UNIT – 1: ELECTROSTATICS

CHAPTER-1

ELECTRIC CHARGES AND FIELDS

Topic-1 Charges, Coulomb's Law and Electric Field

Concepts covered: Charges, Coulomb's law, Electric field, Electric field lines, Electric dipole

Revision Notes

- Electrostatics is the branch of physics that deals with the study of charges at rest.
- On rubbing a glass rod and a silk piece together, the glass rod acquires a positive charge while silk acquires a negative charge.
- The apparatus used to detect charge is known as the gold leaf electroscope (GLE).
- Electric charge is defined as that property of matter according to which the electrons repel each other and the electron and a proton get attracted to each other.
- The charge present on the electron is equal and opposite to the charge on the proton.
- The charge on a body is expressed as $q = \pm ne$, where n is an integer (i.e., number of electrons present in the body) and e is the charge on an electron /a proton. The charge on electron is $e^- = -1.6 \times 10^{-19}$ C and charge on proton is $e^+ = +1.6 \times 10^{-19}$ C.

Scan to know more about this topic

Electric charges

- Electric charge is conserved. It is the sum of positive and negative charges present in an isolated system, which remains constant.
- Annihilation is an example of the simultaneous destruction of the equal and opposite charges. Here, an electron and a positron combine together to produce a photon.
- The magnitude of the charge is independent of the speed of the particle.
- Conductors are the materials which allow the current to pass through them.
- A charge is always quantized i.e., electric charge is always an integral multiple of e which is known as quantization of charge. $q = \pm ne$
- **Point charge:** When the separation between two charged spheres is much larger than the radius of each sphere, the charged sphere is regarded as a point charge.
- **Coulomb's law:** When two charges q and q_0 are separated by a distance r, the electrostatic force experienced by the charges is

$$F = \frac{1}{4\pi\varepsilon_0}\frac{qq_0}{r^2}.$$

$$\frac{1}{4\pi\varepsilon_0} = 9 \times 10^9 \text{ Nm}^2\text{C}^{-2},$$

ε_0 has a value of 8.85×10^{-12} C^2/Nm^2 and is a constant known as permittivity of free space.

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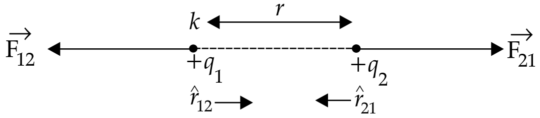
Coulomb's law

- **Coulomb's law in vector form:**



$$\vec{F}_{21} = \frac{1}{4\pi\varepsilon_0}\cdot\frac{q_1q_2}{r^2}\hat{r}_{12}$$

where, $\hat{r}_{12}$ is a unit vector in the direction from q_1 to q_2

and, $$\vec{F}_{12} = \frac{1}{4\pi\varepsilon_0}\cdot\frac{q_1q_2}{r^2}\hat{r}_{21}$$

where, $\hat{r}_{21}$ is a unit vector in the direction from q_2 to q_1.

- Coulomb's force between two charges is independent of the presence of other charges.
- The force on any charge due to a number of other charges is the vector sum of all the forces on that charge due to the other charges taken one at a time. The individual forces are unaffected due to the presence of other charges. This principle is known as the principle of superposition.
- 1 Coulomb = 3×10^9 stat-Coulomb.

  The stat-coulomb is the C.G.S unit of charge. It is also called an electrostatic unit (esu) of charge.
- **1 Coulomb:** When two point charges are placed at a distance of 1 m and exert a force of 9×10^9 N, the charge on each sphere is known as 1 Coulomb.
- Insulating materials are often termed as dielectrics.
- **Continuous charge distribution:** In the usual sense, we deal with charges much greater in magnitude than the charge on an electron, so we can ignore the quantum nature of charges and imagine that the charge is spread in a region in a continuous manner. Such a charge distribution is known as a continuous charge distribution.

  (a) Line charge density, $\lambda = \dfrac{dq}{dL}$

  (b) Surface charge density, $\sigma = \dfrac{dq}{dS}$

  (c) Volume charge density, $\rho = \dfrac{dq}{dV}$

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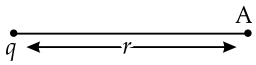
Continuous charge distribution

- The space around a charge up to which its electric force or effect can be experienced is called an electric field.
- The electric field strength due to a point charge 'q' at an observation point 'A' at a distance 'r' from the source charge is given by:

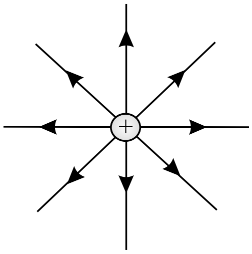
$$\vec{E} = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}\hat{r}$$



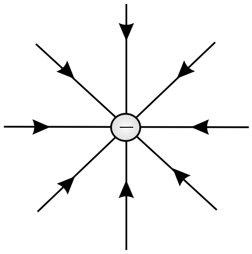
  The unit of an electric field is NC^{-1}.
- The system formed by two equal and opposite charges separated by a small distance is called an electric dipole.
- If a test charge q_0 is placed at a point where the electric field is $\vec{E}$, then force on the test charge is

$$\vec{F} = q_0\vec{E}.$$

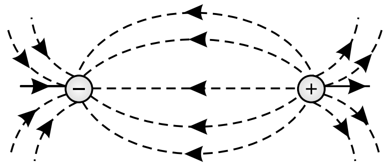
- The electric field inside the cavity of a charged conductor is zero.
- If a charged or an uncharged conductor is placed in an external electric field, the field inside the conductor is zero.
- The torque on a dipole in an electric field is zero, both in a stable as well as in an unstable equilibrium.
- The potential energy of a dipole in an electric field is minimum in a stable equilibrium and maximum in an unstable equilibrium.
- The product of the magnitude of charge (q) of the dipole and the separation (l) between the charges is called the electric dipole moment (p_e), i.e., $p_e = q \times l$
- The unit of a dipole moment is C-m (Coulomb-metre).
- When the observation point lies on the axial line, it is called the end-on position. When the point lies on the equatorial line, it is called broadside-on position or equatorial position.
- The maximum value of the electric field is at the surface of the shell of the charge.
- The surface of a charged conductor is equipotential although the electric field may be different at different points.
- The electric charge resides only on the outer surface of a conductor.
- The electric field inside a charged conductor is zero and it is independent of the shape of the conductor.
- An electric line of force is defined as the curve along which a small positive charge would tend to move when free to do so in an electric field and the tangent to which at any point gives the direction of an electric field at that point.
- The lines of force are continuous smooth curves.
- They start from positive charges and end at negative charges.
- The tangent to a line of force at any point gives the direction of the electric field at that point.
- No two lines of force cross each other.

➢ 

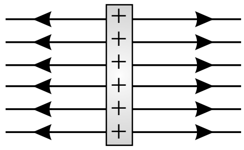
Field lines of a positive point charge



Field lines of a negative point charge



Field lines of an electric dipole



Field lines of a line of equal positive charges.

➢ For a short dipole, we have $r >> l$, the electric field on the equatorial line is given by

$$\vec{E}_e = \frac{1}{4\pi\varepsilon_0}\frac{\vec{p}_e}{r^3}$$

➢ For a short dipole, we have $r >> l$, the electric field on axial line,

$$\vec{E}_a = \frac{1}{4\pi\varepsilon_0}\frac{2\vec{p}_e}{r^3}.$$

➢ For the same distance on the equatorial and axial line, we find:

$$E_a = 2E_e$$

➢ Electric field due to a short dipole at any point, making an angle θ with the axial line is given by

$$E = \frac{1}{4\pi\varepsilon_0}\frac{p_e}{r^2}(1+3\cos^2\theta)^{1/2}$$

and it makes an angle (α) with the axial line such that $\tan\alpha = \frac{1}{2}\tan\theta$.

➢ • A dipole of moment $\vec{p}_e$ in an electric field $\vec{E}$ experiences a torque, given by

$$\vec{\tau} = \vec{p}_e \times \vec{E}$$

or $$\tau = p_e E \sin\theta.$$

- The torque on the dipole is minimum i.e., $\tau_{min} = 0$ when $\theta = 0°$ or $180°$. In this position, the dipole is said to be in equilibrium.
- The equilibrium of the dipole is said to be stable for $\theta = 0°$ and unstable for $\theta = 180°$.
- The torque is the maximum for $\theta = 90°$, we find $\tau_{max} = p_e E$.
- As θ increases from 0° to 180°, τ first increases, becomes maximum and then decreases to zero.

➢ • In a uniform electric field, a dipole experiences only the torque, i.e., the net force on the dipole is zero.
- In a uniform electric field, a dipole experiences only rotatory motion and no translatory motion.
- In a non-uniform electric field, a dipole experiences both torque as well as the net force.
- In a non-uniform electric field, a dipole experiences both rotatory as well as translatory motion.

➢ The electrostatic potential energy of a dipole of moment $\vec{p}_e$ in uniform electric field $\vec{E}$ is given by

$$U_P = -\vec{p}_e \cdot \vec{E} = -p_e E\cos\theta$$

- For $\theta = 0°$, we have $U_0 = -p_e E.$
  It is the minimum value of the potential energy and the dipole is in stable equilibrium.
- For $\theta = 90°$, we have $U_r = 0.$
- For $\theta = 180°$, we have $U_p = p_e E.$

Key Formulae

➢ **Coulomb's law:**

$$F = k\frac{|q_1||q_2|}{r^2}$$

- **Electric field:**

$$E = \frac{|F|}{|q|} = k\frac{|q|}{r^2}$$

Electric field lines radiate outwards from positive charges. The net electric field is zero inside a conductor.

- **Relationship of k to ε_0:**

$$k = \frac{1}{4\pi\varepsilon_0}$$

where, $k = 9 \times 10^9$ Nm^2/C^2

ε_0 = permittivity of free space = 8.85×10^{-12} C^2/Nm^2

Key Words

- **Permittivity:** It is the property of a medium which determines the electric force between two charges situated in that medium.
- **Vitreous charge:** Positive charge
- **Resinous charge:** Negative charge
- **Electrostatic induction:** It is the phenomenon of temporary electrification of a conductor in which opposite charges appear at its closer end and similar charges appear at its farther end, in the presence of a charged body.
- **Dipole field:** The electric field produced by an electric dipole.
- **Force on a point charge in an electric field:** $\vec{F} = q\vec{E}$
- **Line charge density:** $\lambda = \frac{\text{Charge}}{\text{Length}}$
- **Area charge density:** $\sigma = \frac{\text{Charge}}{\text{Area}}$
- **Volume charge density:** $\rho = \frac{\text{Charge}}{\text{Volume}}$

Topic-2 Gauss's Theorem and its Applications

Concepts covered: Electric flux, Gauss's theorem and its applications

Revision Notes

- The flux $\Delta\phi$ of an electric field E through a small area element ΔS is given by

$$\Delta\phi = \vec{E} \cdot \Delta\vec{S}$$

where, $\Delta\vec{S}$ is vector area element.

$$\Delta\vec{S} = \Delta S\hat{n}$$

where, ΔS is the magnitude of the area element and $\hat{n}$ is normal to the area element which can be considered as a plane for sufficiently small ΔS.

Scan to know more about this topic

Electric flux and Gauss's Law

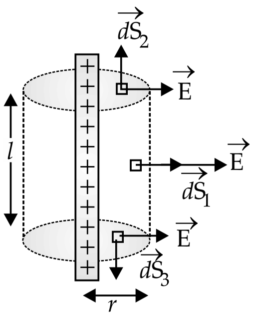
- **Gauss's theorem:** The total electric flux through a closed surface enclosing a charge is equal to $1/\varepsilon_0$ times the charge enclosed by that surface.

Mathematically,

$$\oint \vec{E}.d\vec{S} = \frac{q}{\varepsilon_0}$$

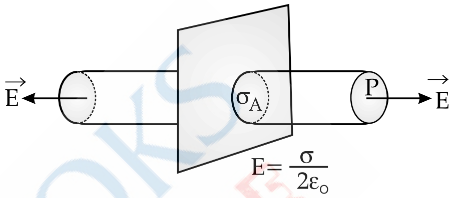
- Electric field due to an infinitely long straight charged wire,

$$E = \frac{\lambda}{2\pi\varepsilon_0 r}$$



➢ Electric field due to a uniformly charged infinite plane sheet, having charge density σ

$$E = \frac{\sigma}{2\varepsilon_0}$$



➢ Electric field due to a uniformly charged thin spherical shell

- When point P lies outside the spherical shell,

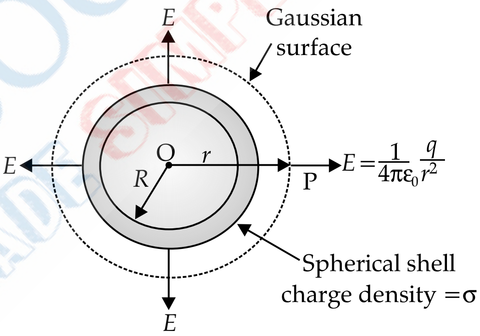
$$E = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r^2} \qquad [\text{for } r > R]$$

- When point P lies on the spherical shell,

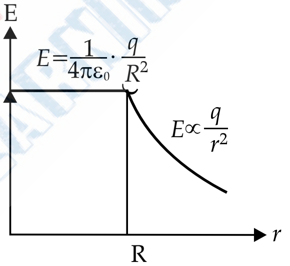
$$E = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{R^2} \qquad [\text{for } r = R]$$

- When point P lies inside the spherical shell,

$$E = 0$$



➢ Variation of E with r for a spherical shell of charge



➢ **Gaussian Surface:** Any hypothetical closed surface enclosing a charge is called the Gaussian surface of that charge.

➢ **Electric Flux:** The electric flux through a given area held inside an electric field is the measure of the total number of electric lines of force passing normally through that area.

Mnemonics

Concept: Nature of electric flux

Mnemonics: EP → EL

EN → FE

Interpretation:

The Electric flux is Positive if the electric field lines Leave the closed surface.

The Electric flux is Negative if the electric field lines Enter the closed surface.

Concept: To find Electric field, divide the Charge (enclosed) by the free space permittivity and area of the Gaussian.

Mnemonics: **E**qually **D**ivide **C**ost **p**er **A**nnum.

Interpretation:

E: Electric field
D: Divide
C: Charge
P: Permittivity
A: Area

Key Formulae

- **Electric flux through an area A:** $\phi = \vec{E} \cdot \vec{A}$
- **Electric flux through a Gaussian surface:** $\phi = \oint \vec{E}.\vec{dA}$
- **Gauss's Law:** $\phi = \dfrac{q_{enc}}{\varepsilon_0}$
- **Electric field due to an infinite line of charge:**

$$E = \frac{\lambda}{2\pi\varepsilon_0 r} = \frac{2k\lambda}{r}$$

- **Electric field due to ring of charge:** $E = \dfrac{kqz}{(z^2+R^2)^{3/2}}$

  or if $z >> R$, $E = \dfrac{kq}{z^3}$
- **Electric field due to a disk charge:**

$$E = \frac{\sigma}{2\varepsilon_0}\left(1 - \frac{z}{\sqrt{z^2+R^2}}\right)$$

- **Electric field due to an infinite sheet:** $E = \dfrac{\sigma}{2\varepsilon_0}$
- **Electric field inside a thin spherical shell:** $E = 0$ [for $r < R$]
- **Electric field outside a thin spherical shell:** $E = \dfrac{Kq}{r^2}$

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CHAPTER-2
ELECTROSTATIC POTENTIAL, POTENTIAL ENERGY AND CAPACITANCE

Topic-1 Electrostatic Potential and Potential Energy

Concepts covered: Electric potential, Potential difference, Electrical potential energy of a system of two point charges and of electric dipole, Conductors and insulators, Free and bound charges, Dielectrics and electric polarisation.

Revision Notes

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Electric Potential

- Electric potential due to a point source charge q at a distance r from it is given by,

$$V = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r}$$

- The potential per unit distance is called a potential gradient. It may be expressed as

$$\frac{dV}{dr}$$

The electric field at a point is related to the negative potential gradient

$$E = -\frac{dV}{dr}$$

- Electric potential due to a dipole

(i) at a point at distance r and making an angle θ with the dipole of moment p_e

$$V_a = \frac{1}{4\pi\varepsilon_0} \cdot \frac{p_e \cos\theta}{r^2}$$

(ii) On the axial line,

$$V_a = \frac{1}{4\pi\varepsilon_0} \cdot \frac{p_e}{r^2}$$

(iii) On the equatorial line,

$$V_e = 0$$

- Electric potential due to an isolated conducting charged sphere of radius R carrying charge Q,

(a) At the surface of the sphere and at every point inside the sphere

$$V = \frac{1}{4\pi\varepsilon_0} \cdot \frac{Q}{R}$$

(b) At points outside the sphere at a distance r

$$V = \frac{1}{4\pi\varepsilon_0} \cdot \frac{Q}{r}$$

where, $r > R$ is the distance of the point from the centre of the sphere.

