCTORS

- There are two types of superconductors: type I and type II. There is no difference in the mechanism of superconductivity in both the types. Both have similar thermal properties at the transition temperature in zero magnetic field.
- The difference lies in their behaviour in a magnetic field, particularly in Meissner effect.

5.12.1 Type-I Superconductors

- In a type-I superconductor, the transition from a superconducting state to normal state, in the presence of a magnetic field, occurs sharply at the critical value H_c. At this point, the field penetrates completely.

- Below H_c, type-I superconductors are perfectly diamagnetic. They completely expel the magnetic field from the interior of the specimen. Upto the critical field strength, magnetization of the material grows in proportion to the external field. At the transition temperature, it suddenly drops to zero to the normal conducting state.
- The magnetic field penetrates only the surface layer and current flows only in this layer. Aluminum and lead are examples of type-I superconductors.
- As superconductivity gets destroyed at low values of critical field, type-I superconductors cannot be used in solenoids for producing large magnetic fields. Such superconductors are also called as **Soft Superconductors**.

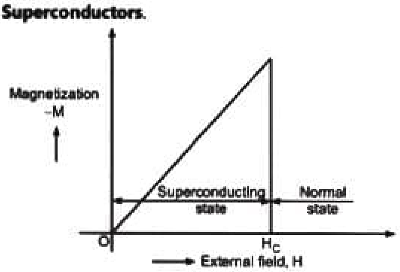


Fig. 5.16 : Magnetization curve for a type-I superconductor

5.12.2 Type-II Superconductors

- Type-II superconductor, also known as **Hard Superconductor** is characterized by two critical fields H_{c1} and H_{c2} ($H_{c1} < H_c < H_{c2}$). It exists in three states: super-conducting, mixed and normal.

Superconducting State

- This occurs upto a critical field H_{c1}. The magnetization increases with the applied magnetic field and the external magnetic flux is completely expelled from the interior of the material.

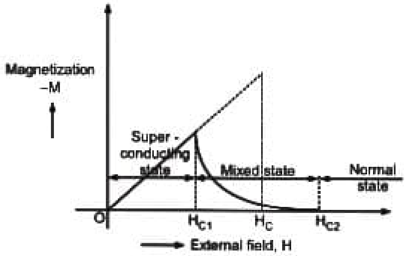


Fig. 5.17 : Magnetization curve in type-II superconductor

Mixed State

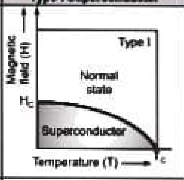
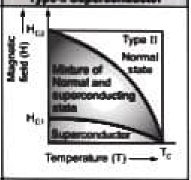
- This region extends from H_{c1} to H_{c2}. At H_{c1}, the magnetic flux penetrates the material. Between H_{c1} and H_{c2}, the material is in a mixed state magnetically but electrically it is a superconductor. Meissner effect is incomplete. In this region, the superconductor is threaded by flux lines and is said to be in a **Vortex State**. Value of H_{c2} may be 100 times higher than H_c (~20 to 50 Wb/m^2).
- As superconductivity is retained upto high values of magnetic fields, type-II superconductors are found useful in applications where high magnetic fields are created. Commercial solenoids wound with type-II superconductors produce high, steady magnetic fields above 10 T.
- Once the magnetic field is created by a superconductor solenoid, it does not require electrical power to maintain it. But the solenoid must be kept below critical transition temperature.

Normal State

- When the magnetic field exceeds critical field strength H_{c2}, magnetization vanishes completely. The sample is penetrated by the external field and superconductivity is destroyed. The specimen reverts from superconducting state to normal state.
- Type-II superconductors have a distinguishing feature. The supercurrents arising in an external magnetic field can flow not only on the surface but also in its bulk. The magnitude of the currents carried is also large when the magnetic field is between H_{c1} and H_{c2}.

Table 5.2: Types of Superconductor – Differences

[May 18]

Sr.	Property	Type-I Superconductor	Type-II Superconductor
1.	Variation of magnetic field with temperature		
2.	Critical magnetic field	Has one critical magnetic field H_c.	Has two critical magnetic fields H_{c1} and H_{c2}.
3.	Transition from superconducting to normal state	Transition from superconducting state to normal state in the presence of a magnetic field occurs sharply at the critical value H_c.	If external magnetic field is less than H_{c1}, material remains superconductor. When external magnetic field increases above H_{c2}, their superconductivity is destroyed.

Sr.	Property	Type-I Superconductor	Type-II Superconductor
4.	Magnetization below and above critical magnetic field	They are perfectly diamagnetic below H_c and completely expel magnetic field from interior of the superconducting phase.	For $H_{c1} < H < H_{c2}$ they exist in magnetically mixed and electronically superconducting state.
5.	Change in magnetization with external magnetic field	Upto H_c magnetization of the material grows in proportion to the external field and then abruptly drops to zero at the transition to the normally conducting state.	The magnetization of Type-II superconductors grows in proportion to the external field upto H_{c1}. The external magnetic flux is expelled from the interior of the material till then. At H_{c1}, magnetic field lines begin penetrating the material. As magnetic field increases further, the magnetic flux through the material increases. At H_{c2}, magnetization vanishes completely. External magnetic field penetrates completely and superconductivity is destroyed.
6.	Current carrying capacity	They are poor carriers of electrical current.	They are good carriers of electrical current.
7.	Magnetic field generation capacity	About 0.01 to 0.2 Wb/m^2 (value of H_c).	About 20 to 50 Wb/m^2 (Value of H_{c2}).
8.	Applications as magnets	Not much useful due to low H_c.	Useful due to high H_{c2}.
9.	Examples	Aluminium, lead, indium	Transition metals and alloys consisting of niobium, silicon and vanadium, Nb-Ti alloys, Nb_3Sn, etc.

5.13 APPLICATIONS OF SUPERCONDUCTIVITY

- The phenomenon of superconductivity finds numerous applications which can be broadly classified into two types.

1. Large-Scale Applications

These are applications requiring large currents, long lengths of superconductors in environments where the magnetic field may be several tesla (1 tesla = 10^4 Oersted). Examples include magnets and power transmission lines, transformers and generators, where current densities of atleast 10^5 amps/cm^2 are required. Superconductors are more advantageous than normal conductors because of their lower resistance and hence smaller power loss.

2. Small-Scale Applications

These are applications involving minute amounts of current or fields. Examples are detection systems like SQUIDS.

5.14 LARGE-SCALE APPLICATIONS

- The cost of energy consumption in the world and the electrical energy in particular are staggering. It is said that about one-fifth the power generated is lost due to I^2R losses. The elimination of even a small fraction of the resistive load will have a staggering impact.
- Another important area of application is the use of high temperature superconductors in the production of strong magnetic fields above the 2 Tesla level. This will eliminate the use of iron cores in motors, generators and transformers resulting in reduced size, weight and losses from iron cores.

Wires and Superconducting Magnets

- As R = 0 for a superconductor, there are no I^2R losses. There is no energy dissipation associated with the flow of a current through a superconductor. A current set up in a closed loop of a superconductor persists, almost forever, without decay.
- Superconducting wires could be used for very economical long distance power transmission, as energy dissipation is low and electrical power transmission can be done at a lower voltage level. Electric generators made with superconducting wire are more efficient than conventional generators wound with copper wire.

Magnetic levitation (Maglev)

- The zero magnetic induction in a superconductor is responsible for levitation effects.
- This phenomenon has led to one of the most spectacular applications, maglev or magnetically levitated train. Superconducting magnetic coils produce the magnetic repulsion required to levitate the train. Maglev trains will not slide over the rails but will float on an air cushion over a magnetised track. As there is no mechanical friction, speeds upto 500 km/hr can be achieved easily. As these trains are capable of very high speeds, they can compete with short hop plane flights in crowded air corridors.

- There are several maglev train test strips and there is talk about a 13 mile commercial line in the Orlando-Florida area and a longer one between Los Angeles and Las Vegas. One proposal is to use an on-board electromagnet to levitate the train above the laminated iron rail in the guide with ~1 cm air gap.
- A second proposal is to use superconducting wire coils in the vehicle to produce a magnetic field of the same polarity as coils in the guides, the repulsive force lifts the vehicle above the track (about 10-15 cm). As iron is not required for the magnetic field, the vehicle could be much lighter.

Electronics Industry

- Superconductors will change the face of the electronics industry, particularly IC fabrication. Currently, due to large amounts of heat generated (I^2R losses) there is a limit to the number of components that can be placed on a single chip. With the use of superconductors, more densely packed chips may be used.
- With the use of superconducting chips in digital electronics, logic delays of 13 pico seconds and switching times of 9 pico seconds have been achieved. By using basic Josephson junctions (refer small-scale applications), sensitive microwave detectors, magnetometers and stable voltage sources have been manufactured.

Computer Industry

- Currently, logic elements operate at speeds of nanoseconds. By using Josephson junctions, information can be transmitted more rapidly and by several orders of magnitude. Research is being conducted on **petaflop** computers. A petaflop is a thousand-trillion floating point operations per second. Today's fastest computer has only achieved **Teraflop** speeds - trillions of operations per second.

Superconducting Magnets

- The most important use of superconductivity has been in the production of high magnetic fields (> 10^5 Gauss or 10 Tesla) over large volumes without a large consumption of electrical power.
- As superconductors are capable of carrying, without energy loss, about 100 times larger current densities as compared to normal conductors like copper, they can be used for building light weight, high intensity, compact magnets useful in various applications. Relatively small superconducting magnets have very economically replaced gigantic water-cooled copper conductor magnets which dissipate several megawatts of electrical power. Superconducting magnets (SCM) find application in many areas in technology, including energy storage devices for electrical power industry, electric motor windings, electromagnetic pumps, etc.
- Superconducting magnets are also used in the field of medicine for NMR (Nuclear Magnetic Resonance) imaging particularly for producing NMR tomography. This is of particular importance for investigating pathological changes in the brain. By applying a strong magnetic field from a superconducting magnet across the body, hydrogen atoms inside the body are forced to take up energy from the magnetic field. This energy is then released at a frequency that can be detected and displayed on a computer. This method is called as Magnet Resonance Imaging (MRI) and is widely used in hospitals.
- Superconducting magnets are also used in high energy physics experiments. Large particle accelerators employ magnets producing high fields for bending and guiding the accelerated particles. Controlled nuclear fusion requires confining high temperature plasma within a closed region. This is done by using superconducting magnets. Superconducting magnets have also been employed for magnetically separating refining ores, isotopes and chemicals.

Military Applications

- Superconductors have found a wide variety of applications in the military. HTSC (high temperature superconductors) are being used to detect mines and submarines.
- Smaller motors are being built by Navy ships using superconducting wires.
- **E-bombs** have been used by the US army in March 2003 when US forces attacked Iraq. These are devices that use strong superconducting magnets to create a fast, high intensity electromagnetic pulse to disable an enemy's electronic equipment.

5.15 SMALL-SCALE APPLICATIONS OF SUPERCONDUCTIVITY

- Brian D. Josephson, a graduate student at Cambridge University, in 1962, predicted that electrical current would flow between two superconducting materials even when they are separated by a non-superconductor or insulator. This tunneling phenomenon is called as the **Josephson Effect.**

- It has been applied to electronic devices such as the SQUID, an instrument capable of detecting and measuring extremely weak magnetic fields.

5.15.1 Josephson Effect

Josephson Junction

Two superconductors connected by a thin layer of insulating material (~ 1-2 nm) is called a **Josephson Junction**. Under suitable conditions, Josephson found that remarkable effects were associated with the tunneling of superconducting electron pairs from a superconductor, through a layer of an insulator, into another superconductor. This junction is called a **Weak Link**. The effect found to be associated with the pair tunneling is called **Josephson Effect**.

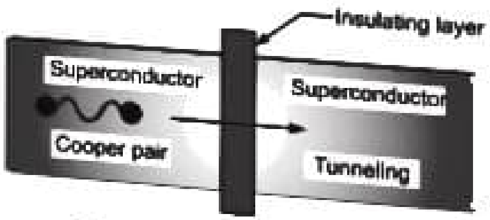


Fig. 5.18 : Josephson junction

(I) DC Josephson Effect

- When two superconductors are separated by a thin insulating layer, Cooper pairs tunnel through the junction and current flows across the junction without any external applied voltage. If this current does not exceed critical current I_c, voltage across the junction is zero. This effect is know...

- In such a case, the energies of the Cooper pair on both the sides of the barrier differ by 2 eV. The alternating supercurrents are accompanied by the emission or absorption of electromagnetic radiation.

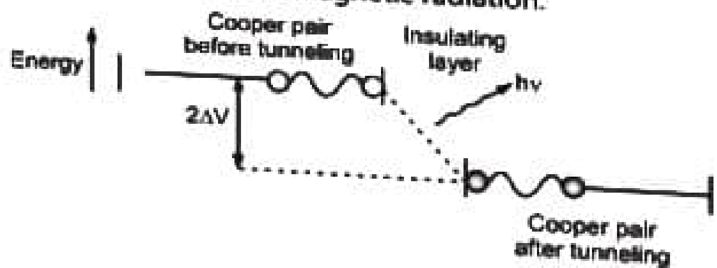


Fig. 5.20 : AC effect

- If ΔV is the finite potential difference between the superconductors, the electron pairs on opposite sides of the barrier differ in energy by an amount 2ΔV = 2 eV.
- Hence, frequency υ of the associated photon will be given by,

$$h\upsilon = 2\,eV \quad \text{or} \quad \upsilon = 2\left(\frac{e}{h}\right)V.$$

- Josephson suggested the determination of h/e from this relation after measuring applied voltage and frequency of emitted radiation. This experiment was carried out between 1967 and 1968. It is one of the simplest methods available to measure the fundamental constant.

5.16 INTRODUC...

- For a better knowledge of semiconductors, one should understand the properties of semiconductors on the basis of band theory of solids. For this, elementary knowledge of electronic configuration of atoms and quantum numbers is quite essential.

5.16.1 Electron Energy States of an Isolated Atom

- An isolated atom of an element with atomic number Z and mass number A consists of a positively charged nucleus, with Z protons and (A – Z) neutrons around which Z electrons revolve in different orbitals. The orbits are characterized by a set of four quantum numbers n, l, m_l and m_s.
- The distribution of electrons in an atom i.e., energy states decide the properties of the element to which the atom belongs. The energy of an electron in an atom depends on n as well as l i.e. energy of the electron is a function of n, l or E = E (n, l).
- As n and l can have only discrete values, the energy E will have discrete values. The energy states characterized by n, l numbers are generally degenerate i.e. electrons with different set of quantum numbers will have the same energy, due to different m_l values for a given l. The state with same n and l will be (2l + 1) degenerate.
- The number of electrons that can have the same energy E (n, l) with given n and l is 2 (2l + 1), the factor 2 is due to two possible values of m_s for each m_l. The state s is non-degenerate and has two electrons. But p, d, f states are respectively 3-fold, 5-fold, 7-fold degenerate and the number of electrons in those states are 6, 10, 14 respectively.
- As such the energy states of an isolated atom will be quite discrete. The energy states of an isolated lithium atom are shown in Fig. 5.21.

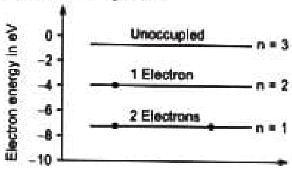


Fig. 5.21

5.17 BAND THEORY OF SOLIDS

- A solid is an aggregate of atoms in very close proximity. For example, a crystal is a periodic arrangement of atoms in which the structure is built up by a regular repetition of a small unit called a **Unit Cell.**
- The energy states of an isolated atom consist of discrete energy levels. But when the atoms are brought into close proximity as in a crystal, the outermost or valence electrons of adjacent atoms interact with each other. The inner or non-valence electrons do not interact significantly at any realizable interatomic distance because they are too closely associated with the nuclei.
- As per Pauli's exclusion principle, since not more than two interacting electrons may have the same energy level, new levels must be established which are discrete but only infinitesimally different. The separation between split energy sublevel is of the order of 10^{-28} eV. This group of related levels in a polyatomic material is called an **Energy Band**.
- In short, in crystals or solids, the allowed energy levels of an atom are modified by the proximity of other atoms in such a way that the discrete energy levels of the individual atoms become bands in solids.
- Each band contains as many discrete levels as there are atoms in the material. In a solid containing N atoms, there are N possible energy levels in each band such that, only two electrons of opposite spin may occupy the same energy level. Thus, the N levels will accommodate a maximum of 2N electrons. In other words, a band formed from N atoms contains 2N energy states.