- Equipotential surface is that surface that has same electric potential at every point on its surface.
- The electric potential energy of system of point charges is defined as the amount of work done in assembling the charges at their locations by bringing them from infinity.

If two point charges q_1 and q_2 are separated by distance r_{12}, then their potential energy is given by

$$U = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_1 q_2}{r_{12}}$$

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Equipotential Surface

- Potential energy of a dipole is equal to the amount of work done in turning the dipole from orientation θ_1 to θ_2 in the field E.

$$U = -pE(\cos\theta_2 - \cos\theta_1)$$

- Conductors are the substances which allow movement of electric charges through them when an external electric field is applied.
- Insulators are the substances which do not allow the movement of electric charges through them when an external electric field is applied.
- In metallic conductors, electrons of outer shells of the atoms are the free charges while the immobile positive ions are the bound charges.
- A dielectric is a substance which does not allow the flow of charges through it but permits them to exert electrostatic forces on one another through it.
- Dielectric substances may be of two types: polar and non-polar. In a non-polar dielectric, the centres of positive and negative charges of a molecule coincide. The molecule then has no permanent (or intrinsic) dipole moment. Examples: oxygen (O_2) and hydrogen (H_2) molecules. In a polar dielectric, the centres of positive and negative charges of a molecule are separated (even when there is no external field). Such molecules have a permanent dipole moment. Example: HCI, water (H_2O) molecules.
- The polarization $\vec{P}$ is defined as the dipole moment per unit volume and its magnitude is usually referred to as the polarisation density.

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Polarization

Key Formulae

- **Electric Potential** is the electric potential energy per unit charge,

$$V = \frac{U}{q},$$

measured in volt; 1 Volt = 1 Joule/Coulomb.
- Electric potential difference or "voltage",

$$\Delta V = V_f - V_i = \frac{\Delta U}{q} = \frac{W}{q},$$

where, U: electric potential energy, W: work done by the electric field.
- Electric potential due to a point charge q at a distance r,

$$V = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r}$$

- Electric field $\vec{E}$ is always perpendicular to equipotential surfaces.
- Radiation between E and V: $V_f - V_i = V = -\int_{\infty}^{r} \vec{E} \cdot \vec{dr}$

Topic-2

Capacitance

Concepts covered: Capacitance, Combination of capacitors, Parallel plate capacitor, Energy stored in the capacitor.

Revision Notes

- The ratio of the charge q and potential V of a conductor is called capacitance (C).

$$C = \frac{q}{V}$$

Scan to know more about this topic

Capacitor & Capacitance

- The unit of capacitance is Farad. It is denoted by F.
- Capacitance of a conductor depends on its (i) size, (ii) shape, (iii) medium surrounding it, and (iv) other conductors in its surroundings.
- The capacitance of a spherical conductor of radius R in a medium of dielectric constant K is, $4\pi\varepsilon_0 R$
- Electrostatic potential energy of a conductor carrying charge q, capacitance C, and potential V, is given by

$$U_p = \int_0^q V dq = \int_0^q \frac{q}{C} dq = \frac{1}{2}\frac{q^2}{C}$$

Since, $q = VC$, hence,

$$\therefore \quad U_p = \frac{1}{2}V^2C \Rightarrow U_p = \frac{1}{2}qV.$$

- 1 Farad = 9×10^{11} stat Farad.
- The stat-Farad is the electrostatic unit of capacitance in the C.G.S. system.
- If two charged conductors are connected to each other, then energy is lost due to sharing of charges, unless, initially both the conductors are at the same potential.
- The energy lost on sharing the charges is generally converted to heat.
- • If a number of capacitors of capacitances C_1, C_2, C_3, ... are connected in series, their equivalent capacitance is given by,

$$\frac{1}{C_s} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \text{...........}$$

  • In series combination, the charge on each capacitor is the same,

$$q_1 = q_2 = q_3 \text{...........} q_n = q$$

  • If V_n be the potential difference across the capacitors and E be the e.m.f. of the charging battery, then:

$$E = V_1 + V_2 + V_3 + \text{...........}, V_n$$

  • As the charge on each capacitor is the same, therefore

$$q = V_1C_1 = V_2C_2 = V_3C_3 \text{...........}$$

the potential difference is inversely proportional to the capacitance. i.e.,

$$V \propto \frac{1}{C}.$$

- In the series combination, the potential difference across the largest capacitor is the least.

➢ • If a number of capacitors of capacitances C_1, C_2, C_3 ...., C_n are connected in parallel, then their equivalent capacitance is given by:

$$C_p = C_1 + C_2 + C_3 + \dots + C_n$$

- In parallel combination, the potential difference across each capacitor is the same and equal to e.m.f. of the charging battery i.e.,

$$V_1 = V_2 = V_3 = \dots = V_n = E$$

But the charge on different capacitors may be different.

- $q_1 + q_2 + q_3 + \dots + q_n = EC_p$
- Since, potential drop across each capacitor is same, therefore,

$$E = \frac{q_1}{C_1} = \frac{q_2}{C_2} = \frac{q_3}{C_3} = \dots = \frac{q_n}{C_n}$$

i.e., the charges on the capacitors are directly proportional to the capacitances or

$$q \propto C.$$

- Parallel combination is useful when we require large value of capacitance.

➢ The equivalent capacitance in the series combination is less than that of the smallest capacitance in the combination.

➢ Force of attraction between the plates of a parallel plate capacitor is given as,

$$F = \frac{1}{2}\left[\frac{QV}{d}\right] = \frac{1}{2}QE = \frac{1}{2\varepsilon_0}\frac{Q^2}{A}$$

where, Q is the charge on the capacitor and d is the separation between the plates.

➢ Energy stored per unit volume in the capacitor filled with the material of dielectric constant K is:

$$U = \frac{1}{2}\varepsilon_0 KE^2$$

➢ In the capacitor, the energy is stored in the form of the electric field, in the space between the plates.

➢ When a dielectric slab is placed between the plates of the capacitor, its capacitance becomes,

$$C' = KC$$

$$K = \frac{C_m}{C_0} = \frac{\text{Capacitance in medium}}{\text{Capacitance in vacuum}}$$

where, K is the dielectric constant of the slab.

➢ On introducing a dielectric slab between the plates of the capacitor, keeping the charging battery connected, potential energy stored increases and becomes K times. However, if the dielectric slab is introduced after disconnecting the battery, the potential energy stored decreases and becomes $\frac{1}{K}$ times.

➢ If a drop is split into n smaller drops each having radius r, charge q, potential V, capacitance C, electric field on the surface E, surface charge density σ and electrostatic potential energy U_p, then

$$C \propto r$$

- $V = \frac{q}{C} = \frac{q_0/n}{C_0/n^{1/3}} = \frac{V_0/n}{n^{1/3}}$
- $\sigma = \frac{q}{4\pi r^2} = \frac{q_0/n}{4\pi(r_0/n^{1/3})^2} = \frac{q_0}{4\pi r_0^2} \times \frac{1}{n^{1/3}} = \frac{\sigma_0}{n^{1/3}}$
- $E = \frac{\sigma}{\varepsilon_0} = \frac{\sigma_0}{\varepsilon_0} \times \frac{1}{n^{1/3}} = \frac{E_0}{n^{1/3}}$
- $U_p = \frac{1}{2}qV = \frac{1}{2}\frac{q_0}{n} \times \frac{V_0}{n^{2/3}} = \frac{U_{p_0}}{n^{5/3}}$

Total energy of n small drops is given by:

$$nU_p = n\left[\frac{U_{p_0}}{n^{5/3}}\right] = \frac{U_{p_0}}{n^{2/3}}$$

➢ **Parallel Plate Capacitor**

- Let a parallel plate capacitor consists of two plates of area A, separated by distance d, having a dielectric slab of the same thickness area of dielectric constant K lying between the plates. Then the capacitance of the capacitor is given by,

$$C = \frac{K\varepsilon_0 A}{d}$$

- The capacitance of the parallel plate capacitor depends on A and d and the medium between the plates (K). It does not depend on the charge on the plates or the potential difference between the plates.
- If we have a number of dielectric slabs of the same area as the plates of the capacitor and thickness t_1, t_2, t_3 .... and dielectric constants K_1, K_2, K_3 .... between the plates, the capacitance of the capacitor is given by:

$$C = \frac{A\varepsilon_0}{\frac{t_1}{K_1}+\frac{t_2}{K_2}+\frac{t_3}{K_3}+....}$$

Here, $d = t_1 + t_2 + t_3 + $ ....

- If a single slab of thickness t and dielectric constant K is introduced between the plates. ($d > t$)

$$C = \frac{A\varepsilon_0}{(d-t)+\frac{t}{K}} = \frac{KA\varepsilon_0}{K(d-t)+t}$$

- If a single slab of conducting material (metal) of thickness t is introduced between the plates, then,

$$C = \frac{\varepsilon_0 A}{d-t}$$

- When the medium between the plates consists of same thickness but areas A_1, A_2, A_3, ... and dielectric constants K_1, K_2, K_3 ...., then capacitance is given by

$$C = \frac{\varepsilon_0(K_1A_1+K_2A_2+K_3A_3.....)}{d}$$

- The polarisation of dielectric and production of induced charge occurs whenever a dielectric is placed in an external electric field.

Key Formulae

- Capacitance, $C = \frac{Q}{V}$
- The capacitance for parallel-plate capacitor filled with a material having dielectric constant K,

$$C = K\varepsilon_0\frac{A}{d}$$

- Maximum charge on a capacitor, $Q = VC$
- Electrical energy stored in a capacitor,

$$U_E = \frac{QV}{2} = \frac{CV^2}{2} = \frac{Q^2}{2C}$$

- Charge per unit area, $\sigma = \frac{q}{A}$
- Energy density, $U = \frac{1}{2}\varepsilon_0 E^2$
- Capacitors in series, $\frac{1}{C_{eff}} = \frac{1}{C_1}+\frac{1}{C_2}$ ...
- Capacitors in parallel, $C_{eff} = C_1 + C_2$...

Mnemonics

Concept: Charge on capacitor

Mnemonics: Vice Chancellor (VC)

Interpretation: Maximum charge on capacitor

$Q = VC$

UNIT – 2: CURRENT ELECTRICITY

CHAPTER-3

ELECTRIC CURRENT

Topic-1

Electric Current, Resistance and Cells

Concepts covered: Mobility, Drift velocity, Ohm's law, Resistance, Resistivity, Conductivity, Electrical energy and power, Temperature dependence of resistance and resistivity, Internal resistance , Potential difference and emf of a cell, Combination of cells

Revision Notes

Scan to know more about this topic

Electric Current

- Electric current is defined as the rate of flow of charge, i.e.,

$$I = \frac{dq}{dt}$$

When charge flows at a constant rate, the corresponding electric current can be written as

$$I = \frac{q}{t}$$

- A current from a cell in the external circuit flows from the positive terminal to the negative terminal. This is called conventional current. Actually, the free electrons flow from the negative terminal to the positive terminal in the external circuit.
- 1 ampere = 6.25×10^{18} electrons flowing per second.
- When an electric current is set up in a conductor, then the electrons drift through the conductor with velocity v_d, is given by

$$v_d = \frac{I}{neA}.$$

where, e is the charge on an electron, E is electric field, m is mass of electron and *T* is the relaxation time.
where, I is the electric current through the conductor, n is the number density of free electrons, A is the area of cross-section and e is the charge on the electron.
- The drift velocity of the electrons under ordinary conditions is of the order of 0.1 mm/s.
- Free electrons move from a region of low potential to a region of high potential.
- The resistance wires are generally made of high resistivity materials such as manganin and eureka.
- The composition of manganin is Cu-84%, Mn-12%, and Ni-4%.
- The composition of eureka is Cu-60% and Ni-40%.
- **Ohm's law:** Current I flowing in a conductor is directly proportional to the potential difference V applied across the ends of the conductor provided the physical conditions such as the temperature, mechanical strain, etc. remain unchanged.

$$I \propto V$$
$$I = GV$$

Here, $G = \frac{1}{R}$ which is known as the conductance of the conductor

So, $$I = \frac{1}{R}V$$

or $$V = IR$$

where, R is a constant and is called resistance of the conductor.
- **Resistance and Resistivity:** Resistance is directly proportional to the length of a conductor and inversely proportional to the area of cross-section. The resistance of the conductor is given as

$$R = \rho\frac{l}{A},$$

Here, $\rho = \frac{m}{ne^2\tau}$ is the specific resistance or resistivity of the material of the conductor.

- In the series combination of resistances, the current is the same through each resistor.
- When a cell is short-circuited, the terminal potential difference across it becomes zero.
- Energy is dissipated in the cell due to its internal resistance.
- The terminal potential difference across a cell decreases as more current is drawn from the cell.
- If a wire of resistance R is cut into n equal parts, then the resistance of each part is $\frac{R}{n}$.
- The temperature coefficient for conductors is positive i.e., resistance increases as the temperature rises.
- The temperature coefficient for the insulators and semiconductors is negative i.e., their resistance decreases as the temperature increases.
- For the same emf, the availability of current from the secondary cell is greater as compared to the primary cell.
- The internal resistance of the cell depends on the area of the plates, the separation between the plates, concentration of the electrolyte, and temperature.
  The emf of the cell does not depend on the above-mentioned factors.
- The terminal potential difference of a cell depends on internal resistance.
- The internal resistance of a cell is,

$$r = \left(\frac{E-V}{V}\right)R.$$

- The voltmeter measures the terminal potential difference across the cell.
- The ideal voltmeter must have infinite resistance. However, it is not possible in practice. It is connected parallel in the circuit.
- The ideal ammeter must have zero resistance. However, such an ammeter is not possible in practice. It is connected in series in the circuit.
- **The emf and terminal potential difference of a cell:** Let the emf of a cell be E and its internal resistance be r. If an external resistance R is connected across the cell through a key, then
  $IR = V =$ potential difference across the external resistance R.
  This is equal to the terminal potential difference across the cell.

$$E = V + IR$$

$$\Rightarrow \quad I = \frac{E-V}{R}$$

$\Rightarrow$ For internal resistance, $\quad E = V + Ir$

So $\quad V = E - Ir$

$\therefore \quad V < E. \quad$ [if $I > 0$]

When current is drawn from a cell, its terminal potential difference is less than the emf.

Scan to know more about this topic

Combination of cells

- • **Series combination of cells:** This combination is used when external resistance (R) of the circuit is much larger as compared to the internal resistance (r) of the cell. i.e., $R >> r$, for maximum current drawn.
  Let n cells, each of emf E and internal resistance r are connected in series across an external resistance R, then the current in the circuit will be

$$I_S = \frac{nE}{R+nr}$$

  • **Parallel combination of cells:** This combination is used when the *external resistance* R, is much smaller as compared to the *internal resistance* (r) of the cell i.e., $R << r$, for maximum current drawn.
  When n cells are connected in parallel across a resistance R, then current through the resistance is given by,

$$I_P = \frac{E}{R + r/n} = \frac{nE}{nR + r}.$$

  • **Mixed combination of cells:** This type of combination is used when the external resistance R is of the same order as the internal resistance r of the cell i.e.,
  $R \approx r$, for maximum current drawn.
  The current through the external resistance is given by

$$\text{Current} = \frac{\text{net EMF}}{\text{net resistance}}$$

$$I_m = \frac{nE}{R+R'} = \frac{nE}{R+\frac{nr}{m}} = \frac{mnE}{mR+nr}.$$

Here, m is the number of rows and n is the number of cells in each row.

- **Variation of resistance on stretching a wire:** Consider a wire of length l_1, area of cross-section A_1, volume V, density d and mass m. It is stretched to length l_2 and area of cross-section changes to A_2. However volume, density, and mass remain unchanged. Suppose the resistance of the stretched wire be R_2, then

Now,
$$R_1 = \rho\frac{l_1}{A_1}$$
$$R_2 = \rho\frac{l_2}{A_2}$$
or,
$$\frac{R_2}{R_1} = \left(\frac{A_1}{A_2}\right)\left(\frac{l_2}{l_1}\right) \quad \text{...(i)}$$
But, volume will remain same,
$$V_1 = V_2$$
$$A_1 l_1 = A_2 l_2$$
or,
$$\frac{A_1}{A_2} = \frac{l_2}{l_1}$$
So,
$$\frac{R_2}{R_1} = \left(\frac{l_2}{l_1}\right)^2 = \left(\frac{A_1}{A_2}\right)^2 \quad \text{...(ii)}$$
When r_1 and r_2 be the radii of cross-section, then
$$A_1 = \pi r_1^2 \text{ and } A_2 = \pi r_2^2$$
Hence,
$$\frac{R_2}{R_1} = \left(\frac{r_1}{r_2}\right)^4 = \left(\frac{A_1}{A_2}\right)^2 = \left(\frac{l_2}{l_1}\right)^2$$

Topic-2

Kirchhoff's Laws

Concepts covered: Kirchhoff's laws , Wheatstone Bridge, Metre Bridge

Revision Notes

- **Kirchhoff's Laws:**

Kirchhoff's first law - (Kirchhoff's Current Law) KCL

Kirchhoff's second law - (Kirchhoff's Voltage Law) KVL

First law: The algebraic sum of currents at a junction is zero i.e.,

$\Sigma I = 0$. This implies that the total current entering a junction (node) is equal to the total current leaving the junction.