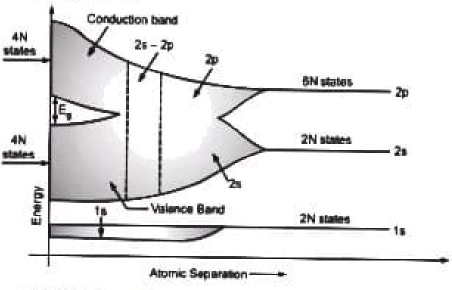


Fig. 5.22 : Formation of energy bands in a diamond crystal

- The imaginary formation of a diamond crystal from isolated carbon atoms is shown in Fig. 5.22. Each isolated carbon atom has an electron structure $1s^2\ 2s^2\ 2p^2$. Each atom has available two 1s states, two 2s states and six 2p states and higher states.
- If we consider N atoms, there will be 2N states of 1s type, 2N states of 2s type and 6N states of 2p type. As the interatomic spacing decreases, these energy levels

split into bands beginning with the outer (n = 2) shell. As the 2s and 2p bands grow, they merge into a single band composed of a mixture of energy levels.

- This band of '2s–2p' levels contains 8N available states. As the distance between atoms approaches the equilibrium interatomic spacing of diamond, this band splits into two bands separated by an energy gap or band gap E_g. The upper band is known as the **Conduction Band** while the lower one is known as the **Valence Band**. Thus, the conduction band contains 4N states and the valence band also contains 4N states.
- So, apart from the low lying and tightly bound 1s levels, the diamond crystal has two bands of available energy levels separated by energy gap E_g. The energy gap E_g does not contain allowed energy levels for electrons to occupy. This gap is also called as **Forbidden Band**.
- The lower 1s band is filled with 2N electrons which originally resided in the collective 1s states of the isolated atoms. However, there were 4N electrons in the original isolated n = 2 shell. (2N in 2s states and 2N in 2p states). These 4N electrons must occupy states in the valence band or the conduction band in the crystal.
- At 0 K, the electrons will occupy the lowest energy states available to them. In the case of the diamond crystal, there are exactly 4N states in the valence band available to the 4N electrons. So at 0 K every state in the valence band will be filled while the conduction band will be completely empty of electrons.
- This arrangement of completely filled and empty energy bands has an important effect on the electrical conductivity of the material. As conduction band is completely empty, the diamond will serve as an insulator.

5.17.1 Valence Band, Conduction Band and Forbidden Energy Gap

Energy Band

- In solids or crystals, allowed energy levels are modified by the proximity of other atoms in such a way that discrete energy levels of individual atoms are converted into series of energy levels. The difference in the energy sublevels is of the order of 10^{-23} eV. This series of energy levels is called **Energy Band**.

Valence Band

- The electrons in the inner shells are strongly bonded to their nuclei while the electrons in the outermost shells are not strongly bonded to their nuclei. It is these electrons which are most affected, when a number of atoms are brought very close together during the formation of a solid. The electrons in the outermost shell are called **Valence Electrons**. The band formed by a series of energy levels containing the valence electrons is known as **Valence Band**.
- The valence band may be defined as a band which is occupied by valence electrons or highest occupied energy band. The valence band is completely filled with electrons at 0 K.

Conduction Band

- The next higher permitted energy band is called the **Conduction Band**. This band may be either empty or partially filled with electrons. Conduction band may be defined as the lowest unfilled permitted energy band. It lies just above the valence band.
- The electrons occupying conduction band are known as **Conduction Electrons** and these electrons move freely in the conduction band.

Forbidden Gap

- The conduction band and valence band are separated by a region or a gap known as **Forbidden Band** or **Forbidden Gap**. This band is collectively formed by a series of nonpermitted energy levels above the top of the valence band to the bottom of the conduction band and is a measure of E_g.
- Thus, E_g is the amount of energy that should be imparted to the electron in the valence band for its migration to the conduction band. These bands are shown in Fig. 5.23.

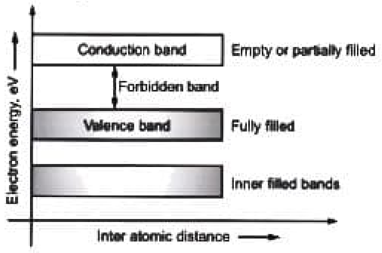


Fig. 5.23 : Valence band, conduction band and forbidden gap at T = 0 K

- If a valence electron happens to absorb enough energy, it jumps across the forbidden energy gap and enters the conduction band. Also, if a conduction electron happens to radiate too much energy, it will suddenly reappear in the valence band once again.

5.18 FERMI ENERGY

(a) Fermi Level in Conductors or Metals

- The statement that a solid is composed of N atoms implies that each atomic level splits into N-energy levels and bands of energy are formed. The filling of the bands follows a simple rule. States of lowest energy are filled first, then the next lowest and so on, till all the electrons are accommodated.
- The highest filled state is called the **Fermi level** and its corresponding energy is called the **Fermi Energy** E_F. The magnitude of E_F depends on the number of electrons per unit volume in the solid because the electron density determines how many electrons must go into the bands.
- At 0 K, all states upto E_F are full and all states above E_F are empty.
- At higher temperatures, the random thermal energy will empty a few states below E_F by elevating a few electrons to yet higher energy states. No transitions to states below E_F occur as they are full. Thus, an electron cannot change its state unless enough energy is provided to take it above E_F.
- The highest filled state in the highest energy band which contains electrons in a metal, at 0 K, is called the Fermi level and its corresponding energy is called the Fermi energy E_F.

(b) Fermi Level in Semiconductors

- In semiconductors, the Fermi level is a reference level that gives the probability of occupancy of states in conduction band as well as in valence band.
- In case of intrinsic semiconductors, the band picture consists of a band of completely filled states called as the **Valence Band** separated from a band of unoccupied states called as the **Conduction Band**, by an energy gap E_g. For an intrinsic semiconductor, the Fermi level lies at the centre of the forbidden band, indicating that the states occupied in conduction band are equal to the states unoccupied in valence band. In other words, for every electron in the conduction band, there is a hole in the valence band.
- So Fermi level in the semiconductors may be defined as the energy which corresponds to the centre of gravity of conduction electrons and holes when **Weighted** according to their energies.

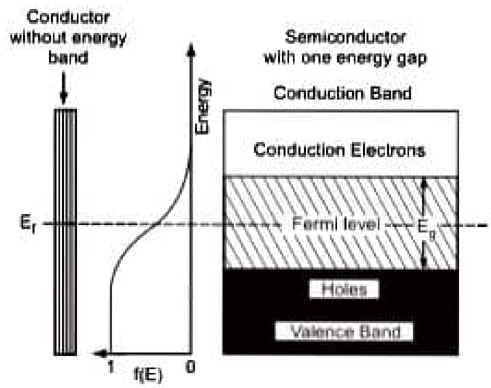


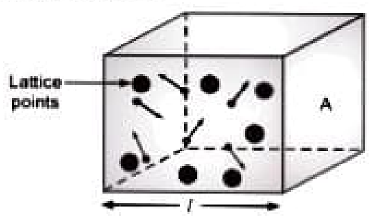
Fig. 5.24

- However, it is to be noted that Fermi level is only an abstraction. A hollow body can have a centre of gravity at the centre where there is no matter. Similarly, a material can have a Fermi level at an energy which is forbidden to all electrons. For example, in an intrinsic semiconductor, the Fermi level is at the centre of the forbidden band.

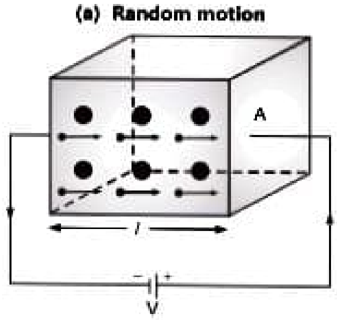
5.19 CONDUCTIVITY OF SEMICONDUCTORS

5.19.1 Conductivity of Conductors

According to the free electron model of an atom, the valence electrons are not attached to individual atoms. They move about freely along all directions among the atoms. These free electrons are called as conduction electrons and they form the **Free Electron Cloud** or **Free Electron Gas** or **Fermi Gas**.