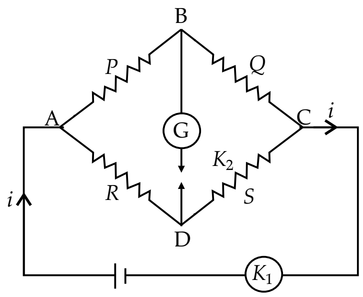
Second law: In a closed loop, the algebraic sum of the emfs is equal to the algebraic sum of the product of resistance and the respective current in them i.e.,

Kirchhoff's I[st] law is based on the conservation of charge. Kirchhoff's 2[nd] law is based on the conservation of energy.

$$\Sigma E = \Sigma IR.$$

- **Wheatstone bridge:**

If in a circuit consisting of four resistances P, Q, R and S, a galvanometer and a battery as shown in figure:



Scan to know more about this topic

Wheatstone Bridge

The Wheatstone bridge is said to be balanced when there is no current through the galvanometer. It means potential at B is equal to that at D. In such a case

$$\frac{P}{Q} = \frac{R}{S}.$$

➢ **Metre bridge or Slide wire bridge:**
It is an application of Wheatstone bridge in which R is fixed and a balance point is obtained by varying P and Q, i.e., by adjusting the position of a jockeys on a 100 cm long resistance wire between two terminals. If the balance point is obtained at length l then

$$\frac{P}{Q} = \frac{R}{S} = \frac{l}{100-l}$$

or
$$S = \left(\frac{100-l}{l}\right)R$$

Resistivity
$$\rho = \frac{SA}{l} = S \times \frac{\pi r^2}{l}$$

Topic-3 Potentiometer and its Applications

Concept covered: Potentiometer, its principle and applications

Revision Notes

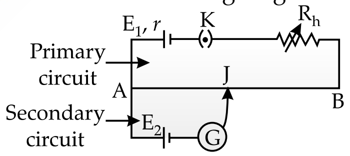
➢ Potentiometer is a device mainly used to measure emf of a given cell and to compare emf's of cells. It is also used to measure the internal resistance of a given cell.

➢ **Superiority of potentiometer over voltmeter:** An ordinary voltmeter cannot measure the emf accurately because it draws some current to show the deflection. As per the definition of emf, it is the potential difference when a cell is in an open circuit or no current through the cell. Therefore voltmeter can only measure the terminal voltage of a given cell.
Potentiometer is based on the no deflection method. When the potentiometer gives zero deflection, it does not draw any current from the cell i.e., the potentiometer is effectively an ideal instrument of infinite resistance for measuring the potential difference.

Scan to know more about this topic

Potentiometer

➢ **Circuit diagram:** Potentiometer consists of a long resistive wire AB of length L (about 6 m to 10 m) made of manganin or constantan. A battery of known voltage E_1 and internal resistance r called supplier battery or drive cell, is connected across AB through a key and rheostat in series. This is called primary circuit.
One terminal of another cell E_2 (whose emf to be measured) is connected at one end of the primary circuit and the other terminal at any point on the resistive wire through a galvanometer G. This forms the secondary circuit.



where, J = Jockey
K = Key
R = Resistance of potentiometer wire
R_h = Variable resistance which controls the current through the wire AB.

➢ • The specific resistance (ρ) of the potentiometer wire must be high but its temperature coefficient of resistance (α) must be low.
• All higher potential points (terminals) of primary and secondary circuits must be connected together at point A and all lower potential points must be connected to point B or jockey.
• The value of the known potential difference must be greater than the value of the unknown potential difference to be measured.
• The potential gradient must remain constant. For this, the current in the primary circuit must remain constant and the jockey must not be in contact with the wire.

- The diameter of the potentiometer wire must be uniform everywhere.

➢ **Potential gradient (k):** Potential difference (or fall in potential) per unit length of potentiometer wire is called potential gradient. i.e.,

$$k = \frac{V(\text{volt})}{L(\text{m})}$$

where, $V = IR = \left(\frac{E}{R + R_h + r}\right)R.$

So $k = \frac{V}{L} = \frac{IR}{L} = \frac{I\rho}{A} = \left(\frac{E}{R + R_h + r}\right)\frac{R}{L}$

➢ **Potential gradient k directly depends Upon:**
- the resistance per unit length (R/L) of potentiometer wire.
- the radius of potentiometer wire (i.e., Area of cross-section).
- the specific resistance of the material of potentiometer wire (i.e, ρ).
- the current flowing through potentiometer wire (I).

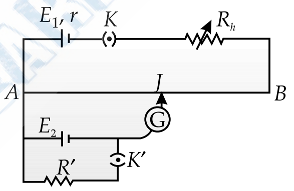
➢ **Potential gradient k indirectly depends upon:**
- the emf of battery in the primary circuit (i.e., E_1).
- the resistance of rheostat in the primary circuit (i.e., R_h).

➢ **Sensitivity of a potentiometer:** A potentiometer is sensitive, if:
- it is capable of measuring very small potential differences, and
- it shows a significant change in balancing length for a small change in the potential difference being measured.

➢ **Ideal voltmeter:** A potentiometer can be regarded as an ideal voltmeter with infinite resistance because it does not draw any current from the source of emf at the null point.

Key Formulae

➢ To determine the internal resistance of a primary cell



- Initially in secondary circuit, key K′ remains open and balancing length (l_1) is obtained. Since cell E_2 is in open circuit so its emf balances on length l_1 i.e.,

$$E_1 = kl_1. \quad \text{... (i)}$$

- Now key K′ is closed so cell E_2 comes in closed circuit. If the process is repeated again then potential difference V balances on length l_2 i.e.,

$$V = kl_2.$$

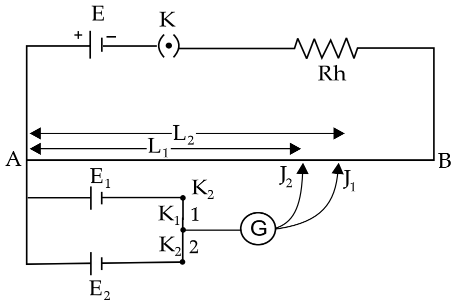
- Internal resistance,

$$r = \left(\frac{E_2}{V} - 1\right) \cdot R'$$

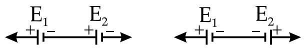
$$r = \left(\frac{l_1 - l_2}{l_2}\right)R'$$

➢ Comparison of emf's of two cells: Let l_1 and l_2 be the balancing lengths with the cells E_1 and E_2 respectively then

$$E_1 = kl_1 \text{ and } E_2 = kl_2 \Rightarrow \frac{E_1}{E_2} = \frac{l_1}{l_2}$$



➢ Let $E_1 > E_2$ and both are connected in series. If balancing length is l_1 when cells assist each other and its length l_2 when they opposes each other as shown:

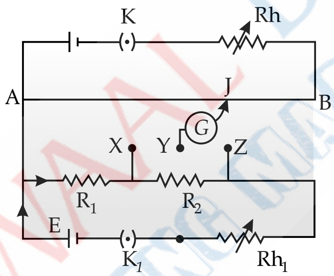


then, $(E_1 + E_2) = kl_1;\ (E_1 - E_2) = kl_2$

$$\Rightarrow \quad \frac{E_1+E_2}{E_1-E_2} = \frac{l_1}{l_2} \text{ or } \frac{E_1}{E_2} = \frac{l_1+l_2}{l_1-l_2}$$

➢ **Comparison of resistances:** Let the balancing length for resistance R_1(when XY is connected) be l_1 and let the balancing length for resistance $R_1 + R_2$ (when YZ is connected) be l_2.

Then $IR_1 = kl_1$ and $I(R_1 + R_2) = kl_2$



$$\frac{R_1}{R_2} = \frac{l_1 - l_2}{l_2}$$

Mnemonics

Concept : Factors on which the potential gradient of potentiometer depends

Mnemonics : Post-**G**raduates and **D**octorates **A**ll **R**eside at **C**hennai.

Interpretation:

P : Potential

G : Gradient

D : depends on

A : Area of cross-section

R : Resitivity of wire

C : Current through wire

❑❑

UNIT – 3: MAGNETIC EFFECTS OF CURRENT AND MAGNETISM

CHAPTER-4

MOVING CHARGES AND MAGNETISM

Topic-1 Magnetic Field

Concepts covered: Magnetic field, Oersted's experiment, Biot-Savart's law

Revision Notes

- **Oersted's Experiment:** A compass needle suffers a deflection, when it is placed near a wire carrying an electric current. When the direction of current is reversed, the direction of deflection of the needle gets reversed also. This proves that a current-carrying conductor produces a magnetic field around it. This property of a current carrying wire having the magnetic field around it is called the magnetic effect of current.
- **Biot-Savart's law:** The magnetic field due to a current-carrying element is given by the following relation:

$$\vec{B} \propto \frac{q\left(\vec{v}\times\vec{r}\right)}{r^3}$$

  - If θ be the angle between $I\vec{dl}$ and $\vec{r}$, then:

$$B = \frac{\mu_0}{4\pi}\cdot\frac{Idl}{r^2}\sin\theta$$

  - $\vec{B}$ is perpendicular to both $I\vec{dl}$ and $\vec{r}$.
  - The current element plays the same role in producing a magnetic field as the point charge does in producing an electric field.
  - Biot-Savart's law is the analogue of the Coulomb's law in electrostatics.

Scan to know more about this topic

Oersted's Experiment

Scan to know more about this topic

Biot Savart's law

- Magnetic field due to a current loop of radius R at its centre is,

$$\vec{B} = \left(\frac{\mu_0}{4\pi}\right)\left(\frac{2\vec{p}_m}{R^3}\right)$$

where, p_m is the magnetic dipole moment.

- **Force on a charge moving in a magnetic field:** A charge q moving with velocity $\vec{v}$ at an angle θ with the magnetic field $\vec{B}$ experiences the magnetic Lorentz force,

$$F = qvB\sin\theta$$

In vector notation, it can be written as: $\vec{F} = q(\vec{v}\times\vec{B})$

- The direction of this force is perpendicular to both $\vec{v}$ and $\vec{B}$.
- This force is maximum when the charged particle is moving perpendicular to the direction of the field (θ = 90°) and minimum when the charged particle is moving along the field (θ = 0°).

Mnemonics

Concept : Force (F) on a Charge (Q) Moving with velocity (v) Perpendicular to a Magnetic Field (B)

Mnemonics : Fast **Q**uality **V**isualizes **B**usiness

Interpretation:

$$F = Q\,v\,B$$

- **Lorentz force:** The total force, acting on a charge q moving with velocity $\vec{v}$ in the electric field $\vec{E}$ and magnetic field $\vec{B}$ is known as Lorentz force.

  The expression for this force is given by,

  $$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

- Force on a current carrying conductor in a magnetic field

  $$F = IlB \sin\theta$$

  or

  $$\vec{F} = I(\vec{l} \times \vec{B})$$

  F is maximum when $\theta = 90°$ and zero when $\theta = 0°$ or $180°$.

  $$F_{max} = IlB$$

- Magnetic field at the centre of a coil carrying current I is having N number of turns

  or

  $$B = \frac{\mu_0 NI}{2R}$$

  $$K.E._{max} = \frac{q^2B^2r_0^2}{2m}$$

  $$\frac{\mu_0}{4\pi} = 10^{-7}\ \text{T mA}^{-1}.$$

Key Formulae

- The force per unit length between the two long parallel conductors carrying currents I_1 and I_2 are separated by a distance r is given by

  $$\vec{F_m} = q_0(\vec{v} \times \vec{B})$$

- Force between current elements,

  $$F = \frac{\mu_0 I_1 I_2 L}{2\pi r}$$

- Magnetic field at a distance d due to an infinitely long current carrying conductor

  $$B = \frac{\mu_0 I}{2\pi d}$$

- Force on a current carrying conductor in a magnetic field

  $$F = I\ \ell\ B\sin\theta$$

- Lorentz force = $\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$

- Magnetic field at the centre of a coil carrying current I is having N number of turns

  $$B = \frac{\mu_0 NI}{2R}$$

- The magnetic field due to a current carrying element is given by

  $$\vec{B} = \frac{\mu_0}{4\pi} \cdot \frac{I\,\vec{dl} \times \hat{r}}{r^2}$$

Topic-2

Ampere's Circuital Law

Concepts covered: Ampere's circuital law, Force on moving charge in uniform magnetic and electric fields.

Revision Notes

- **Ampere's circuital law:** It states that the line integral of the magnetic field around a closed path threading or passing through this closed circuit is μ_0 (the permeability of the free space) times of total current. i.e.,

$$\oint \vec{B}\cdot\vec{dl} = \mu_0 I.$$

Scan to know more about this topic

Ampere's circuital Law

- Magnetic field due to a straight solenoid is $\mu_0 n$I, within it, and $\frac{\mu_0 nI}{2}$ at the edges.
- $\vec{F_m}$ is always perpendicular to $\vec{v}$. So, the charged particle experiences a centripetal force.
  - The current-carrying solenoid behaves like a bar magnet. Its polarity can be determined by using the right-hand thumb rule or right-hand fist rule in the same way as we do for the current carrying coil threading or passing through the closed circuit.
  - Magnetic field at the ends of a long current-carrying solenoid is nearly

$$B_{end} = \frac{1}{2}\mu_0 nI$$

- The magnetic field due to a straight solenoid is

$$B = \mu_0 nI$$

where, n = number of turns per unit length and I is the current in the coil.
- The straight solenoid can be treated as a toroid of infinite radius. Remember, that the magnetic field due to a toroid is independent of its radius.
- The magnetic field due to a straight current carrying conductor at a given point is

$$B = \frac{\mu_0}{4\pi}\cdot\frac{I}{r}(\sin\theta_1 + \sin\theta_2).$$

  - The magnetic field at the centre of the current carrying coil is given by

$$B_r = \frac{\mu_0}{4\pi}\cdot\frac{2\pi I}{R}N$$

  - The direction of the magnetic field is given by the **right-hand thumb rule** as follows:
    Hold the axis of the coil in the right-hand rule such that the fingers curl in the direction of the current. Then, the outstretched thumb gives the direction of the magnetic field.
  - The current-carrying coil behaves as a magnetic dipole of the moment,

$$p_m = N\pi R^2 I = N \times (\text{area of coil}) \times I$$

  - The unit of magnetic dipole moment (p_m) is A.m^2.
  - At a far away point, where $r >> R$, we find:

$$B = \frac{\mu_0}{4\pi}\cdot\frac{2\pi R^2 I}{r^3}.$$

$$B = \frac{\mu_0}{4\pi}\cdot\frac{2p_m}{r^3}$$

  - If the conductor is infinitely long, then $\phi_1 = \phi_2 = 90°$. Hence, magnetic field due to infinite straight current carrying conductor is given by the following relation:

$$B_\infty = \frac{\mu_0}{4\pi}\cdot\frac{I}{r}(\sin 90° + \sin 90°)$$

or

$$B_\infty = \frac{\mu_0}{4\pi}\cdot\frac{I}{r}\times 2$$

where, 'r' is the distance from the conductor at which the magnetic field is to be found

Key Formulae

- Radius of path of a charged particle in a magnetic field:

$$r = \frac{mv}{q_0 B}$$

- Magnetic field due to a straight current carrying conductor at a given point:

$$B = \left(\frac{\mu_0 I}{4\pi r}\right)(\sin\theta_1 + \sin\theta_2)$$

- Magnetic field at the centre due to a circular wire:

$$B = \left(\frac{\mu_0}{4\pi}\right)\left(\frac{2\pi NI}{R}\right)$$

Mnemonics

Concept : Magnetic field due to a current-carrying solenoid
Mnemonics : BILLI
Interpretation:
B : The strength of the magnetic field can be increased by
I : Increasing the amount of current in the circuit or
L : Lengthening the solenoid by increasing the number of coils
LI : Locking Iron as a means of inducing magnetism, thus indirectly strengthening the magnetic field

Topic-3

Current Carrying Conductors and Moving Coil Galvanometer

Concepts covered: Force on a current carrying conductor in a uniform magnetic field. Torque experienced by a current loop in uniform magnetic field, Moving coil galvanometer, Conversion to ammeter and voltmeter.

Revision Notes

- Magnetic force per unit length between two parallel and infinitely long current- carrying conductors is given by the following relation:

$$\frac{F_m}{l} = \frac{\mu_0}{4\pi}\cdot\frac{2I_1I_2}{r}$$

  - Here, $\vec{F}_m / l$ is the force per unit length of the either wire and $\vec{r}$ is the separation between the wires.
  - The force is attractive when the currents are in the same direction.
  - The force is repulsive when the currents are in the opposite directions.

Scan to know more about this topic

Force between two long parallel current carrying conductors

- **1 Ampere:** 1 ampere is the value of that steady current which, when maintained in each of the two very long, straight, parallel conductors of negligible cross-section, and placed 1m apart in vacuum, would produce on each of these conductors a force equal to 2×10^{-7} newton per metre of length.

- The galvanometer consists of a coil, with many turns, free to rotate about a fixed axis, in a uniform radial magnetic field. When a current flows through the coil, a torque acts on it. This torque acting is

$$\tau = NI\,AB$$

A spring provides a counter torque kφ that balances the magnetic torque NIAB; resulting in a steady angular deflection φ. In equilibrium $k\varphi = NI\,AB$. Where k is the torsional constant of the spring.

- The more the number of turns in the coil of a tangent galvanometer, the higher is its sensitivity.
- To increase the range of the voltmeter by n times, its total resistance should also be increased by n times.
- A suspended coil galvanometer can measure the current of the order of a nano ampere.
- The ballistic galvanometer is a specially designed moving coil galvanometer used to measure the charge flowing through it for a very small interval of time.
- In the ballistic galvanometer, the coil is wound over a non-metallic frame.
- The current through the tangent galvanometer is given by

$$I = k \tan \theta$$

where, k is called reduction factor

$$k = \frac{2B_e r}{\mu_0 n},$$

where, B_e is the Earth's magnetic field, r is the radius of the coil, and n number of turns in the coil.
- To convert a galvanometer to an ammeter, an appropriate small value resistance r_s, called shunt resistance, is to be connected in parallel with the galvanometer coil; so that most of the current passes through the shunt.
- To convert a galvanometer to a voltmeter, an appropriate large resistance R is to be connected in series with the galvanometer.

Key Formulae

- Magnetic force per unit length between two parallel and infinitely long current-carrying conductors

$$\frac{F_m}{l} = \frac{\mu_0}{4\pi} \cdot \frac{2I_1 I_2}{r}$$

- For moving coil galvanometer,

current (I) $\propto$ deflection (θ)

or $$I = \left(\frac{NBA}{k}\right)\theta.$$

Key Terms

- **Current sensitivity:** $\varphi I = \left(\frac{NBA}{K}\right)$
- **Voltage sensitivity:** $\frac{\varphi}{V} = \left(\frac{NBA}{K}\right)\left(\frac{CI}{V}\right) = \left(\frac{NBA}{K}\right)\left(\frac{1}{R}\right)$
- Shunt in parallel to be connected to convert a galvanometer to ammeter, $S = \frac{I_g R_g}{(I - I_g)}$
- Resistance in series to be connected to convert a galvanometer to voltmeter $R = \left(\frac{V}{I_g}\right) - R_g$

Mnemonics

Concept : Galvanometer to ammeter and Voltmeter conversion.

Mnemonics : Go to **V**aishali & **R**ead **S**anskrit.

Interpretation:

G : Galvanometer to
V : Voltmeter
R : Resistance in
S : Series

Mnemonics : Go to **A**nghu & **S**tudy **P**hysics.

Interpretation:

G : Galvanometer to
A : Ammeter
S : Shunt in
P : Parallel

CHAPTER-5

MAGNETISM AND MATTER

Topic-1

Magnetic Dipole

Concepts covered: Current loop as magnetic dipole and its magnetic dipole moment, Magnetic dipole moment of a revolving electron,
Magnetic field intensity due to a magnetic dipole, Torque on a magnetic dipole

Revision Notes

- **Bar magnet as a magnetic dipole:**

  A bar magnet has two magnetic poles known as the North pole and the South pole, each of pole strength m. If the separation between the poles (also known as magnetic length) is l, then the bar magnet is said to have a magnetic dipole moment represented as:

$$\vec{M} = m\,\vec{l}$$

  The direction of the magnetic dipole moment is from south pole to north pole of the bar magnet.

Scan to know more about this topic

Magnetic dipoles & dipole moment

- The lines of magnetic force run in closed loops both inside and outside a bar magnet continuously.
- The magnetic dipole moment of a magnetic substance is mainly due to the spinning of electrons.
- The magnetic field due to a short dipole at distance a on the axial line is

$$B_e = \frac{\mu_0}{4\pi} \cdot \frac{2p_m}{a^3}$$

  and that on the equatorial line is

$$B_e = \frac{\mu_0}{4\pi} \cdot \frac{p_m}{a^3}.$$

- The magnetic field does not interact with stationary charges.
- When a magnetic dipole of moment p_m moves from unstable equilibrium to stable equilibrium position in a magnetic field B, the kinetic energy gained by it will be $2p_m$B.
- **Torque on a magnetic dipole in uniform magnetic field:** A magnetic dipole of dipole moment M when placed in a uniform magnetic field B experiences a torque,

$$\tau = MB\sin\theta.$$

  where, θ is the angle between $\vec{M}$ and $\vec{B}$.

  or, $$\vec{\tau} = \vec{M} \times \vec{B}$$

- Time period of oscillation of a magnetic dipole in a magnetic field B, is given by

$$T = 2\pi[I/M\,B_e]^{1/2}$$

  where, I is the moment of length L and pole strength is $p_m = q_m L$.
  It is a vector quantity directed from the south to the north pole.
- Cutting a bar magnet into two equal pieces perpendicular to its length produces magnets of the same pole strength but half the dipole moment.
- The force between two magnetic poles of strength q_m and q'_m separated by a distance r is represented as

$$F = \frac{\mu_0}{4\pi} \cdot \frac{q_m q_m}{r^2}$$

Key Formulae

- **Torque experienced by a magnetic dipole of dipole moment M when placed in a uniform magnetic field B:**

$$\tau = MB\sin\theta,$$

where, θ is the angle between $\vec{M}$ and $\vec{B}$.

- **The magnetic field due to a short dipole at distance 'a' on the axial line:** $B_a = \frac{\mu_0 m}{2\pi r^3}$

- **The magnetic field due to a short dipole at distance 'a' on the equatorial line:** $B_e = \frac{\mu_0 m}{4\pi r^3}$

Mnemonics

Concept : Magnetic dipole moment
Mnemonics : Madam **D**ona **M**artin **n**ever **c**ame to **A**sia
Interpretation:
M : Magnetic
D : Dipole
M : Moment
n : Number of turns
c : current
A : Area
(Magnetic dipole moment = Number of turns × Current flowing × Area of loop)

Topic-2 Magnets

Concepts covered: Bar magnet as an equivalent solenoid, Magnetic field lines, Diamagnetic, paramagnetic and ferromagnetic substances. Electromagnets, Permanent magnets

Revision Notes

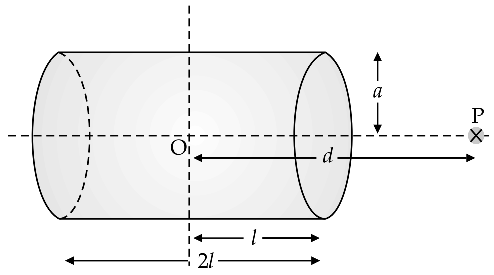
- **Magnetic Field:** The region or space around a magnet, current-carrying conductor, or moving charge, in which magnetic effect can be experienced is called a magnetic field.
  - The magnetic field strength is also called magnetic induction. It is denoted by $\vec{B}$.
  - Magnetic induction is a vector quantity.
  - The magnetic induction may be geometrically represented by the lines of the magnetic field in the same way as the electric field is represented by the electric field lines.
  - The lines of magnetic induction are closed curves (continuous curves). However, it may be remembered that the electric field lines are the curves originating from the positive charge and ending at the negative charge.
  - The lines of magnetic induction for the uniform magnetic field are parallel and equally spaced, but that for the non-uniform magnetic field are curves or unequally spaced or both.
  - The SI unit of magnetic induction is tesla (T) or Weber/metre^2 (Wb/m^2).
  - The CGS unit of magnetic induction is Maxwell/centimetre^2 (Mx/cm^2) or Gauss (G).
- **Bar magnet as an equivalent solenoid:** If a solenoid of length 2*l*, radius *a* with current I having *n* number of turns per unit length, then the magnetic moment of solenoid,

$$M\ (= NIA)\ \text{Or},\ M = (n\times 2l)\times I\times \pi a^2$$

$$\therefore M = 2lnI\pi a^2$$

- and magnetic field of the solenoid at a distance *d*

$$B = \frac{\mu_0 2M}{4\pi d^3}$$



- Magnetic moment of a bar magnet is equal to magnetic moment of an equivalent solenoid that produces same magnetic field.
- **Gauss' Law for Magnetic Fields:** Gauss' Law for magnetism applies to the magnetic flux through a closed surface.
  - It shows that no magnetic monopoles exist and total flux through closed surface will be zero.
  - The Gauss's law for magnetic fields in integral form is given by

$$\phi = \int \vec{B}.d\vec{A} = 0$$

- **Diamagnetic substances:** Diamagnetic substances are those which have tendency to move from stronger to the weaker part of the external magnetic field.

  The field lines are repelled or expelled and the field inside the material is reduced.

  When placed in a non-uniform magnetic field, the bar will tend to move from high to low field.

  Some diamagnetic materials are bismuth, copper, lead, silicon, nitrogen (at STP), water and sodium chloride.

  For diamagnetic substances:

  $-1 \leq \chi < 0$

  $0 \leq \mu_r < 1$

  $\mu > \mu_0$
- **Paramagnetic substances:** Paramagnetic substances are those which get weakly magnetised when placed in an external magnetic field. They have tendency to move from a region of weak magnetic field to strong magnetic field.

  Some paramagnetic materials are aluminium, sodium, calcium, oxygen (at STP) and copper chloride.

  For paramagnetic substances:

  $0 < \chi < \varepsilon$

  $1 < \mu_r < (1+\varepsilon)$

  $\mu > \mu_0$
- **Ferromagnetic substances:** Ferromagnetic substances are those which gets strongly magnetised when placed in an external magnetic field. They have strong tendency to move from a region of weak magnetic field to strong magnetic field. In ferromagnetic substances the field lines are highly concentrated.

  Some ferromagnetic substances are: iron, cobalt, nickel, gadolinium, alloy Alnico, etc. The ferromagnetic property depends on temperature. At high enough temperature, a ferromagnet becomes a paramagnet.

  For ferromagnetic substances:

  $\chi >> 1$

  $\mu_r >> 1$

  $\mu >> \mu_0$
- **Electromagnets and factors affecting their strengths:** Electromagnet is also known as a solenoid having a core of iron with wire wrapped around on it. Factors affecting the strength of electromagnets are:
  - nature of core material
  - strength of current passing through the coil
  - number of turns of wire
  - shape and size of the core
- **Permanent magnets:** Magnets whose magnetic field is generated by internal structure of material itself.
  - Permanent magnets have consistent non-varying magnetic field having north and south pole linked with it.
  - Magnetic fields of permanent magnets are the sum of nuclear spins, electron spins and orbits of electrons.
  - Permanent magnets produce a longitudinal magnetic field between the poles.

Key Terms

- **Magnetic line of force:** May be defined as the curve, the tangent to which at any point gives the direction of the magnetic field at that point.
- **Bohr's magneton:** It is defined as the magnetic moment associated with an electron due to its orbital motion in the first orbit of a hydrogen atom.
- **Gauss's law in magnetism:** The net magnetic flux through a closed surface is zero.

Mnemonics

Concept : Four characteristics of magnetic field lines.

Mnemonics : I love new stories. **T**ina found new Cookies.

Intrepretation :

(i) **I -** Imaginary Lines
(ii) **N, S -** Extended North to South pole
(iii) **T -** Tangent gives (magnetic) field direction
(iv) **N, C -** Never Cross each other

UNIT – 4: ELECTROMAGNETIC INDUCTION AND ALTERNATING CURRENTS

CHAPTER-6

ELECTRO MAGNETIC INDUCTION

Topic-1 Faraday's Laws and Lenz's Law

Concepts covered: Electromagnetic Induction, Faraday's laws, Induced emf and current, Lenz's law.

Revision Notes

- **Magnetic flux:**
  - The dot product of magnetic field $\vec{B}$ and the area element $\vec{dA}$ is called magnetic flux. The number of magnetic field lines passing through a given area element is known as the magnetic flux.
  - The magnetic flux is denoted by ϕ, if $\vec{B}$ be the magnetic field through the area element $\vec{dA}$, then, the flux through the area is given by:

$$d\phi = \vec{B}\cdot\vec{dA} = BdA\cos\theta,$$

where, θ is the angle between the area vector and the magnetic field.

- **Magnetic flux density:** Change in magnetic flux per unit change in area is called magnetic flux density. For $\vec{B}$ parallel to $\vec{dA}$, we have, $\theta = 0°$

then $d\phi = B(dA)\cos 0° = B(dA)$

Therefore, $B = \dfrac{d\phi}{dA}$

i.e., magnetic induction is equal to the magnetic flux density. In other words, the magnetic field may be measured in terms of magnetic flux density. From the above equation, we find

$$\text{Unit of } B = \frac{\text{Unit of } d\phi}{\text{Unit of } dA}$$

or
$$\text{T} = \frac{\text{Wb}}{\text{m}^2}$$

Tesla = Weber per square metre.

- **Electromagnetic Induction:** When the magnetic flux linked with a coil changes, an emf is set up in the circuit. The phenomenon is called electromagnetic induction.
- **Induced emf and current:** When the magnetic flux linked with a coil changes, the emf is set up in the circuit which is called **induced emf.**

  The current which is set up in the circuit due to induced emf is called **induced current.**
- Electromagnetic induction converts mechanical energy into electrical energy.
- When a bar magnet is dropped into a coil, the electromagnetic induction in the coil opposes its motion, So the magnet falls with an acceleration less than the acceleration due to gravity.
- **Faraday's Laws of Electromagnetic Induction:**
  - Whenever, the magnetic flux linked with a circuit changes, induced emf is produced.
  - The induced emf lasts as long as the change in magnetic flux continues.
  - The magnitude of induced emf (E) is directly proportional to the rate of change in magnetic flux.

    Thus, if $d\phi$ be the change in magnetic flux during the time dt, then:

    $$e \propto -\frac{d\phi}{dt} \text{ or } e = k\frac{d\phi}{dt}$$

    where, k is the constant of proportionality. In SI, $k = -1$, hence,

    $$e = -\frac{d\phi}{dt}.$$

    It is called **Faraday's flux rule**.

    The negative sign indicates that the induced emf opposes the change in magnetic flux. In SI units, the change in flux ($d\phi$) is measured in weber, dt in second, and E in volt.

    Hence, volt = weber/second, i.e., $\text{V} = \frac{\text{Wb}}{\text{s}}$.

Scan to know more about this topic

Electromagnetic Induction in 3D

- **Lenz's law:** Lenz's law explains the negative sign in Faraday's flux rule, $E = -\frac{d\phi}{dt}$.

  It states that the induced emf is such that it opposes the very cause that produces it.
- **Lenz's law is in accordance with the law of conservation of energy:** As the induced emf opposes the cause that produces it, therefore mechanical work needs to be done to continue the process. It is the mechanical energy which is converted into electrical energy, in accordance with the law of conservation of energy.

Scan to know more about this topic

Lenz's Law

- If a rod of length ℓ moves perpendicular to a magnetic field B with a velocity v, then the induced emf produced across it, is given by $B \ell v$. It is also called motional emf.
- When a conductor of length R rotates with an angular frequency ω in a uniform magnetic field B, the induced emf is $B\omega R^2/2 = B2\pi f \ell^2/2 = BAf$

  Here, ω = angular velocity of rotation, $A = \pi \ell^2$ = area of circle and f = frequency of rotation

Key Formulae

- Magnetic flux,

  $$\phi = BA\cos\theta,$$

  where, θ is the angle between the area vector and the magnetic field.
- Induced emf,

  $$e = -N\frac{d\phi}{dt},$$

  where, N is the number of turns of the coil.

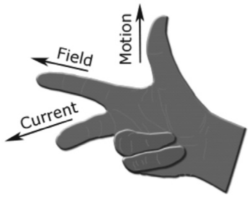
- emf induced in a linearly moving conductor in a uniform magnetic field:
  $\varepsilon = B \ell V$
- emf induced in a rotating conductor in a uniform magnetic field:
  $\varepsilon = B\omega \ell^2/2$.