(a) Random motion



(b) Directed motion

Fig. 5.25 : Current flow in conductors

In the absence of an external electrical field, the electrons move randomly in all directions [See Fig. 5.25 (a)]. When an electric field is applied to the metal, the random motion becomes directed [See Fig. 5.25 (b)]. This type of directed motion is known as **Drift**. The drift velocity v of the electrons depends upon the electron mobility μ_e and the applied electric field E.

- The drift velocity v is given by

$$v = \mu_e E \qquad \text{... (5.21)}$$

Let A = conductor cross-section area

n = electron density (i.e. number of free electrons per unit volume of the conductor)

l = length of the conductor

V = voltage applied across the two ends of the conductor

E = electric field applied.

- Then the charge crossing the cross-section 'A' of the conductor in unit time is equal to n × (v × A) e. This rate of flow of charge constitutes the current.

i.e. $$I = n v A e \qquad \text{... (5.22)}$$

Substituting for v from equation (5.21), we get

$$I = n \mu_e E A e \qquad \text{... (5.23)}$$

Now, substituting for $E = \frac{V}{l}$ in equation (5.23), we get

$$I = n \mu_e \frac{V}{l} A e \qquad \text{... (5.24)}$$

$$\therefore \quad \frac{V}{I} = \frac{l}{A} \cdot \frac{1}{n \mu_e e} \qquad \text{... (5.25)}$$

By Ohm's law, we have,

$$R = \frac{V}{I} \qquad \text{... (5.26)}$$

$$\therefore \quad R = \frac{l}{A} \cdot \frac{1}{n \mu_e e} \qquad \text{... (5.27)}$$

But $$R = \rho \frac{l}{A} \qquad \text{... (5.28)}$$

where, ρ is the resistivity of the conductor. Comparing equations (5.27) and (5.28), we get,

$$\rho = \frac{1}{n \mu_e e} \qquad \text{... (5.29)}$$

The unit of ρ is ohm-m.

- Conductivity 'σ' is defined as the reciprocal of resistivity.

∴ Conductivity,

$$\sigma = \frac{1}{\rho} = n e \mu \text{ mho/m} \qquad \text{... (5.30)}$$

- Now, current density J is defined as the current flowing across the unit cross section.

From (5.23), we have,

$$J = \frac{I}{A} = n e \mu_e E \qquad \text{... (5.31)}$$

From (5.30) and (5.31), we have

$$J = \sigma E \quad \text{or} \quad \sigma = \frac{J}{E}$$

5.19.2 Conductivity in a Semiconductor [May 18]

Fig. 5.26 shows the total current flow in a semiconductor. This current is a sum of current flow due to electron flow and hole flow.

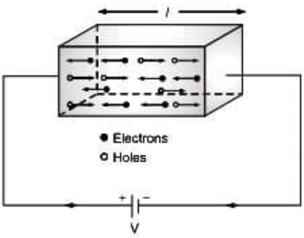


Fig. 5.26 : Current flow in a semiconductor

In a semiconductor, let

n_e = electron density in the conduction band

n_p = hole density in valence band

μ_e = electron mobility

μ_p = hole mobility

v_e = drift velocity of electrons

v_p = drift velocity of holes

A = cross section of the semiconductor

V = voltage applied across the semiconductor of length l

The current due to electrons is given by

$$I_e = n_e v_e A e \qquad \text{... (5.32)}$$

and the current due to holes is given by

$$I_p = n_p v_p Ae \quad \dots (5.33)$$

Therefore, total current flowing through the semiconductor will be,

$$\text{Total current, } I = I_e + I_p$$

$$I = n_e v_e Ae + n_p v_p Ae$$

$$\therefore \quad I = Ae (n_e v_e + n_p v_p) \quad \dots (5.34)$$

The drift velocity of a charged particle in electric field E is,

$$v = \mu E$$

$\therefore$ For electrons, $v_e = \mu_e E$

and for holes, $v_p = \mu_p E$

$$\text{But} \quad E = \frac{V}{l}$$

$$\therefore \quad v_e = \mu_e \frac{V}{l} \quad \dots (5.35)$$

$$v_p = \mu_p \frac{V}{l} \quad \dots (5.36)$$

Substituting equations (5.35) and (5.36) in equation (5.34), we get

$$I = Ae \left(n_e \mu_e \frac{V}{l} + n_p \mu_p \frac{V}{l}\right)$$

$$I = \frac{AeV}{l} (n_e \mu_e + n_p \mu_p) \quad \dots (5.37)$$

$$\therefore \quad R = \frac{V}{I} = \frac{l}{Ae (n_e \mu_e + n_p \mu_p)} \quad \dots (5.38)$$

$$\text{But} \quad R = \rho \frac{l}{A} \quad \dots (5.39)$$

$\therefore$ Resistivity of the given semiconductor is given by [comparing equations (5.38) and (5.39)],

$$\rho = \frac{1}{e (n_e \mu_e + n_p \mu_p)} \text{ ohm-m} \quad \dots (5.40)$$

The conductivity is reciprocal of resistivity.

$\therefore$ Conductivity

$$\sigma = \frac{1}{\rho} = e (n_e \mu_e + n_p \mu_p) \text{ mho/m} \quad \dots (5.41)$$

Hence, conductivity in a semiconductor is a sum of conductivity due to both electrons and holes.

$$\text{Or} \quad \sigma_{sc} = \sigma_e + \sigma_p$$

From equation (5.34),

$$\frac{I}{A} = e (n_e \mu_e + n_p \mu_p) E$$

$\therefore$ The current density

$$J = \frac{I}{A} = e (n_e \mu_e + n_p \mu_p) E \quad \dots (5.42)$$

From (5.41) and (5.42),

$$J = \sigma E$$

Case (i): Intrinsic Semiconductor

- For intrinsic semi conductors, number of electrons and holes are exactly same,

$$n_e = n_p = n_i$$

$\therefore$ Conductivity of an intrinsic semiconductor is

$$\sigma_i = e n_i (\mu_e + \mu_p)$$

Case (ii): N-type Extrinsic Semiconductor

- For N-type semiconductors, electron concentration is much greater than the hole concentration.

$$\therefore \quad n_e >> n_p \quad \text{or} \quad n_e \mu_e >> n_p \mu_p$$

$$\text{Hence} \quad \sigma_N \approx e n_e \mu_e$$

- If n_a is electron concentration or concentration of donor atoms, then,

$$\sigma_N \approx e n_d \mu_e \quad (\text{as } n_e \approx n_d)$$

Case (iii): P-type Extrinsic Semiconductor

- In P-type semiconductor, electron concentration is negligibly small in comparison to hole concentration.

$$\text{Then} \quad n_p >> n_e \quad \text{or} \quad n_p \mu_p >> n_e \mu_e$$

$$\therefore \quad \sigma_p = e n_p \mu_p$$

- If n_a is acceptor atom concentration then $\sigma_p \approx e n_a \mu_p$ (as $n_p \approx n_a$)

Problem 5.5: *Calculate the current produced in a small Germanium plate of area 1 cm² and of thickness 0.3 mm when a P.D. of 2 V is applied across the faces.*

Given:

$$n_i = 2 \times 10^{19} /m^3$$
$$e = 1.6 \times 10^{-19} C$$
$$\mu_e = 0.36 \ m^2/\text{volt-sec}$$
$$\mu_h = 0.17 \ m^2/\text{volt-sec}$$

Solution: Data:

$$A = 1 \times 10^{-4} m^3$$
$$V = 2 \text{ volts}$$
$$l = 0.3 \text{ mm} = 0.3 \times 10^{-3} \text{ m}$$

Formula:

$$I = n_i e (\mu_e + \mu_h) \frac{V}{l} \cdot A$$

Solution:

$$I = 2 \times 10^{19} \times 1.6 \times 10^{-19} (0.36 + 0.17) \frac{2 \times 10^{-4}}{0.3 \times 10^{-3}}$$

$$= \boxed{1.13 \text{ amp.}}$$

***Problem 5.6:** Calculate the conductivity of pure silicon at room temperature when the concentration of carriers is 1.5×10^{16} / m^3 and the mobilities of electrons and holes are 0.12 and 0.05 m^2/V - sec respectively at room temperature.*

Data: $n_i = 1.5 \times 10^{16}$ /m^3, $\mu_e = 0.12$ m^2/V-sec,

$\mu_h = 0.05$ m^2/V-sec.

Formula: $\sigma_{in} = \sigma_n + \sigma_p$

$\sigma_{in} = n_i e(\mu_e + \mu_h)$

Solution: $\sigma_{in} = 1.5 \times 10^{16} \times 1.6 \times 10^{-19}$ (0.12 + 0.05)

$= \boxed{4.1 \times 10^{-4} \text{ mho/m}}$

***Problem 5.7:** Calculate the conductivity of the Germanium specimen if a donor impurity is added to the extent of one part in 10^8 Germanium atoms in room temperature.*

***Given:** Avogadro number = 6.02×10^{23} atoms/moles*

At. wt. of Ge = 72.6

Density of Ge = 5.32 g/cm^3

Mobility μ_e = 3800 cm^2/ V-sec

Formula: $\sigma = e n_d \mu_e$

Solution: Concentration of Ge atoms

$$= \frac{6.02 \times 10^{23}}{72.6} \times 5.32$$

$$= 4.41 \times 10^{22} \text{ /cm}^3$$

Since there is one donor atom per 10^8 Germanium atoms then

$$n_d = \frac{4.41 \times 10^{22}}{10^8} = 4.41 \times 10^{14} \text{ / cm}^3$$

In N-type semiconductor, n > p

then $\sigma = e n_d \mu_e$

$= 1.6 \times 10^{-19} \times 4.41 \times 10^{14} \times 3800$

$= \boxed{0.268 \text{ mho/cm.}}$

***Problem 5.8:** The resistivity of an n-type semiconductor is 10^{-6} Ω cm. Calculate the number of donor atoms which must be added to obtain the resistivity.*

Given: μ_e = 1000 cm^2/V-sec.

Data: $\rho = 10^{-6}$ Ω cm

μ_e = 1000 cm^2/V-sec

Formula: Resistivity $\rho = \dfrac{1}{n_d e \mu_e}$

Solution: $n_d = \dfrac{1}{\rho e \mu_e}$

$$\therefore \quad n_d = \frac{1}{10^{-6} \times 1.6 \times 10^{-19} \times 1000}$$

$= \boxed{6.25 \times 10^{21} \text{ atoms.}}$

***Problem 5.9:** Calculate the conductivity of extrinsic silicon at room temperature if the donor impurity added is 1 in 10^8 silicon atoms.*

***Given:** At room temperature,*

$n_i = 1.5 \times 10^{10}$ per cm^3

μ_e = 1300 cm^2 / volt-sec

and number of silicon atoms per unit volume = 5×10^{22}.

Formula: $\sigma_n = ne \mu_e$

Solution: If there is 1 donor atom per 10 silicon atoms, then the number of donor atoms per cm^3

$$n_d = \frac{\text{number of silicon atoms/unit volume}}{10^8}$$

$$= \frac{5 \times 10^{22}}{10^8} = 5 \times 10^{14}$$

Assuming all the donors are ionised and n >> p, hole conduction can be neglected.

$\therefore \quad \sigma_n = n e \mu_e$

$\sigma_n = n_d e \mu_e$

$= 5 \times 10^{14} \times 1.6 \times 10^{-19} \times 1300$

$= \boxed{0.104 \text{ mho/cm.}}$

***Problem 5.10:** In Germanium, the energy gap is 0.75 eV. What is the wavelength at which Germanium starts to absorb light ?*

Data: E_g = 0.75 eV

Formula: $E_g = h\upsilon = \dfrac{hc}{\lambda}$

Solution: Energy gap in a semiconductor is the minimum energy required to shift an electron from the top of valence band to the bottom of the conduction band. If photons of minimum energy hυ are absorbed by a material to enable electrons to cross the energy gap, then

$h\upsilon = E_g$

$$\therefore \quad E_g = h\upsilon = h\frac{c}{\lambda} = \frac{6.625 \times 10^{-34} \times 3 \times 10^8}{\lambda} \text{ J}$$

$$= \frac{6.625 \times 10^{-34} \times 3 \times 10^8}{1.6 \times 10^{-19} \times \lambda} \text{ eV}$$

i.e. $E_g = \dfrac{12400}{\lambda}$ eV, if λ is in A.

$$\therefore \quad \lambda = \frac{12400}{E_g} = \frac{12400}{0.75}$$

$\therefore \quad \boxed{\lambda = 1653 \text{ A}^\circ}$

Problem 5.11: *Calculate the average thermal velocity, the drift velocity and the mobility of electrons in copper in an electric field of 100 V/cm. Calculate also the density of the electric currents. The resistivity of copper is 1.72×10^{-8} ohm-m at 25°C. Boltzmann constant is 1.38×10^{-23} J/K, density of copper is 8.9×10^3 kg/m³ and At. wt. is 63.54.*

Data: $E = 100$ V/cm, $\rho = 1.72 \times 10^{-8}\ \Omega$-m,

$k = 1.38 \times 10^{-23}$ J/K, density $= 8.9 \times 10^3$ kg/m³,

At. wt. = 63.54.

Formulae: (i) $v = \sqrt{\frac{3kT}{m}}$, (ii) $v_d = \mu E$, (iii) $\sigma = ne\mu = \frac{1}{\rho}$.

Solution: At equilibrium, the electrons follow the Maxwell-Boltzmann distribution. So their average K.E. for each degree of freedom is $\frac{1}{2}$ kT. For particles moving in three dimensions, we can write,

$$\frac{1}{2} mv^2 = \frac{3}{2} kT$$

$$\therefore \quad v = \left(\frac{3\,kT}{m}\right)^{1/2}$$

$$= \left(\frac{3 \times 1.38 \times 10^{-23} \times 298}{9.1 \times 10^{-31}}\right)^{1/2}$$

$$v = 1.16 \times 10^5 \text{ m/sec.}$$

Since each copper atom contributes one valence electron to the conduction band, the number of electrons/m³ will be equal to the number of copper atoms/m³.

$$\therefore \text{No. of electrons/m}^3 = n = \frac{6.02 \times 10^{26} \times 8.9 \times 10^3}{63.54}$$

$$= 0.84 \times 10^{29} \text{ atoms/m}^3$$

$$\text{Mobility } \mu = \frac{1}{\rho \cdot n \cdot e}$$

$$\mu = \frac{1}{1.72 \times 10^{-8} \times 0.84 \times 10^{29} \times 1.6 \times 10^{-19}}$$

$$= 4.33 \times 10^{-3} \text{ m}^2\text{/volt-sec}$$

Drift velocity $v_d = \mu \cdot E$

$$= 4.33 \times 10^{-3} \times 100$$

$$\therefore \quad \boxed{v_d = 0.433 \text{ m/sec.}}$$

Problem 5.12: *Calculate the conductivity of pure silicon at room temperature when the concentration of carriers is 1.6×10^{10} /cm³.*

μ_e = 1500 cm²/volt-sec

μ_h = 500 cm²/volt-sec at room temperature

Data: $n_i = 1.6 \times 10^{10}$/cm³

μ_e = 1500 cm³/V-sec

μ_h = 500 cm³/V-sec

Formula: $\sigma_{in} = \sigma_n + \sigma_p$

Solution:

$$\sigma_{in} = n_i e (\mu_e + \mu_h)$$

$$= 1.6 \times 10^{10} \times 1.6 \times 10^{-19} (1500 + 500)$$

$$= \boxed{5.12 \times 10^{-6} \text{ mho/cm}}$$

5.20 HALL EFFECT AND HALL COEFFICIENT

5.20.1 Hall Effect [Dec. 17, 18, May 19]

- It often becomes necessary to determine whether a material is an N-type or a P-type semiconductor. Measurement of conductivity alone does not give this information as no distinction can be made between hole and electron conduction.
- Hall effect is used to differentiate between the two types of carriers. It provides a means of determining the density and mobility of charge carriers and gives information about the sign of the predominant charge carrier.
- If a piece of conductor (metal or semiconductor) carrying a current is placed in a transverse magnetic field, an electric field is produced inside the conductor in a direction normal to both the current and the magnetic field. This phenomenon is known as **Hall Effect** and the voltage so generated is called as **Hall Voltage**.

Explanation of the Effect

- Assume that the sample material is an N-type semiconductor. The current flow consists, almost entirely, of electrons moving from right to left. This movement corresponds to the direction of conventional current from left to right as shown in Fig. 5.27 (a).
- If v is the drift velocity of the electrons moving perpendicular to the magnetic field B, there is a downward force Bev acting on each electron. This causes the electrons to be deflected in the downward direction. This makes negative charges to accumulate on the bottom face of the slab [See Fig. 5.27 (b)] leaving positive ions on the top surface.
- This gives rise to a potential difference along the top and bottom faces of the specimen across points M and N with the bottom face being negative. This potential difference causes a field E_H in the negative y-direction

and so a force eE_H acts on the electrons in the upward direction.