Key Terms

- **Magnetic flux:** The magnetic flux through any surface placed in a magnetic field is the total number of magnetic lines of force crossing the surface.
- **Electromagnetic induction:** The phenomenon of production of induced emf (and hence induced current) due to a change of magnetic flux linked with a closed circuit with a coil is called electromagnetic induction.

Mnemonics

Concept : Fleming's Right Hand Rule



Mnemonics : Mother, Father, Child

Interpretation :

M: Motion (relative) (represented by thumb)

F : Field (magnetic) (Represented by first finger)

C : Current (represented by second finger)

Topic-2 Eddy Currents, Self and Mutual Induction

Concepts covered: Self and Mutual inductances, Eddy currents, Transformer

Revision Notes

- The production of induced emf in a circuit, when the current in the neighbouring circuit changes, is called mutual induction.
  When the circuit of the primary coil is closed or opened, deflection is produced in the galvanometer of the secondary coil. This is due to the phenomenon of mutual induction.

Scan to know more about this topic
Mutual Inductance

- The mutual induction between two coils depends on the following factors:
  - The number of turns of primary and secondary coils.
  - The shape and size or geometry of the two coils.
- **Coefficient of mutual induction:**
  - Suppose, the instantaneous current in the primary coil is I. Let the magnetic flux linked with the secondary coil be ϕ. It is found that the magnetic flux is proportional to the current i.e.,
    $$\phi \propto I \quad \text{or} \quad \phi = MI \qquad \text{... (i)}$$
    where, M is the constant of proportionality. It is called as the coefficient of mutual induction.
    The induced emf (e) in the secondary coil is given by,
    $$e = -\frac{d\phi}{dt} = -M\frac{dI}{dt} \qquad \text{...(ii)}$$
  - The negative sign is in accordance with the Lenz's law, i.e., the induced emf in the secondary coil opposes the variation of current in the primary coil.
  - From the equation (ii), we find
    $$M = \frac{e}{\left(\frac{dI}{dt}\right)}$$

- Therefore, unit of $M = \dfrac{\text{V}}{\text{As}^{-1}} = \text{VA}^{-1}\text{s}.$

➢ The production of induced emf in a circuit, when the current in the same circuit changes is known as self-induction.

Scan to know more about this topic

Self Induction

- Suppose the instantaneous current in the circuit is I. If the magnetic flux linked with the solenoid is ϕ, then it is found that:

$$\phi \propto I \quad \text{or} \quad \phi = LI \qquad \text{... (iii)}$$

where, L is the constant of proportionality. It is called as the coefficient of self-induction.

The induced emf in the coil is given by,

$$e = -\frac{d\phi}{dt} = -L\frac{dI}{dt} \qquad \text{... (iv)}$$

- The negative sign is in accordance with Lenz's law, i.e., the induced emf opposes the variation of current in the coil.
- From equation (iv), we find: $L = \dfrac{e}{\left(\dfrac{dI}{dt}\right)}$

Then, the coefficient of self-induction is the ratio of induced emf in the circuit to the rate of change of the current in the circuit.

- **Unit of** L**:** The unit of self-induction is called Henry (symbol H).

From equation (iv), we find that if $dI/dt = 1$, $e = 1$ V, then

$$L = 1\text{H} \Rightarrow \textit{Unit of } L = \text{VA}^{-1}\text{s}.$$

➢ **The self-inductance of a coil depends on the following factors:**

- area of cross-section
- the number of turns
- permeability of the core.

➢ Unit of induction, Henry, $H = \dfrac{\text{Wb}}{\text{A}} = \dfrac{\text{Vs}}{\text{A}} = \Omega.\text{s}$

➢ The inductance of a circular coil is given by,

$$L = \frac{\phi}{I} = \frac{BAN}{I} = \frac{\mu}{4\pi}\cdot\frac{(2\pi NI)}{rI}\times AN \qquad \left[\because B = \frac{\mu}{4\pi}\cdot\frac{2\pi NI}{r}\right]$$

$$= \frac{\mu N^2}{2r}A = \frac{\mu N^2}{2r}\times\pi r^2$$

or

$$L = \frac{\mu N^2 \pi r}{2}$$

Here, ϕ = Magnetic flux from the coil, I = Current through the coil, A = Area of the coil, r = Radius of the coil. N = Total number of turns of the coil, μ = Permeability of the medium.

➢ The inductance of a solenoid of length L is given by:

$$L = \frac{\phi}{I} = \frac{BAN}{I} = \left(\frac{\mu_0 NI}{l}\right)\frac{AN}{I} \qquad \left[\because B = \frac{\mu NI}{l}\right]$$

or

$$L = \frac{\mu_0 N^2 A}{l} = \mu_0 n^2 Al = \mu_0 n^2 V \qquad \left[\because n = \frac{N}{l}\right]$$

Here, $n = N/l$ = number of turns per unit length and $V = Al$ i.e., the volume of the solenoid.

➢ The inductance in series is given by:

$$L_s = L_1 + L_2 + L_3 + ...$$

➢ The inductance in parallel is given by:

$$\frac{1}{L_P} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + ...$$

➢ If two coils of inductance L_1 and L_2 are coupled together, then their mutual inductance is given by,

$$M = k\sqrt{L_1 L_2},$$

where, k is called coupling constant.

- The value of k lies between 0 and 1. For perfectly coupled coils, $k = 1$. Perfectly coupled means that the magnetic flux of one coil is completely linked with the second coil. When there is no coupling, $M=0$ and $k=0$.
- The mutual inductance of two coils is given by,

$$M = \frac{\mu_0 N_1 N_2 A}{l} = \mu_0 n_1 n_2 A l = \mu_0 n_1 n_2 \pi r_1^2 l$$

- Eddy currents are currents which circulate in conductors like swirling eddies in a stream. They are induced by changing magnetic fields and flow in closed loops, perpendicular to the plane of the magnetic field.
- Eddy currents do not cause sparking.
- **Eddy current:** In the year 1895 A.D., Foucault discovered that if a metallic plate is moved in a magnetic field, the induced current is set up in the plate. It flows in concentric loops within the plate. Such a current is called **eddy current**. In accordance with Lenz's law, the induced current opposes the cause that produces it.
- If a current I is set up in a coil of inductance L, then the magnetic field energy stored in it is given by:

$$U_p = \frac{1}{2} L I^2.$$

Scan to know more about this topic

How does a Transformer work?

- **Transformer:** A transformer is an electrical device for converting an alternating current at low voltage into high voltage or vice versa.
- If transformer increases the input voltage, it is called a step-up transformer and if it decreases the input voltage, it is called a step-down transformer.
- $$\frac{\text{Output emf}}{\text{Input emf}} = \frac{\varepsilon_2}{\varepsilon_1} = \frac{N_2}{N_1}$$
- $\frac{N_2}{N_1}$ is called the turn ratio of the transformer.
- Currents in primary and secondary,

$$\frac{I_1}{I_2} = \frac{\varepsilon_2}{\varepsilon_1} = \frac{N_2}{N_1}$$

- Efficiency of the transformer,

$$\eta = \frac{\text{Output power}}{\text{Input power}} \times 100\%$$

- The direct current (DC) cannot be stepped up or stepped down with a transformer.

Mnemonics

Concept : Loss in transformer

Mnemonics : He Carried Extra Food

Interpretation :

H : Hysteresis loss

C : Copper loss

E : Eddy current loss

F : Flux loss

Key Formulae

- $\phi = MI$
- **Mutual inductance of two coils:** $M = \frac{\mu_0 N_1 N_2 A}{l}$
- $\phi = LI$
- **Self inductance of a circular coil:** $L = \frac{\mu N^2 \pi r}{2}$
- **Magnetic field energy stored in a coil:** $U = \frac{LI^2}{2}$
- **Current, Voltage and number of turns relation of transformer:** $I_1/I_2 = \varepsilon_2/\varepsilon_1 = N_2/N_1$
- **Efficiency of transformer:** η = (Output power / Input power) × 100%

Key Terms

- **Eddy Currents:** Currents induced in solid metallic masses when the magnetic flux threading through them changes.
- **Self Induction:** Phenomenon of production of induced emf in a coil when a changing current passes through it.
- **Mutual induction:** Phenomenon of production of induced emf in one coil due to a change of current in the neighbouring coil.

CHAPTER-7

ALTERNATING CURRENT

Topic-1 Alternating Current

Concepts covered: Alternating current, peak and rms value, reactance and impedance

Revision Notes

Scan to know more about this topic

"Alternating voltage and current"

- An alternating current is a current whose magnitude changes continuously with time and direction reverses periodically.
- It is represented by sine curve or cosine curve
  $I = I_0 \sin \omega t$ or $I = I_0 \cos \omega t$,
  where, I is the instantaneous value of the current and I_0 is the peak value of the current.
- Frequency (f) of an alternating current is the number of cycles which get completed per second.
  i.e., $$f = \frac{\omega}{2\pi}$$
- Average value of A.C. is defined as that value of direct current which sends the same charge in a circuit at the same time as it sent by the given alternating current in its half-time period.
  $$I_{av} = \frac{2I_0}{\pi} = 0.637\, I_0$$
- Root mean square or virtual or effective value of a.c. is defined as that value of a direct current which produces the same heating effect in a given resistor as is produced by the given alternating current when passed for the same time.
  $$I_{rms} = \frac{I_0}{\sqrt{2}} = 0.707 I_0$$
- Impedance is a quantity that measures the opposition of a circuit to the flow of current through it.
- I_{rms} = 70.71% of I_0.
- E_{rms} = 70.71% of E_0
- I_{av} = 63.66% of I_0.
- E_{av} = 63.66% of E_0
- The part of the impedance in which the phase difference between the current and emf is $\pi/2$ is called reactance.
- If the current lags behind emf by $\pi/2$, then the reactance is called inductive.
- If the emf lags behind the current by $\pi/2$, then the reactance is called capacitive.
- If the emf is in phase with the current, then the circuit is called resistive.
- Hot wire ammeter and voltmeters can be used both in a.c. as well as d.c. circuits.
- The non-sinusoidal complex waveform of an a.c. is obtained when a number of harmonic superpose on one another.

Key Formulae

- $I_{av} = \frac{2I_0}{\pi} = 0.637 I_0$
- $I_{rms} = \frac{I_0}{\sqrt{2}}$
- I_{rms} = 70.71% of I_0.

- $E_{rms} = 70.71\%$ of E_0
- $I_{av} = 63.66\%$ of I_0.
- $E_{av} = 63.66\%$ of E_0
- Average power $= \frac{1}{2} E_0 I_0 \cos\phi = E_{rms} I_{rms} \cos\phi$
- Inductive reactance, $X_L = \omega L$
- Capacitance reactance, $X_C = \frac{1}{\omega C}$
- Net reactance, $X_L \sim X_C = X_L - X_C = \omega L - \frac{1}{\omega C}$

Key Terms

- **Direct current:** It is that current which flows with a constant magnitude in the same fixed direction.
- **Phasor:** A rotating vector that represents a sinusoidally varying quantity is called a phasor.
- **Reactance:** The non-resistive opposition to the flow of A.C. is called reactance. It may be inductive reactance (X_L) or capacitive reactance (X_C).

Topic-2

LCR Series Circuit

Concepts covered: Reactance and impedance of different types of circuits, LC oscillations, LCR series circuit; Resonance; Power in a.c. circuits, Wattless current

Revision Notes

Scan to know more about this topic

LCR Series Circuit

- Sign for phase difference (ϕ) between I and V for series LCR circuit.

  ϕ is positive, when $X_L > X_C$.
  ϕ is negative, when $X_L < X_C$.
  ϕ is zero, when $X_L = X_C$.
- The L.C.R. series circuit is said to be in resonance when $X_L = X_C$ i.e., when $\omega L = \frac{1}{\omega C}$.

  and $\omega = \frac{1}{\sqrt{LC}}$ is called resonant frequency.
- At series resonant frequency, $\omega_0 = \frac{1}{\sqrt{LC}}$, we have
  - $Z = R$ which is the minimum value of impedance.
  - When $\phi = 0$, i.e., I and E are in phase with each other.
  - V_L is equal in magnitude and opposite to V_C.
  - Potential drop across C and L together is zero.
  - $E = V_R$.
  - The impedance is minimum i.e., $Z = R$ and $\omega_0 = \frac{1}{\sqrt{LC}}$.
- The ϕ varies, between – 90° to + 90°, with frequency. Also, $\phi = 0$ at resonant frequency, $\omega_0 = \frac{1}{\sqrt{LC}}$.

- **Power in a.c. circuit:** The power in LCR series circuit is given by

$$P = EI = E_0 I_0 \cos(\omega t - \phi).$$

- Power in an LCR series circuit consists of two components as follows,
  - Virtual power component $= \frac{1}{2} E_0 I_0 \cos(2\omega t - \phi)$.

    It has a frequency twice as that of a.c. Its value over the complete cycle is zero.
  - Real power component $= \frac{1}{2} E_0 I_0 \cos\phi$. The power is dissipated.
- Cos ϕ is called the power factor of the circuit.
  - $P = VI$ is called apparent power.
  - $P_x = VI\cos\phi$ is called active power.
  - $P_y = VI\sin\phi$ is called reactive power.
  - $P = \left[P_x^2 + P_y^2\right]^{1/2}$
- The average power i.e., energy dissipated in the LCR circuit:

$$P_a = \frac{E_0 I_0}{2} \cdot \cos\phi$$

$$\text{Power factor} = \cos\phi = \frac{\text{Resistance}}{\text{Impedance}}$$

$$= \frac{\text{True power}}{\text{Apparent power}}$$

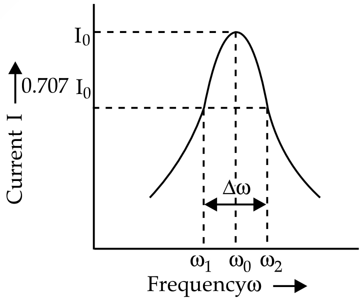
- Impedance for LCR series circuit

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \left[R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2\right]^{1/2}$$

- At resonance: $X_L = X_C$ and $S_L = S_C$.

  Also $X = 0$ and $S = 0$

  and $Z = R$.
- At resonance, V is in phase with I.
- At series LCR resonance, the current is maximum and is given by $I_{max} = \frac{V}{R}$.
- **I vs. ω graph of a LCR circuit:**



- **Bandwidth:** The **bandwidth (*BW*)** of a resonant circuit is defined as difference in frequency below and above the resonant frequency for which the current is equal to or greater than 70.7% of its resonant value.
- **Q-factor:** ***Q factor*** is a measure of the quality of a resonance circuit represented by the letter Q. It is defined as the ratio of resonant frequency and bandwidth.

$$Q = \omega_0/\Delta\omega = \frac{1}{R}\sqrt{\frac{L}{C}}$$

It may also calculated as: $Q = \frac{X_L}{R} = \frac{V_L}{V_R}$

At resonance, $V_R = V$ and $V_L = V_C$

$\therefore Q = \frac{V_L}{V} = \frac{V_C}{V}$

- LC circuit comprises of a fully charged capacitor and a totally de-energized Inductor. In such circuit, the inductor begins to absorb energy from the capacitor. Magnetic energy stored in inductor rises, causing the capacitor to discharge i.e., electric energy stored in capacitor decreases. When the Inductor is completely charged, the electrical energy of capacitor becomes zero. The Inductor now begins to charge the capacitor using the energy stored in it.

  This process repeats - transfer of energy from capacitor to the inductor and then back to the capacitor. This is LC oscillation. LC Oscillations are the continual flow of energy from one device to another.
- The maximum value of current in the LR circuit is V/R, where, V is applied emf.
- The maximum charge on the capacitor in RC circuit is VC.
- The current in RC circuit decays both while charging as well as discharging.

Key Formulae

- Impedance for LCR series circuit

$$Z = \sqrt{R^2 + X^2} = \left[R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2\right]^{1/2}$$

- At resonant frequency

  $Z = R, \omega_0 = \frac{1}{\sqrt{LC}}$
- Power factor $= \cos\phi = \frac{\text{Resistance}}{\text{Impedance}}$

  $= \frac{\text{True power}}{\text{Apparent power}}$

  $Q = (1/R)(L/C)$

Key Terms

- **Resonant frequency:** The frequency at which the current amplitude I_0 attains a peak value is called natural or resonant frequency .
- **Acceptor circuit:** The series resonant circuit is also called an acceptor circuit.

Mnemonics

Concept : Phase difference in pure capacitive and pure inductive circuit.
Mnemonics: LUCCI **L**eft **V**aroda. **IVAN L**eft Chennai.
Interpretation:
C : Capacitive Circuit
C : Current
L : Leads
V : Voltage
I : Inductive Circuit
V : Voltage
L : Leads
C : Current

Topic-3 a.c. Generator

Revision Notes

- The frequency of household a.c. in India is 50 hertz.
- The time period of a.c. is equal to the time taken by the a.c. generator coil to complete one rotation.
- Comparison of a.c. power supply and d.c. power supply:

  Merits:
  - The generation cost of a.c. is less than that of d.c.
  - It can be made available in a wide range of voltages using transformers.
  - The a.c. devices such as motors are mechanically more robust and stout than the d.c. devices.
  - The power loss in a.c. transmission is negligible as compared to that in d.c. transmission.
  - The a.c. can be easily converted to d.c. The reverse is not true.
  - For reducing alternating current, we can use choke coils in which the loss of energy is much less than that in the rheostat used for reducing d.c.

  Demerits:

  (i) The a.c. is more dangerous and fatal than d.c.

  (ii) The 220 V a.c. supply has the peak value of about 311 V, which can cause more severe shock to the persons coming in contact with it.

  (iii) The a.c. is transmitted mostly at the outer surface of the wire, so the conductor needs to be in the form of several stranded wires.

  (iv) The a.c. contains higher harmonics in addition to the fundamental frequency.

  (v) The a.c. cannot be used for electrolysis, electroplating, electrorefining, electro-typing, etc.

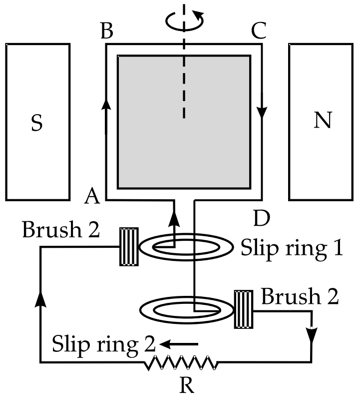
- **a.c. Generator:** It converts mechanical energy into electrical energy in the form of alternating current.

  Scan to know more about this topic

  a.c. generator

  Construction: The main parts of a.c. generator are: (i) field magnet, (ii) the armature (iii), the slip rings, (iv) the brushes.

  Field magnet is a strong horseshoe permanent magnet. The armature having a soft iron core, is rotated rapidly in the magnetic field between the poles of the field magnet. The armature is connected to two coaxial metallic slip rings. Brushes are made of carbon.



  (a) Initially,

$$e = \frac{d\phi}{dt}$$

$$e = BAN\omega \sin \omega t$$

$$e = e_0 \sin \omega t$$

  Here, $e_0 = BAN\omega$

  and $\omega = 2\pi f$

  e_0 is called the peak value of induced emf.

Key Formulae

- $$e = BAN\omega \sin \omega t$$

  $$e = e_{0s} \sin \omega t$$

  Here, $e_0 = BAN\omega$

  and $\omega = 2\pi f$

Mnemonics

Concept : Fleming's right hand rule is applicable for generator. Fleming's left hand rule is applicable for motors.
Mnemonics: **L**eft **H**anded **G**uy helped **R**ight **H**anded **M**am.

Interpretation:
L : Left
H : hand rule
G : Generators
R : Right
H : hand rule
M : Motors

❑❑

UNIT – 5: ELECTROMAGNETIC WAVES

CHAPTER-8

ELECTRO MAGNETIC WAVES

Topic-1 Displacement Current

Concepts covered: Maxwell's Equations, Displacement Current, Electromagnetic wave and its characteristics

Revision Notes

- **Maxwell's equations:**

  The mathematical expressions for Gauss' law in electrostatics, the Gauss' law in magnetostatics, the Faraday's law of electromagnetic induction, and the modified Ampere's law of circuital current, written in the suitable form are called Maxwell's equations. The suitable forms and the characteristics, in brief, are listed below:
- **Gauss' law in electrostatics:** It states that the total electric flux through a Gaussian surface is equal to the charge enclosed by it divided by free space permittivity. It means,

$$\phi = \frac{q}{\varepsilon_0} \text{ and } \phi = \oint_S E.dS$$

Characteristics:
- It is a time-independent steady-state equation.
- The charge acts as a source and sink for the electric field lines.

  Gauss law in magnetism: It states that the total magnetic flux through a closed Gaussian surface is zero. i.e.,

$$\oint_S \vec{B} \cdot \vec{dS} = 0$$

Characteristics:
- It expresses the well-known observation that an isolated magnetic pole does not exist.
- It is a time-independent equation.
- There is no source or sink of the magnetic field lines.

- **Faraday's law of electromagnetic induction:** It states that the induced emf is equal to the rate of change of magnetic flux. i.e.,

$$E = -\frac{d\phi}{dt}$$

$$\oint_S \vec{E} \cdot \vec{dl} = \oint_S \frac{d}{dt}(\vec{B}.\vec{dS})$$

Characteristics:
- It is a time-dependent equation.
- It relates the space integration of electric field (E) with the time variation of magnetic field (B).
- It shows that the variation of magnetic field generates an electric field.

- **Modified Ampere's Law:** It states that the line integral of the magnetic field is equal to $\mu_0 \times$ (the sum of conduction current and the displacement current) i.e.,

$$\oint \vec{B} \cdot \vec{dl} = \mu_0(I_c + I_d)$$

$$= \mu_0\left[I_c + \varepsilon_0 \frac{d\phi_E}{dt}\right]$$

Displacement current is that current which comes into existence, in addition to the conduction current, whenever the electric field and hence the electric flux changes with time.

Characteristics:

- It is a time-dependent equation.
- It relates the space integration of magnetic field (B) with the time variation of electric field (E).
- It shows that the variation of electric field generates a magnetic field.
- If the conduction current I_c is zero,

then,
$$\oint \vec{B} \cdot \vec{dl} = \mu_0\varepsilon_0 \oint_S \frac{d}{dt}(E.dS)$$

i.e., the time-varying electric field, say between the plates of the capacitor, generates a magnetic field.

Scan to know more about this topic

Displacement Current

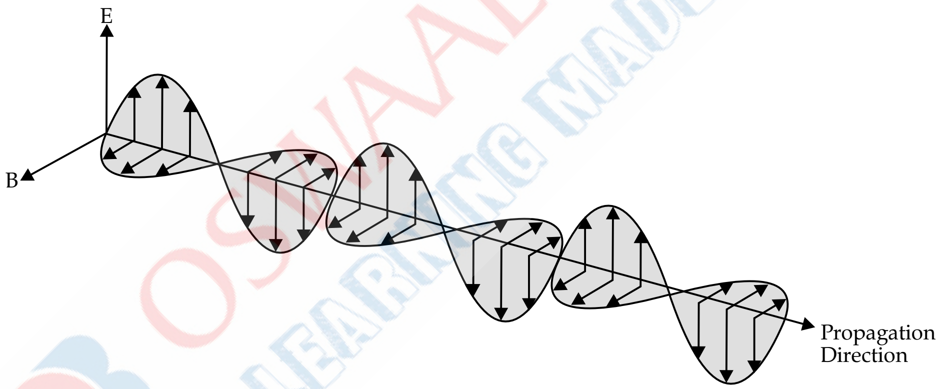
- **Electromagnetic waves:** The waves are produced by the accelerated charge. The electric and magnetic fields produced by the accelerated charged particle, changes with time. Hence, it radiates electromagnetic waves. For example, the electron jumping from the outer to the inner orbit of the electron radiates electromagnetic waves. Similarly, the electrical oscillations in the LC circuit can produce EM waves. Even electric sparking generates EM waves.

Scan to know more about this topic

Electromagnetic Waves

Characteristics

- EM waves are propagated as electric and magnetic fields, oscillating in mutually perpendicular directions.



- EM waves travel in a vacuum along a straight line with a velocity 2.997924591 × 10^8 ms^{-1} which is often assumed as 3 × 10^8 ms^{-1}.
- EM waves are not affected by electric and magnetic fields.
- The electric and magnetic field components are related to each other as $E = Bc$, where, $c = 3 \times 10^8$ ms^{-1}.
- In principle, the electromagnetic waves can be of wave length (λ) from 0 to ∞. Also, corresponding frequency (f) can be from ∞ to 0. The λ and f are related as

$$c = f\lambda.$$

Key Formulae

- Displacement current between the plates of capacitor,

$$I_D = \varepsilon_0 \frac{d(EA)}{dt} = \varepsilon_0 A \frac{dE}{dt}$$

$$= \varepsilon_0 A \frac{d}{dt}\left(\frac{V}{d}\right) = \frac{\varepsilon_0 A}{d}\frac{dV}{dt} = C\frac{dV}{dt}.$$

Here, E = electric field between the plates of a capacitor, V = potential difference, d = separation between the plates, C = capacitance of the capacitor, A = area of plates.

- For the EM waves, the energy density is given by

$$U_e = \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2}\frac{B^2}{\mu_0}$$

- In EM waves, half of the energy is electric and the other half is magnetic i.e., the total energy density of EM waves is

$$U_{EM} = \frac{1}{2}\varepsilon_0 E^2 + \frac{B^2}{2\mu_0}$$

- $$\frac{1}{\mu_0 \varepsilon_0} = c^2.$$

- The variation in magnetic field causes electric field and vice versa.
- In the EM waves, $\vec{E} \perp \vec{B}$ both $\vec{E}$ and $\vec{B}$ being in the same phase.
- In the EM waves:

$$E = E_0 \sin(\omega t - kx).$$
$$B = B_0 \sin(\omega t - kx).$$

- The EM waves travel in the direction of $\vec{E} \times \vec{B}$ i.e., EM waves propagate perpendicular to both $\vec{E}$ and $\vec{B}$.

Topic-2 Electromagnetic Spectrum

Concept covered: Electromagnetic spectrum

Revision Notes

- The various regions of the EM wave spectrum can be assigned the wavelength ranges as follows:

S.No.	Name of the region	Wavelength range (m)	Method of Generation
1.	γ-rays	$\leq 0.5 \times 10^{-10}$	Due to the radioactive decay of the nucleus.
2.	X-rays	0.5×10^{-12} to 0.5×10^{-7}	Bombardment of high atomic weight atoms with electrons, knocking out of electrons from innermost orbital or inner shell electrons.
3.	Ultraviolet rays	0.5×10^{-8} to 0.4×10^{-6}	The movement of electrons from one energy level to the other energy level in the inner shell.
4.	Visible light	0.4×10^{-6} to 0.8×10^{-6}	Electrons in atoms emit light when they move from one energy level to a lower energy level.
5.	Infrared	0.8×10^{-6} to 0.5×10^{-3}	Vibration of atoms and molecules.
6.	Microwaves	1×10^{-4} to 1×10^{-1}	Specially designed oscillators, Klystron valve or magnetron valve.
7.	Radio waves	1×10^{-1} to 1×10^{6}	Oscillating LC circuits, Rapid acceleration and deceleration of electrons in the aerials.

Scan to know more about this topic

Electromagnetic Spectrum

Mnemonics

Concept : Arrangement of electromagnetic waves in decreasing order of wavelength.

Mnemonics: **R**oman **M**an **I**nvented **V**ery **U**nique **X**-ray **G**uns.

Interpretation:

R : Radio waves

M : Microwaves

I : Infrared

V : Visible

U : UV-rays

X : X-rays

G : Gamma-rays

UNIT – 6: OPTICS

CHAPTER-9

RAY OPTICS & OPTICAL INSTRUMENTS

Topic-1 Reflection,Refraction and Dispersion

Concepts covered: Reflection, spherical mirrors, Refraction, lenses and their combinations and Dispersion through a prism

Revision Notes

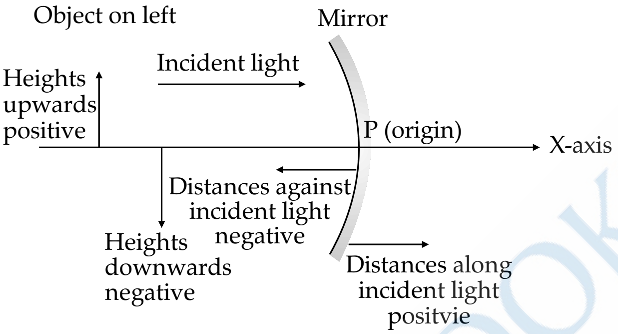
- Light is a form of energy. Ray of light represents the direction of propagation of light energy.
- The speed of light in vacuum is the highest speed attainable in nature. Its approximate value is 3.0×10^8 m/s.
- When light falls on any object/surface, there are three possible optical phenomenon i.e., reflection, refraction and absorption of light by the object/surface.
- By law of conservation of energy, sum of reflected, absorbed and transmitted light is always equal to the incident light.
- Depending upon the amount of light it reflects, transmits or absorbs, the object is classified into reflector, transmitter or absorber of light.
- **Reflection of Light:** When light falls on an object, it bounces the light in the same medium from where the light comes. This is called the reflection of light.
  Mirrors are good reflectors. A mirror can be made by silvering a metal surface or silvering one side of glass plate.
- **Laws of reflection:** It is observed that light obeys the following laws while reflecting from any type of surface.
  - The angle of incidence is equal to the angle of reflection, and
  - The incident ray, the normal to the surface at the point of incidence and the reflected ray, all lie in the same plane.
- **Spherical Mirrors:** Curved shaped mirrors are known as spherical mirrors. On the basis of curve of reflecting surface, spherical mirrors are categorised as:
  - **Concave mirror:** A spherical mirror, whose reflecting surface is curved inwards is called a concave mirror. It means reflecting (polished) surface faces the centre of the sphere using which it is made.
  - **Convex mirror:** A spherical mirror whose reflecting surface is curved outwards is called a convex mirror.
- **Important Terms related to Spherical Mirrors:**
  - The mid point or the centre of the reflecting surface of the mirror is known as pole of the mirror. It is represented by P.
  - The centre of the hollow sphere from which the mirror is made, is known as centre of curvature. It is represented by C. Centre of curvature in concave mirror is in front of the mirror and in convex mirror, it is behind the mirror.
  - An imaginary straight line which joins the pole and centre of curvature of the mirror is known as principal axis and the distance between the centre of curvature and pole of the mirror is called the radius of curvature. It is represented by R.
  - The point on the principal axis where, after reflection, the rays parallel to the principal axis meet (in case of concave mirror) or appear to diverge from (in case of convex mirror) is known as the focus of the spherical mirror and is represented by F.

- The distance of the focus from the pole is known as focal length and is represented by f.
- Mirrors in which radius of curvature is much larger than aperture, there will be relation between R and f such that

$$f = \frac{R}{2}$$

- The image is virtual replica of an object. If rays emanating from a point actually meet at another point, then the point is real image of the object; The image will be virtual if the rays do not actually meet but appear to meet at the point when produced backward.

➢ **The Cartesian Sign conventions:**



➢ **Image formation in concave mirror for different positions of object quality:**

Position of the object	Position of the image	Size & quality of the image	Nature of the image
At infinity	At the focus F	Highly diminished, point sized	Real and inverted
Beyond C	Between F and C	Diminished	Real and inverted
At C	At C	Same size	Real and inverted
Between C and F	Beyond C	Enlarged	Real and inverted
At F	At infinity	Highly enlarged	Real and inverted
Between P and F	Behind the mirror	Enlarged	Virtual and erect

➢ **Image formation in convex mirror for different positions of object quality:**

Position of the object	Position of the image	Size & quality of the image	Nature of the image
At infinity	At the focus F, behind the mirror	Highly diminished, point sized	Virtual and erect
Between infinity and the pole P of the mirror	Between P and F, behind the mirror	Diminished	Virtual and erect

➢ **Mirror formula:** In a spherical mirror, there is a relation between object distance u, image distance v and principal focal length of the mirror f.

$$\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$$

Scan to know more about this topic

Mirror Formula and magnification

➢ **Magnification by Mirror:** The extent by which mirror enlarges or reduces the size of image with respect to object is called the magnification factor of mirror. It is represented by m. If size of an object is h_o and its image by spherical mirror is h_i, then magnification factor of mirror is

$$m = -\frac{v}{u} = \frac{h_i}{h_o}$$

➢ **Refraction of light:** Refraction is deviation of light when it obliquely travels from one medium to another medium. Snell experimentally found the following laws of refraction.

➢ **Laws of Refraction of Light:**

Scan to know more about this topic

Refraction of Light

- The incident ray, the refracted ray and the normal to the interface of two transparent media, at the point of incidence, all lie in the same plane.
- The ratio of sine of angle of incidence to the sine of angle of refraction is a constant, for the light of a given colour and for the given pair of media. This constant value is called the refractive index of the second medium with respect to the first medium.

$$\frac{\sin i}{\sin r} = \text{constant } (n_{21})$$

This is known as Snell's law.

From Snell's law, $\sin i = \sin r \times n_{21}$.

It shows that if $\angle i = 0$, then $\angle r$ is also zero. This proves that the light rays do not deviate when they travel normally from one medium to another.