- Under equilibrium, the upward force due to the electric field just balances the downward force due to the magnetic field.

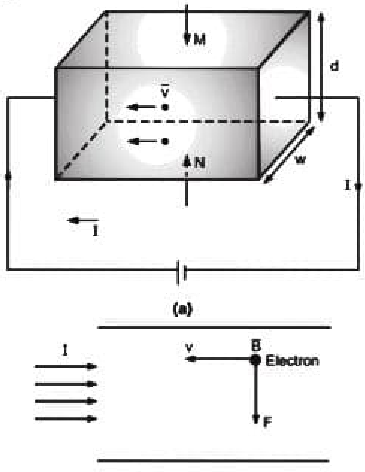


Fig. 5.27 : Hall effect

Thus, $e E_H = e B v$

$$\therefore \quad E_H = vB \qquad \dots (5.43)$$

- If I is the current in the x-direction then,

$$I = n vAe$$

$$\text{or} \quad v = \frac{I}{neA} \qquad \dots (5.44)$$

where n is the concentration of charge carriers.

$$\therefore \quad E_H = \frac{BI}{neA} \qquad \dots (5.45)$$

$$\text{Also} \quad E_H = \frac{V_H}{d}$$

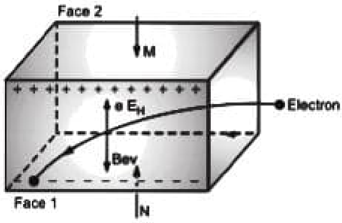


Fig. 5.28 : Motion of electrons in an n-type semiconductor

where V_H is the Hall voltage named after the scientist Hall who first predicted and measured the Hall voltage.

$$\therefore \quad V_H = E_H d \qquad \dots (5.46)$$

Substituting this in expression (5.45),

$$V_H = \frac{1}{ne} \cdot \frac{BId}{A} \qquad \dots (5.47)$$

$$\text{or} \quad V_H = R_H \frac{BId}{A} \qquad \dots (5.48)$$

$$\text{where} \quad R_H = \frac{1}{ne}$$

is the Hall coefficient for any charge e. ... (5.49)

- If J_x is the current density of charge carriers in x-direction then,

$$V_H = \frac{1}{ne} \cdot BJd \quad \left(\text{as } J = \frac{I}{A}\right) \qquad \dots (5.50)$$

In this specimen, as the dominant charge carriers are electrons,

$$\therefore \quad V_H = -\frac{1}{ne} BJd \qquad \dots (5.51)$$

- In expression (5.50), all three quantities V_H, B and J can be measured. Hence, Hall coefficient and current density can be found.

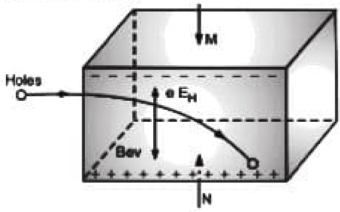


Fig. 5.29 : Motion of holes in p-type semiconductor

- Similarly, formulae can be derived for P-type semiconductors. All the formulae are same except that the Hall coefficient will be positive.
- The sign of the Hall voltage gives the sign of the charge carrier and this provides one of the few methods by which the sign of the charge carrier can be ascertained.

$$\therefore \text{ Hall voltage, } V_H = R_H \cdot \frac{BId}{A} = R_H BJd \qquad \dots (5.52)$$

5.20.2 Hall Coefficient (R_H) [Dec. 17, May 19]

- The Hall coefficient R_H is determined by measuring the Hall voltage that generates the Hall field. If V_H is the Hall voltage across the sample of thickness d then

$$V_H = E_H d \qquad \dots (5.53)$$

Also, the Hall voltage is given by,

$$V_H = R_H \frac{BId}{A} \quad \text{... (5.54)}$$

If w is the width of the sample, then its cross-section will be d × w.

$$\therefore \quad V_H = R_H \frac{BId}{dw} = R_H \frac{BI}{w} \quad \text{... (5.55)}$$

or

$$R_H = \frac{w}{BI} V_H = \frac{1}{nq} \quad \text{... (5.56)}$$

- As all quantities in relation (5.56) are measurable except for n, this relation is used to find the number of charge carriers per unit volume. For metals such as Na, Cu, Ag and Au, the value of n given by this equation is close to the number of valence electrons per unit volume.
- In the case of semiconductors, the interpretation becomes more complex. However, it should be noted that the Hall voltage varies inversely as n, so one would expect it to be larger for semiconductors than for metals.

5.20.3 Applications of Hall Effect

Determination of Type of Semiconductor

- For an N-type semiconductor, the Hall coefficient is negative whereas for a P-type semiconductor, it is positive. Thus, the sign of Hall coefficient is used to determine whether a given semiconductor is N or P-type.

Calculation of Charge Carrier Concentration

- The Hall voltage V_H is measured by placing two probes at the centres of the top and bottom faces of the sample as shown in Fig. 5.29. If $\vec{B}$ is the magnetic flux density, then

$$n = \frac{1}{e} \cdot \frac{BId}{A} \cdot \frac{1}{V_H}$$

- Current I is measured using a current measuring device. Therefore, R_H and hence n can be calculated.

Determination of Mobility

- If conduction is due to one type of charge carriers, for example electrons, then

$$\sigma = ne\,\mu_e$$

$$\mu_e = \frac{\sigma}{ne} = \sigma R_H$$

$$\mu_e = \sigma \cdot \left(\frac{V_H A}{B I d}\right)$$

Knowing σ, and measuring other parameters as in the above applications, the mobility of electrons μ_e can be determined.

Problem 5.13: *Find the drift velocity for the electron in silver wire of radius 1.00 mm and carrying a current of 2 amperes. Density of silver is 10.5 g/cm³.*

Data: r = 1.00 mm, I = 2 amp, density = 10.5 g/cc.

Formula: $v = \frac{I}{q \cdot n \cdot A}$

Solution: $I = q\,n\,v\,A$

Silver is monovalent. So each atom may be assumed to contribute one electron. One gram atomic weight of silver, 108 g, has 6×10^{23} atoms (Avogadro's number).

The density of silver is 10.5 g/cm³. So 108 g will occupy

$$108/10.5 \approx 10.3 \text{ cm}^3.$$

$\therefore$ Number of electrons per unit volume, $n = \frac{6 \times 10^{23}}{10.3} = 6 \times 10^{22}$

or $n = 6 \times 10^{28}$ per m³

The cross-sectional area of wire,

$$A = \pi r^2 = \pi (10^{-3})^2 \approx 3 \times 10^{-6} \text{ m}^2$$

Now,

$$v = \frac{I}{q \times n \times A}$$

$$= \frac{2}{(1.6 \times 10^{-19}) \times (6 \times 10^{28}) \times (3 \times 10^{-6})}$$

$$\boxed{v = 7 \times 10^{-5} \text{ m/sec.}}$$

Problem 5.14: *Find the current density in the wire of the preceding example.*

Solution: Current density

$$J = \frac{I}{A} = \frac{2.0 \text{ amperes}}{3.0 \times 10^{-6} \text{ m}^2}$$

$$\therefore \quad \boxed{J = 6.7 \times 10^5 \text{ A/m}^2}$$

Problem 5.15: *A silver wire is in the form of a ribbon 0.50 cm wide and 0.10 mm thick. When a current of 2A passes through the ribbon perpendicular to a 0.80 T magnetic field, how large a hall voltage is produced along the width ? The density of silver is 10.5 g/cm³.*

Data: d = 0.50 cm, t = 0.10 mm, I = 2 amp, B = 0.80 T, density = 10.5 g/cc.

Formula: $V_H = \frac{1}{nq} \cdot \frac{BId}{A}$

Solution: The atomic weight of silver is 108, so the number of atoms in 1 cm^3 is

$$n = (6 \times 10^{23}) \left(\frac{10.5}{108}\right) \approx 6 \times 10^{22} \text{ per cm}^3$$

Silver is monovalent and we can assume that each atom contributes one electron.

$\therefore$ Number of electrons per $m^3 = 6 \times 10^{28}$

$$A = 0.05 \times 0.001 = 5 \times 10^{-5} \text{ m}^2$$

$$\text{Hall voltage, } V_H = \frac{1}{nq} \cdot \frac{BI \cdot d}{A}$$

$$= \frac{1}{6 \times 10^{28} \times 1.6 \times 10^{-19}} \times \frac{0.80 \times 2.0 \times 0.05}{5 \times 10^{-5}}$$

$$\approx \boxed{1.67 \times 10^{-7} \text{ volt.}}$$

***Problem 5.16:** A copper specimen having length 1 metre, width 1 cm and thickness 1 mm is conducting 1 amp current along its length and is applied with a magnetic field of 1 Tesla along its thickness. It experiences a Hall effect and a Hall voltage of 0.074 microvolts appears along its width. Calculate the Hall coefficient and the mobility of electrons in copper. Conductivity of copper is $\sigma = 5.8 \times 10^7 (\Omega m)^{-1}$.*

Data: $I = 1$ m, $d = 1$ cm $= 10^{-2}$ m, $t = 1$ mm $= 10^{-3}$ m,

$B = 1$ Tesla, $I =$ amp. $V_H = 0.074 \times 10^{-6}$ volts,

$\sigma = 5.8 \times 10^7 (\Omega m)^{-1}$

Formulae: (i) $V_H = R_H \cdot \frac{BId}{A}$, (ii) $\sigma = \frac{\mu}{R_H}$.

Solution: (i) $$R_H = \frac{V_H \cdot A}{BId} = \frac{0.074 \times 10^{-6} \times 10^{-2}}{1 \times 1 \times 10^{-2}}$$

$$= \boxed{0.074 \times 10^{-6} \text{ m}^3/\text{coulomb}}$$

(ii) $$\mu = \sigma R_H = 5.8 \times 10^7 \times 0.074 \times 10^{-6}$$

$$= \boxed{4.292 \text{ m}^2/\text{volt-sec.}}$$

SUMMARY

- **Dipole :** The torque experienced by a magnet when placed in an external field is called dipole moment.
- **Types of Magnetic Materials :** Depending upon the permanent magnetic dipole present a magnetic material can be classified as (i) Paramagnetic (ii) Ferromagnetic (iii) Antiferromagnetic and (iv) Ferromagnetic.
- **Hysterics Curve :** A plot of B-H of a magnetic material is called the hysterics curve.
- **Free Electrons :** In conductors the electrons are free to move within the specimen.
- **Free Electron Theory :** Proposed by Drude-Lorentz treats electrons like gas molecule.
- **Quantized Energy :** Quantum-mechanical treatment of free electron gave the concept of discrete energy level.
- **Conductivity :** The electrical conductivity is given by $\sigma = ne\mu$.
- **Ohm's Law :** Ohm's law is given by $J = 6E$
- **Superconductivity:** A conductor having zero electrical resistance is called a superconductor and this phenomenon is called as superconductivity.
- **Critical Transition Temperature (T_c) :** The temperature below which superconductivity is exhibited.
- **Superconductivity Vanishes :** If temperature, magnetic field and current density exceed the critical value. For superconducting state, $T < T_c$, $H < H_c$ and $J < J_c$.
- **Meissner Effect :** The expulsion of magnetic field/flux from the interior of the specimen, when cooled below the critical temperature.
- Variation of critical magnetic field with temperature is given by

$$H_c(T) = H_c(0) \left[1 - \frac{T}{T_c}\right]^2$$

where $H_c(0)$ is the critical magnetic field at 0 K.
- **Type-I Superconductors :** Are pure specimens which expel completely magnetic field lines. They exhibit perfect diamagnetism. They are also called as soft superconductors.
- **Type-II Superconductors :** Are characterized by two critical fields. Between the two critical fields, the magnetic flux partially penetrates the material. Above the upper critical field flux, penetration is total. They are also called as hard superconductors.
- **Josephson Effect :** Tunneling of current between two superconductors separated by an insulator is known as Josephson effect.
- **Dc Josephson Effect :** The flow of a dc current across the Josephson junction, in the absence of any electric or magnetic field is known as dc Josephson effect.

- **Ac Josephson Effect :** When a dc voltage is applied across the Josephson junction, RF current oscillations are setup across the junction along with the emission or absorption of electromagnetic radiation. This is known as ac Josephson effect.
- **Energy Bands :** In crystals or solids, the allowed energy levels of an atom are modified by the proximity of other atoms in such a way that the discrete energy levels of the individual atoms become bands. Each band contains as many discrete levels as there are atoms in the material.
- **Elements are Classified** as (i) Conductors, (ii) Semiconductors and (iii) Insulators.
- **Valence Band :** The band formed by a series of energy levels containing the valence electrons.
- **Conduction Band :** The lowest unfilled permitted energy band is called the conduction band.
- **Band Gap :** The energy required for an electron to jump from the valence band to the conduction band is called the **Band Gap** or forbidden gap of the semiconductor.
- **Semiconductors :** Materials having properties intermediate between those of conductors and insulators.
- **Semiconductors are of Two Types :** (i) Intrinsic and (ii) Extrinsic.
- **Intrinsic Semiconductors** are those which are pure (free from electroactive and crystalline defects).
- **Doping** is the process of adding an impurity to intrinsic semiconductors to increase its conductivity.
- **Extrinsic Semiconductors** are obtained by doping an intrinsic semiconductor. They are of two types: (i) p-type extrinsic semiconductor, (ii) n-type extrinsic semiconductor.
- **P-Type Semiconductor :** An extrinsic semiconductor formed by doping a trivalent impurity is called a p-type semiconductor. In this type, holes are the majority charge carriers and electrons are the minority charge carriers.
- **N-Type Semiconductor :** An extrinsic semiconductor formed by doping a pentavalent impurity is called as n-type semiconductor. In this type, electrons are the majority charge carriers and holes are the minority charge carriers.
- **Conductivity :**

  For a Metal, electrical conductivity,

  $$\sigma = n_e e \mu_e$$

  For a Semiconductor :

  $$\sigma_{sc} = e (n_e \mu_e + n_p \mu_p)$$

  - For an intrinsic semiconductor, $\sigma_{in} = e\, n_i (\mu_e + \mu_p)$
  - For a p-type extrinsic semiconductor, $\sigma_p = e\, n_p \mu_p = e\, n_a \mu_p$
  - For an n-type extrinsic semiconductor, $\sigma_n = e\, n_e \mu_e = e\, n_d \mu_e$
- **Fermi Energy (E_F) :** The highest filled state in the highest occupied energy band at 0 K is called the Fermi level for a metal. The corresponding energy is called the Fermi energy (E_F).
- **Fermi Level in Semiconductors** is defined as the energy which corresponds to the centre of gravity of conduction electrons and holes when weighted according to their energies. It is a reference level that gives the probability of occupancy of states in conduction band as well as in valence band.
- **The Fermi-Dirac Probability** distribution function P(E) gives the probability that an energy state of energy E is occupied by an electron at T K.

  $$P(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$

- **The Fermi Level** in intrinsic semiconductors is exactly in the middle of the forbidden gap.

  $$E_F = \frac{E_c + E_v}{2}$$

- The position of the Fermi level in a **P-Type Extrinsic Semiconductor** is close to the valence band as holes are the majority charge carriers.
- The Fermi level in an **N-Type Extrinsic Semiconductor** is close to the conduction band as electrons are the majority charge carriers.
- **Hall Effect :** When a current carrying specimen (I) is placed in a transverse magnetic field (B), an electric field 'E' is induced in the specimen perpendicular to both I and B. This phenomenon is called as Hall effect and the voltage hence developed is called as Hall voltage.
- **Hall Voltage,** $V_H = R_H \cdot \frac{BId}{A}$
- **Hall Coefficient,** $R_H = \frac{1}{nq}$.