- If the first medium is free space then the refractive index is known as the absolute refractive index of the second medium. The absolute refractive index of a medium is expressed by

$$n_2 = \frac{\text{Velocity of light in free space}}{\text{Velocity of light in mediun}} = \frac{c}{v} \text{ since, } c > v \Rightarrow n_2 > 1$$

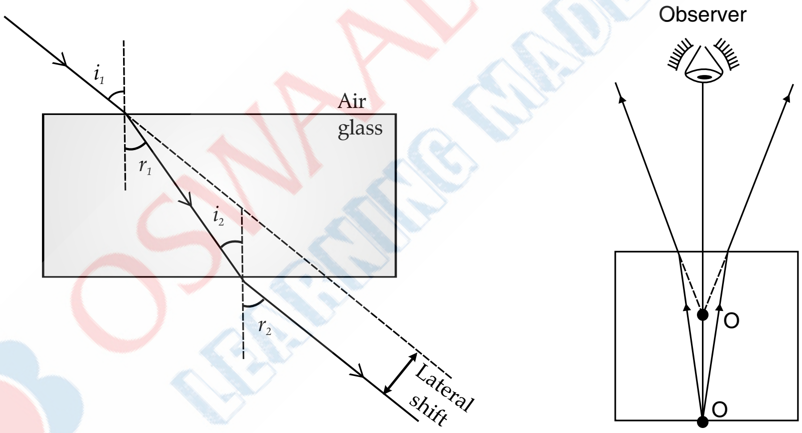
- If a ray of light enters from one medium to another medium in such a way that bending of light happens away from normal, then second medium is optically rarer with respect to the first medium. If bending of light is towards normal, then second medium is optically denser with respect to the first medium.

➢ **Principle of Reversibility:** According to the principle of reversibility, the path of light is reversible even if it is going through several media. It means light follows exactly the same path when its direction is reversed.
- Applying this rule, we may find that if light travels through several media say medium 1 to medium 2 and then to medium 3, then to medium 1 then,

$$n_{21} \times n_{32} \times n_{13} = 1$$

- Though refraction rules are universal but direction of emergent ray depends upon the shape of the medium or in other words, on the shape and angle between incident and emergent interfaces (refracting surfaces).

➢ **Refraction through Glass Slab:**
- In a glass slab, refracting surfaces are plane and parallel to each other.
- Emergent ray is parallel to the incident ray but it suffers lateral displacement.



- The apparent depth of the object is always less than actual depth when looking through glass or water.

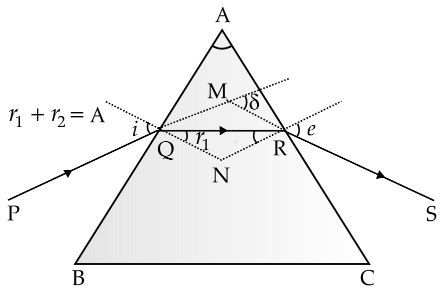
$$\text{Rise of image} = \text{Real depth}\left(1 - \frac{1}{n_{21}}\right)$$

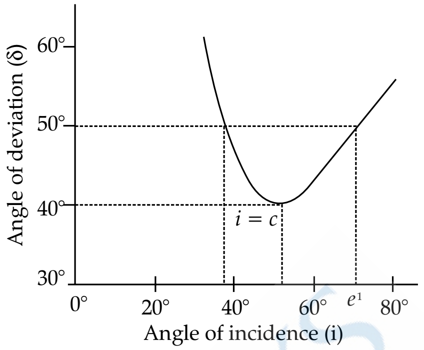
Here, $$n_{21} = \frac{\text{Real depth}}{\text{Apparent depth}}$$

➢ The following phenomena occur due to the refraction of light:
- Bottom surface of water pool seems to be raised.
- The letter appears to be raised when we observe it through a glass slab.
- Object looks bigger than its actual size and raised when we dip it into liquid.
- Twinkling of stars.
- Delayed sunset and early sunrise.

➢ **Refraction through Prism:**
- In prism, refracting surfaces are planes but inclined to each other.
- Refracted ray always bends towards the base.
- Angle of deviation, $\delta = (i - r_1) + (e - r_2)$

- **Angle of minimum deviation:** When incident angle is gradually increased, the angle of deviation initially decreases and after obtaining a minimum value, it starts increasing again. This angle obtained at the lowermost point is called angle of minimum deviation δ_m.





- At minimum deviation stage, it is observed that angle of $i_1 = i_2 (= i)$ and $r_1 = r_2 (= r)$, then

$$r = \frac{A}{2} \qquad \text{[using (ii)]}$$

$$i = \frac{\delta_m + A}{2} \qquad \text{[using (i)]}$$

$$n_{21} = \frac{n_2}{n_1} = \frac{\sin\left[\frac{(A+\delta_m)}{2}\right]}{\sin\left[\frac{A}{2}\right]}$$

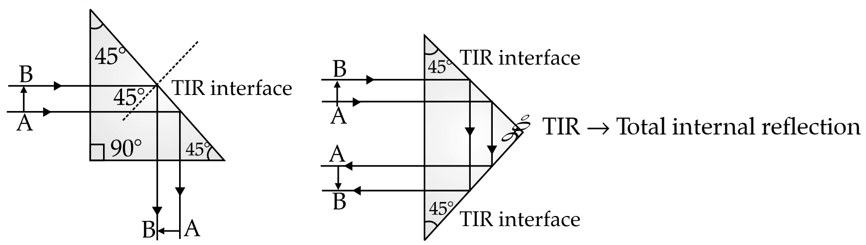
- For thin prism, $\delta_m = (n_{21} - 1)A$. This equation implies that thin prisms do not cause much deviation of light.
- When light travels from an optically denser medium to a rarer medium at the interface, it is reflected into the same medium for a certain angle of incidence. This reflection is called total internal reflection.
- Critical angle is that value of incident angle for which angle of refraction is 90°. The refracted ray just brushes the surface. The critical angle for water-air, glass-air and diamond-air are 45°, 42° and 24° respectively.

$$n_{12} = \frac{1}{\sin C} \qquad \text{(where, } C \text{ is critical angle)}$$

- If the angle of incidence is more than the critical angle, refraction is not possible and incident ray reflects in denser medium. This process is known as total internal reflection.

➢ **Conditions for total internal reflection:**
- The light should travel from denser medium to the rarer medium.
- Angle of incidence should be larger than the critical angle.

➢ **Applications of total internal reflection:**
- For optical communication in optical fibres.
- **Prism:** Prisms designed to bend the light by 90° or by 180° make use of total internal reflection. Such type of prisms are also used to invert images without changing their size.



➢ **Refraction at spherical surface:** If the rays are incident from a medium of refractive index n_1, to another medium of refractive index n_2, the formula comes out to be

$$\frac{n_2}{v} - \frac{n_1}{u} = \frac{n_2 - n_1}{R}$$

where, R = Radius of curvature of spherical surface and object is placed in rarer medium.

u = Object distance from spherical surface

v = Image distance from spherical surface

- **Lens:** A lens is a piece of transparent glass which is bounded by two surfaces out of which at least one surface is spherical. There are two types of lenses:
  - **Convex lens:** A convex lens is one which is thin at edges and thick at centre.
  - **Concave lens:** A concave lens is one which is thick at edges and thin at centre.
- **Relation between object distance, image distance with focal length of lens:**

$$\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$$

- **Magnification by lens:**

$$m = \frac{\text{Height of the image } (h')}{\text{Height of the object } (h)} = \frac{v}{u}$$

- **Power of a lens:** The power of a lens is defined as the reciprocal of its focal length. It is represented by the letter P. The power P of a lens of focal length f is given by

$$P = \frac{1}{f}$$

The SI unit of power is dioptre when focal length is in metre. It is denoted by D. Hence, one dioptre is a power of lens whose focal length is 1 metre.

When two or more lenses are combined, then the power of combined lens is sum of individual power of lenses.

$$P = P_1 + P_2 + ...$$

- **Lens maker's Formula:**

$$\frac{1}{f} = (n_{21} - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \qquad \left(n_{21} = \frac{n_2}{n_1}\right)$$

So, the above formula is used to make lenses of required power. Hence, this formula is known as lens maker's formula.

Scan to know more about this topic

Lens Maker's Formula

- **Image formation in convex lens for different positions of object quality:**

Position of the object	Position of the image	Size & quality of the image	Nature of the image
At infinity	at focus F_2	Highly diminished, point sized	Real and inverted
Beyond $2F_1$	Between F_2 and $2F_2$	Diminished	Real and inverted
At $2F_1$	at $2F_2$	Same sized	Real and inverted
Between $2F_1$ and $2F_2$	Beyond $2F_2$	Enlarged	Real and inverted
At Focus F_1	At infinity	Infinitely enlarged	Real and inverted
Between focus F_1 and optical centre	On the same side of the lens as object	Enlarged	Virtual and erect

- **Image formation in concave lens for different positions of object quality:**

Position of the object	Position of the image	Size & quality of the image	Nature of the image
At infinity	At focus F_1	Highly diminished point sized	Virtual and erect
Between infinity and the optical centre O of the lens	Between focus F_1 and optical centre O	Diminished	Virtual and erect

- **Dispersion of white light through prism:** Splitting of white light into its constituent colours is known as dispersion of light. This is due to the various colours having different speeds in a medium and hence different deviations.
  - The seven constituent colours of white light are violet, indigo, blue, green, yellow, orange and red. The acronym of this colour band is **VIBGYOR**.
  - Different colours of light have different wavelengths and different speed in medium. This is the cause of dispersion.
  - In vacuum, the speed of light is independent of wavelength. Thus, vacuum (or air approximately) is a non-dispersive medium in which all colours travel with the same speed. This also follows from the fact that sunlight reaches us in the form of white light (combination of all colours) and not as its components in day (noon) time. On the other hand, glass is a dispersive medium.

Scan to know more about this topic

Dispersion of Light

- **Angular dispersion through thin prism,**

$$\delta_V - \delta_R = (n_V - n_R)A.$$

The relation shows that it depends upon the angle of prism A.

- **Power of dispersion,**

$$\omega = \frac{\delta_V - \delta_R}{\delta_Y} = \frac{n_V - n_R}{n_Y}$$

It is independent of A. It is property of dispersive material.

- **Recombination of white light:** If we place an inverted identical prism after the first prism, all components colours of light recombine again and became a beam of white light.
- **Phenomenon related to dispersion of light:**
  - **Formation of Rainbow:** Rainbow is the natural phenomenon of dispersion of light. After a rain shower when sky becomes clear and sunny, we may observe a rainbow in a direction opposite to the direction of Sun when Sun is at our backside. It is caused due to the combined effect of refraction, total internal reflection and dispersion of sunlight by the raindrops suspended in the air.
  - In **primary rainbow**, there is only single total internal reflection before different colours reach observer's eye. In this rainbow, observer watches red colour at top and violet at bottom.
  - In **secondary rainbow**, there are two total internal reflections before different colours reach observer's eye. In this rainbow, observer watches violet colour at top and red at bottom.
  - Secondary rainbow is higher (50° – 53°) on sky than the primary rainbow (40° – 42°).
  - Intensity of secondary rainbow is lower than the primary rainbow.

Key Formulae

- Mirror formula $\frac{1}{u} + \frac{1}{v} = \frac{1}{f} = \frac{2}{R}$
- Magnification, $m = \frac{-v}{u} = \frac{f}{f-u} = \frac{f-v}{f}$
- Refractive index, $n = \frac{c}{v}$
- For total internal reflection Refractive index of denser medium, $n = \frac{1}{\sin C}$
- The conditions for total internal reflection are as follows:
  - The light must travel from denser to rarer medium.
  - Angle of incident should be larger than critical angle.
- Lens maker's Formula, $\frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2}\right]$

- Thin Lens formula, $\frac{1}{v}-\frac{1}{u}=\frac{1}{f}$, $m=\frac{h'}{h}=\frac{v}{u}$, $m=\frac{h_1}{h}=\frac{v}{u}$
- Snell's law of refraction, $\frac{\sin i}{\sin r}$ = constant (n_{21})
- $n_{21} \times n_{32} \times n_{13} = 1$
- Rise of image = Real depth $\left(1-\frac{1}{n_{21}}\right)$
- Deviation through prism, $\delta = (i - r_1) + (e - r_2)$
- For thin prism, $\delta_m = (n_{21} - 1)A$
- Relation between refractive index, angle of prism and minimum deviation

$$n_{21} = \frac{\sin \frac{(\delta_m + A)}{2}}{\sin\left(\frac{A}{2}\right)}$$

- Power of lens, $P = \frac{1}{f}$
- When two or more lenses are combined, then the power of combined lens is sum of individual power of lenses.

  $P = P_1 + P_2 + ...$
- Angular dispersion through thin prism, $\delta_v - \delta_r = (n_v - n_r) A$.
- Power of dispersion, $\omega = \frac{\delta_v - \delta_r}{\delta_y} = \frac{n_v - n_r}{n_y}$

Mnemonics

Concept : Mirror formula and Lens formula

Mnemonics: Current leads in Capacitive circuit

Interpretation:

For Mirror $\frac{1}{v}+\frac{1}{u}=\frac{1}{f}$

Magnification

$m=-\frac{v}{u}$ (For mirror)

Mnemonics: Voltage leads in Inductive circuit

Interpretation:

For Lens $\frac{1}{v}-\frac{1}{u}=\frac{1}{f}$

Magnification

$m=-\frac{v}{u}$ (For mirror)

Mnemonics

Concept : Movement of a light ray moves from denser to rarer medium.

Mnemonics: **D**ear **F**riend **A**sk **F**or **N**oodles.

Interpretation:

D : Denser to

R : Rarer

F : Faster

A : Away

F : from

N : normal

(When a light ray moves from denser to rarer medium, it moves faster and moves away from normal.)

Topic-2 Optical Instruments

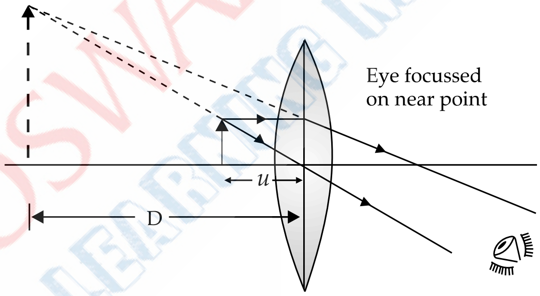
Concept covered: Microscope, Telescope.

Revision Notes

- Based upon reflecting and refracting properties of mirrors, lenses and prisms, number of optical devices and instruments have been designed.
- **Microscope** is an optical instrument which helps us to see and study micro objects or organisms. It forms magnified image of the object.
- **Telescope** is an optical instrument which helps us to see and study far off objects magnified and resolved (with clarity).
- We generally set these instruments at two different image vision positions and they are as follows:
  - **Image at least distance of distinct vision:** This is the least distance from eye where we are able to see objects distinctly. For normal human eye, the distance is 25 cm from our eye.
  - **Image at relaxed vision:** This is the distance from eye where we are able to see objects distinctly in relaxed vision with no strain to eye . For normal human eye, the distance is infinity from our eye.
  - Magnification at distinct vision is always greater than magnification at relaxed vision.
- **Simple Microscope:** Convex lens behaves as simple microscope.
- The magnifying power of the simple microscope
  - For least distance of distinct vision,

$$m = 1 + \frac{D}{f}$$

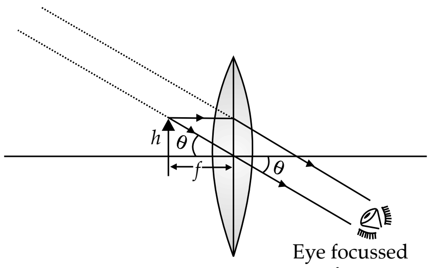
where, D is the least distance of distinct vision of the eye and f is focal length of the lens.



- For relaxed eye,

$$m = \frac{D}{f}$$

From above formulae, it is clear that for larger magnifying power, the focal length of the convex lens should be small.



The angular magnification by optical instruments is the linear magnification by lenses only. It means magnification of an instrument means how many times it enlarges the image of an object. So it can be written as

$$m = \frac{h'}{h}$$

where, h is size of object (in one dimension) and h' is the size of image.

➢ **Compound Microscope:** For much large magnification, compound microscope is used. It is a combination of two convex lenses when the magnification of each lens is compounded.

- The two lenses are placed coaxially and the distance between them is adjustable.
- The lens towards the object is called objective and that towards the eye is called eyepiece.
- The final image formed by the compound microscope is magnified and inverted.
- Total magnification by compound lens,

$$m = m_o \times m_e$$

where, m_o is magnification by objective lens and m_e is magnification by eyepiece.