IMPORTANT FORMULAE

- Drift velocity, $\bar{v}_x = \frac{eE}{m}\tau$
- Collision time, $\tau = \frac{\lambda}{v_x}$
- Mobility of electron, $\mu = \frac{\bar{v}_x}{E}$
- Conductivity, $\sigma = \frac{ne^2\tau}{m}$
- $\sigma = ne\mu$
- The magnetic induction inside the specimen (superconductor) is given by,

$$B = \mu_0(H + M) \quad \text{(Normal state } T > T_c\text{)}$$

For $T < T_c$, $B = 0$

$\therefore \mu_0(H + M) = 0$ (Superconducting state)

or $H = -M$

- The variation of critical field with temperature is,

$$H_c(T) = H_c(0)\left[1-\left(\frac{T}{T_c}\right)\right]^2$$

- The critical current density,

$$J_c = \frac{\text{Critical current}}{\text{Area of the ring}}$$

$$J_c = \frac{2\pi RH_c}{\pi R^2} = \frac{2H_c}{R}$$

- Ohm's law is given by $J = 6E$
- Drift velocity, $v = \mu_e E$
- For metals
  - Current, $I = n\mu_e\frac{V}{l}\cdot A\cdot l$
  - Resistivity, $\rho = \frac{1}{ne\mu_e}$
  - Conductivity, $\sigma = \frac{1}{\rho} = n\mu_e$
- For semiconductors
  - Current, $I = l\cdot A\cdot\frac{V}{\rho}(n\mu_e + p\mu_h)$ (for semiconductors)
  - Resistivity, $\rho = \frac{1}{e(n\mu_e + p\mu_h)}$ (for semiconductors)
  - Conductivity, $\sigma = \frac{1}{\rho} = e(n\mu_e + p\cdot\mu_h)$
  - Conductivity, $\sigma_i = en_i(\mu_e + \mu_h)$ (for intrinsic semiconductors)
  - Conductivity, $\sigma_n = n_e e\mu_e = n_d e\mu_e$ (for n-type semiconductors)
  - Conductivity, $\sigma_p = n_h e\mu_h = n_a e\mu_h$ (for p-type semiconductors)
- Hall voltage, $V_H = R_H\cdot\frac{BId}{A}$
- Hall coefficient, $R_H = \frac{1}{nq}$
- Mobility, $\mu = \sigma R_H$.

UNSOLVED PROBLEMS

1. A material has resistivity of 1.54×10^{-8} Ωm at room temperature. There are $5.8\times10^{28}/m^3$ electrons. The Fermi energy of the conductor is 5.5 eV. Calculate (i) the velocity of electrons with Fermi energy, (ii) mean free path. [**Ans.** 1.39×10^6 m/s, 5.56×10^{-8} m]
2. The relaxation time of conduction electrons in a material is 3×10^{-14} s. If the density of electrons is $5.8\times10^{28}/m^3$, calculate the resistivity of the material and the mobility of electrons. [**Ans.** 2.017×10^{-28} Ωm, $5.31\times10^{-3}\ m^2V^{-1}s^{-1}$]
3. A metal has resistivity 1.43×10^{-8} Ωm and density of conduction electrons $6.5\times10^{28}/m^3$. Find relaxation time. [**Ans.** 3.82×10^{-14} sec]
4. The mobilities of carriers in intrinsic germanium sample at room temperature are $\mu_e = 3600\ cm^2$/volt-sec and $\mu_p = 1700\ cm^2$/volt-sec. If the density of electrons is same as holes and is equal to 2.5×10^{13} per cm^3, calculate the conductivity. [**Ans.** 2.12 mho/m]
5. Calculate the number of acceptors to be added to a Germanium sample to obtain the resistivity $\rho = 10$ ohm. cm. Given $\mu = 1700\ cm^2$/volt-sec. [**Ans.** 3.676×10^{14} per cm^3]
6. At room temperature the conductivity of a silicon crystal is 5×10^{-4} mho/cm. If the electron and hole mobilities are 0.14 m^2/volt-sec and 0.05 m^2/volt-sec, determine the density of carriers. [**Ans.** $1.64\times10^{16}/m^3$]
7. The specific density of tungsten is 18.8 g/cm^3 and its atomic weight is 184.0. Assume that there are two free electrons per atom. Calculate the concentration of free electrons. Avogadro No. = 6.025×10^{23} / gmole. [**Ans.** $2.5\times10^{23}/cm^3$]
8. Compute the conductivity of copper for which $\mu_e = 34.8\ cm^2$/volt-sec and d = 8.9 gm/cm^3. Assume that there is one free electron per atom. Av. No. = 6.025×10^{23} / g mole, atomic weight of Cu = 63.5. If an electric field is applied across such a copper bar with an intensity of 10 V/cm, find the average velocity of free electrons. [**Ans.** 47.02×10^{-4} mho/cm, 348 cm/sec.]

9. The resistivity of copper wire of diameter 1.03 mm is 6.51 ohm per 300 m. The concentration of free electrons in copper is $8.4 \times 10^{28} / m^3$. If the current is 2 A, find (a) mobility, (b) drift velocity, (c) conductivity.
[Ans. 0.413 m^2/volt-sec, 0.286×10^{-20} m/sec, 55.5×10^8 mho/m**]**
10. Calculate the energy gap in silicon if it is given that it is transparent to radiation of wavelength greater than 11000 A°. **[Ans.** 1.13 eV**]**
11. An N-type semiconductor is to have a resistivity of 10 ohm-cm. Calculate the number of donor atoms which must be added to achieve this. Assume, μ_e = 500 cm^2/volt-sec. **[Ans.** 12.5×10^{23}**]**

EXERCISE

1. What is magnetic material? Give the types of magnetic material?
2. Explain the hystersis curve. Classify magnetic materials on the basis of hytersis curve.
3. Discuss the Drude-Lorentz classical free electron theory.
4. Derive the formula for the electrical conductivity.
5. Derive the relation between mobility and conductivity.
6. What are the assumptions of classical free electron theory ? Derive expression of conductivity of metals.
7. Write short notes on (a) Relaxation time, (b) Mean free path, (c) Collision time, (d) Drift velocity, (e) Mobility.
8. State an explain microscopic ohm's law. Derive formula for it.
9. Explain the effect of temperature on conductivity of a material.
10. What is superconductivity ? What are the characteristics of superconductors ?
11. Explain Meissner effect, isotope effect, critical temperature and critical field.
12. What are the types of superconductors ? Where do they find application ?
13. Enumerate the different applications of superconductors. How are they advantageous as compared to normal conductors ?
14. Explain some properties of type-I and type-II superconductors.
15. Describe in brief the formation of energy bands in solids.
16. Explain the terms : valence band, conduction band and forbidden energy gap.
17. Derive an expression for conductivity in an intrinsic and extrinsic semiconductor.
18. Explain Hall effect and Hall coefficient.
19. What is Fermi energy ? Show the location of Fermi energy levels in intrinsic and extrinsic semiconductors.
20. State Hall effect. Derive the formula for Hall voltage and Hall coefficient.
21. What is Fermi function ? Show that the Fermi level lies at the centre of the energy gap in an intrinsic semiconductor.
22. State and explain the applications of Hall effect.

UNIVERSITY QUESTIONS

December 2017

1. On the basis of domain theory explain B-H curve and hence explain retentively and coactivity. **[6]**
2. What is Superconductivity ? Explain Meissner Effect in Superconductors. **[2+4]**
3. What is Hall effect? Derive an expression for Hall Coefficient. **[6]**

May 2018

1. Discuss the different types of magnetic materials interms of magnetic moments. **[6]**
2. Prove Bohr magneton $\mu_B = e\hbar/ 2m$. Differentiate between hard and soft magnetic materials. **[6]**
3. What is Microscopic Ohm's Law? Differentiate between Type I and Type II superconductors. **[6]**
4. Derive an expression for conductivity in an intrinsic and extrinsic semiconductor. **[6]**
Calculate conductivity of pure silicon when the concentration of carriers is 1.6×10^{10} /cm^3, and μe = 1500 cm^2/V-s, μh = 500 cm^2/V-s.

December 2018

1. What are Ferrites and Garnets? Write their general formula. Determine the magnetization and flux density of the diamagnetic, if its magnetic susceptibility is -0.4×10^{-5} and magnetic field in it is 10^4 A/m. **[6]**
2. Prove Bohr Magnetron μ_B = eh/2m. Differentiate between hard and soft magnetic materials. **[6]**
3. What is Superconductivity? Explain Meissner effect in superconductor. **[6]**
4. What is Hall effect? Derive an expression for Hall coefficient of p and n type semiconductor. **[6]**

May 2019

1. Write formula of Ferrites and Garnets. **[6]**
2. Explain Meissner effect in superconductors.
3. What is Hall Effect? Derive an expression for Hall voltage VH and Hall coefficient R_H. **[6]**

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