- For least distance of distinct vision, magnification by objective lens is

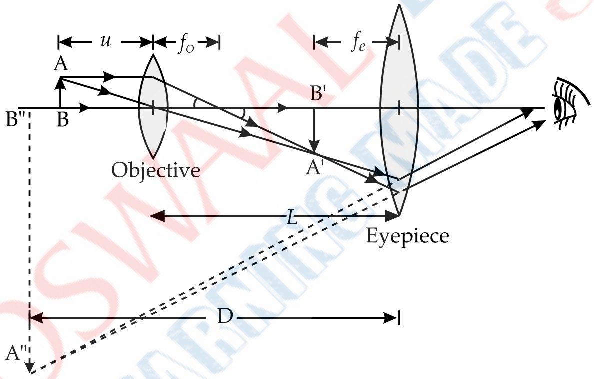
$$m_o = \frac{v_o}{u_o} \approx \frac{L}{f_o}$$

where, L is the distance between the objective and the eyepiece. It is called the tube length of the compound microscope.

- Eyepiece lens acts as simple microscope.
- Magnification by eyepiece lens,

$$m_e = 1 + \frac{D}{f_e}$$

Hence, Magnification by compound lens $= \frac{L}{f_o}\left(1 + \frac{D}{f_e}\right)$



➢ **For Relaxed Eye (normal adjustment):** For relaxed eye, the magnification by objective lens remain same, the magnification by eyepiece will be

$$+\frac{D}{f_e}$$

Hence, the total magnification of compound microscope in relaxed eye condition is

$$m = \frac{L}{f_o} \times \frac{D}{f_e}$$

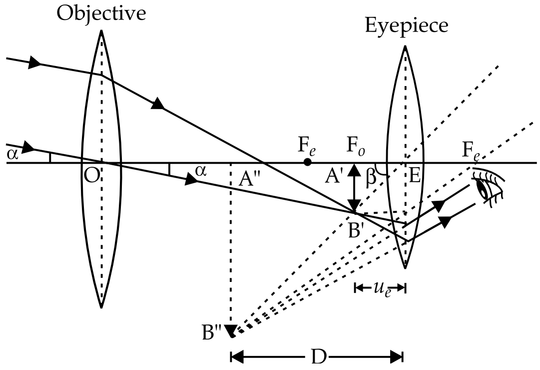
➢ **Properties of Compound Microscope:**

- For large magnification of a compound microscope, both f_o and f_e should be small.
- If the length of the microscope tube increases, then its magnifying power increases.
- Generally f_o is much smaller. So, the object is placed very near to principal focus.
- The aperture of the eyepiece is generally small so that whole of the light may enter the eye.
- The aperture of the objective is also small, so the field of view may be restricted.

➢ **Magnification by Telescope**

- Telescope is an instrument to magnify and resolve far off objects.
- Far off objects make much smaller angle at our eye. Telescope makes that angle larger without much intensity loss.
- To maximise the intensity, aperture size of objective lens is quite large. It focuses a bright point size image at its focal plane.
- With eyepiece, we will observe the point size image to final inverted magnified image. This type of telescope is known as astronomical telescope.

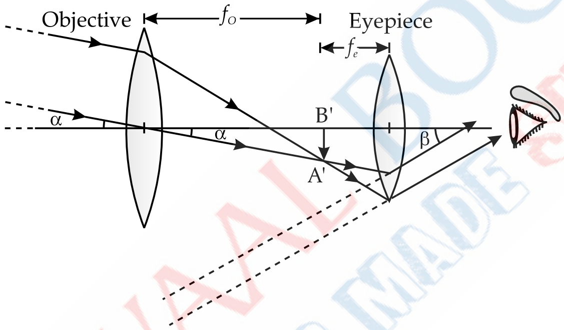
- For least distance of distinct vision,



$$m = -\frac{f_o}{f_e}\left(1+\frac{f_e}{D}\right)$$

➢ **For Relaxed Eye (normal adjustment):**

$$m = \frac{\alpha}{\beta} = -\frac{f_o}{f_e}$$

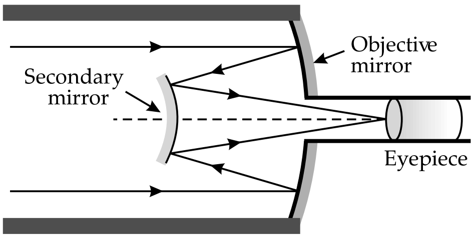


➢ **Properties of astronomical telescope:**
- For larger magnifying power, f_o should be large and f_e should be small.
- The length of the tube of an astronomical telescope is $L = f_o + f_e$ for relaxed vision adjustment.
- When the length of the tube of the telescope increases, f_o increases and magnifying power also increases.

➢ **Limitations of refractive telescope:**
- Large objective lens makes the telescope very heavy. So, it is difficult to handle it easily.
- It has spherical and chromatic aberrations.

➢ **Modern Telescope (Reflective Telescope):**
- Reflecting telescope consists of a concave mirror of large radius of curvature in place of objective lens.
- A secondary convex mirror is used to focus the incident light, which passes through a hole in the objective primary mirror .
- The magnifying power of the reflecting telescope is

$$m = \frac{f_o}{f_e}$$



➢ **Advantages of reflective telescope:**
- Very sharp point image by objective mirror removes spherical aberrations.
- As it is very light, large aperture of parabolic mirror can be used for desired magnification.
- This is based on the principle of reflection and there will be no chromatic aberrations.

Key Formulae

- Magnification of simple microscope

$$m = 1+\frac{D}{f} \text{ (for distinct vision)}$$

$$m = \frac{D}{f} \text{ (For relaxed eye)}$$

- Magnification by compound microscope

$$\frac{L}{f_o}\left(1+\frac{D}{f_e}\right) \text{ or } \frac{v_o}{u_o}\left(1+\frac{D}{f_e}\right) \text{ (for distinct vision)}$$

$$\frac{L}{f_o}\times\frac{D}{f_e} \text{ or } \frac{v_o}{u_o}\times\frac{D}{f_e} \text{ (for relaxed eye)}$$

- Magnification by telescope

$$m = -\frac{f_o}{f_e}\left(1+\frac{f_e}{D}\right) \text{ (for distinct vision)}$$

$$m = -\frac{f_o}{f_e} \text{ (for relaxed eye)}$$

CHAPTER-10

WAVE OPTICS

Topic-1 Huygens Principle

Concepts covered: Wavefront, Huygens principle.

Revision Notes

- Wave theory of light was proposed by Huygens in 1678. Following are the assumptions of this theory:
  - Huygens suggested that each point on the source of light acts as a centre of disturbance from which the waves spread out in all directions.
  - The locus of all the particles in a medium vibrating in the same phase is called wavefront.
  - The wavefront due to a point source is spherical and due to a line source is cylindrical. The wavefront corresponding to a parallel beam of light rays is plane.
  - The direction of propagation of the light (ray of light) is perpendicular to the wavefront.
  - Each point on a wavefront acts as a source of a new disturbance called secondary wavelet.
  - Secondary wavelets spread out as spherical secondary wavefronts with the speed of light.
  - The tangential surface to all the secondary wavefronts gives the new **wavefront.**
  - The intensity of the secondary wave front is given as $I = I_0(1 + \cos\phi)$, where, ϕ is the angle between the original direction of propagation and the direction of observation. This shows that the secondary wave front has zero intensity in the backward direction.
  - The wave theory explains the laws of reflection, refraction, rectilinear propagation, interference, diffraction, as well as dispersion of light.
  - The wave theory fails to explain the photoelectric effect of light.
  - Huygens had assumed that the light waves propagate in a hypothetical medium called ether. It was supposed to possess very high elasticity and very low density. However, later on, it was found that no material medium is required for the propagation of light.
  - Huygens had also proposed that light waves are longitudinal in nature. As such it could not explain the polarisation of light. Later on, it was found that the light propagates as transverse waves which can be polarized.

Scan to know more about this topic

Huygens Principle of Secondary Wavelets

Key Terms

- **Wavefront:** A wavefront is defined as the continuous locus of all such particles of the medium which vibrates in the same phase at any instant.
- **Ray of Light:** A ray of light is the path along which light travels. It is always normal to the wavefront.

Topic-2 Interference

Concepts covered: Interference, Young's double-slit experiment, Coherent sources.

Revision Notes

- The redistribution of the intensity of the light waves due to the superposition of waves is called interference.
- The interference was discovered by Thomas Young in 1801.
- To obtain a sustained interference, we must have:
  - Sources of light must be monochromatic and of the same frequency and constant phase difference.
  - Two sources must be coherent. (Two sources of light are said to be coherent if the phase difference between them remain constant throughout.)
  - Amplitudes of the two sources should preferably be equal.
  - The distance between the two sources must be small.
  - The sources must be narrow.
  - The distance between the sources and the screen should be large.
  - The interfering light waves must be in the same state of polarisation.

Scan to know more about this topic

Interference of Waves

- **Young's double-slit experiment:**
  - The **fringe width** is the same for all fringes in Young's double-slit experiment and is given by:

$$\beta = \lambda\frac{D}{d}$$

where, d is the distance between the two sources.

  - The location of n^{th} bright fringe on the screen is given by:

$$y_n(b) = n\beta = n\lambda\frac{D}{d}.$$

Here, $y_n(b)$ is the distance of n^{th} bright fringe from centre, and $n = 0, 1, 2, 3...$

  - The distance of n^{th} dark fringe is given by:

$$y_n(d) = (2n-1)\frac{D\lambda}{d}$$

where, $n = 1, 2, 3.....$

  - The angular separation $\theta_n(b)$ for n^{th} bright fringe is given by:

$$\theta_n(b) = \frac{n\beta}{D} = n\frac{\lambda}{d},$$

where, $n = 0, 1, 2, 3,.....$

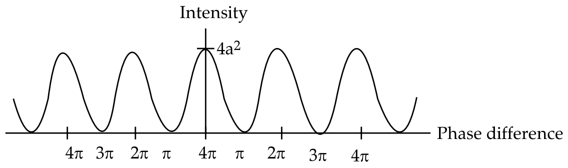
  - The angular separation for n^{th} dark fringe is given by:

$$\phi_n(d) = (2n-1)\frac{\lambda}{d}.$$

where, $n = 1,2,3......$

Scan to know more about this topic

Young's double slit experiment



- If one of the slit is closed, then the distribution of the intensity of light both for coherent as well as non-coherent sources is the same.
- In the interference, the energy is redistributed in space. There is no loss or gain of energy.
- **Sustained interference** cannot be obtained in the absence of coherent sources.
- The distance of the interference fringes is measured from the central maximum.
- The amplitude of the light waves is proportional to the area of the slit.

  i.e., $A \propto$ area of the slit.
- If slit width increases, the contrast between the fringes decreases. For very large width, uniform illumination occurs.
- When the separation between the slits,

$$d = \frac{\beta}{2}$$

  where, β = fringe width, uniform illumination occurs.
- Young's double-slit experiment confirms the wave nature of light.
- Central fringe with white light interference is white with coloured fringes around it. In such a case, the violet fringe is nearer to the central maximum and the red one is the farthest.
- If the Young's experiment is repeated in a medium of refractive index μ, the fringe width is given by:

$$\beta(\mu) = \frac{\lambda D}{\mu d}.$$

- When one of the slits of Young's double-slit experiment is partially closed, the contrast between the fringes decreases.
- If each of the two slits is illuminated by independent sources, no interference pattern is obtained on the screen. Instead, general illumination occurs. Note that in such a case, the two slits behave as non-coherent sources.
- If a transparent sheet of film of thickness t is introduced in the light ray from one slit, the interference pattern is shifted to the same side.
- The number of fringes by which the fringe pattern shifts is given by:

$$N = \frac{(\mu - 1)t}{\lambda},$$

  where, μ is the refractive index of the sheet or film.

  In the above case, the central fringe is shifted by

$$\Delta x = \frac{(\mu - 1)t}{\lambda} D.$$

- The sheet introduces an additional path difference equal to $(\mu - 1)t$.

Key Formulae

- Amplitude and intensity at any point in an interference pattern:

  Resultant amplitude, $A = \sqrt{a_1^2 + a_2^2 + 2a_1a_2\cos\phi}$

  Resultant intensity, $I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\phi$
- Distance of n^{th} bright fringe from the centre of the screen,

$$y = \frac{n\lambda D}{d}, n = 1, 2, 3, ...$$

- Distance of n^{th} dark fringe from the centre of the screen,

$$y = (2n - 1)\frac{D\lambda}{d}, n = 1, 2, 3....$$

- Fringe width,

$$\beta = \frac{D\lambda}{d}$$

- $$\frac{I_{max}}{I_{min}} = \frac{(a_1 + a_2)^2}{(a_1 - a_2)^2}$$

Key Facts

- **Fringe width:** It is the separation between two successive bright or dark fringes, on the observation screen do not change with time are called a sustained interference pattern.
- **Sustained interference:** The interference patterns in which the positions of maxima and minima of intensity on the observation screen do not change with time, are called a sustained interference pattern.

Mnemonics

Concept : Phase difference for constructive and destructive interference

Mnemonics: **P**ranab **D**hawan **D**eparted **O**tty by **C**hennai **E**xpress .

Interpretation:

P : Phase

D : Difference

D : For Destructive interference

O : Odd (i.e., $(2n + 1)\pi$]

C : For Constructive interference

E : Even [i.e., $2n\pi$]

Topic-3 Diffraction

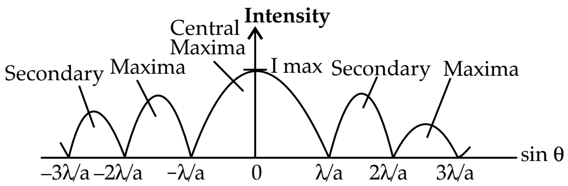
Concept covered: Fraunhoffer's diffraction due to a single slit.

Revision Notes

- The diffraction is the phenomenon of bending of light waves around the corners of obstacles or the apertures.
- Due to the diffraction, the waves encase into the geometrical shadows of the obstacle or aperture.
- Due to the larger wavelength of sound, its diffraction can be easily detected in daily life around the windows, doors, buildings, etc. The same is not the case with light, due to its shorter wavelength.
- The diffraction of radio waves can be observed even around hills, due to their much longer wavelength.
- When the size of the obstacle is much larger as compared to the wavelength, only a geometrical shadow of the obstacle is obtained.
- The centre of the geometrical shadow is a bright spot due to diffraction at the edges. The intensity of this bright spot increases as the size of the obstacle decreases.
- The centre of the diffraction pattern due to a circular aperture, when no lenses are used (Fresnel) may be bright or dark depending on the position of the screen.
- The centre of the diffraction pattern due to a circular aperture, when lenses are used (Fraunhofer) is always bright.
- Fraunhofer diffraction is a special case of Fresnel diffraction when the incident and diffracted beams are made parallel.
- The diffraction of light is visible only near the edges of the shadows of the obstacle. But the diffraction of sound can be observed even in other parts of the shadow.
- Due to the lower degree of diffraction, the light waves appear to be travelling in straight lines. However, due to the higher degree of diffraction, the sound wave may appear to deviate from the straight-line path.
- The diffraction mainly depends on the following two factors:

  (i) size of the aperture or obstacle.

  (ii) wavelength
- For diffraction, the size (d) of the obstacle or the aperture should be of the order of the wavelength (λ). That is $d \approx \lambda$, i.e., when $d >> \lambda$, only geometrical shadow appears. And when $d << \lambda$, reflection and not diffraction occurs.



Key Formulae

- Distance of n^{th} minimum from the centre of the screen

$$x_n = \frac{nD\lambda}{d}$$

- Angular position of n^{th} secondary maximum

$$\theta_n' = (2n+1)\frac{\lambda}{2d}$$

- Distance of n^{th} secondary maximum from the centre of the screen

$$x_n' = (2n+1)\frac{D\lambda}{2d}$$

- Width of central maximum,

$$\beta_0 = \frac{2D\lambda}{d}$$

UNIT – 7: DUAL NATURE OF RADIATION AND MATTER

CHAPTER-11

DUAL NATURE OF RADIATION AND MATTER

Topic-1 Photoelectric Effect

Concepts covered: Wave particle duality, Photoelectric effect, Hertz Lenard's observations, Einstein's photoelectric equation, Particle nature of light.

Revision Notes

- Max Planck proposed the quantum theory of light. According to this theory, the energy of each packet or quantum of light (also called a photon) is given by

$$E = h\nu = \frac{hc}{\lambda}$$

  - The rest mass (m_0) of the photon is zero.
  - The energy of the photon is completely kinetic.
  - Momentum of the photon is

$$p = \frac{h}{\lambda} = \frac{h\nu}{c}$$

  - Mass of the moving photon is

$$m = \frac{h\nu}{c^2} = \frac{h}{c\lambda}$$

- **Einstein's photoelectric equation:**
  - The Einstein's photoelectric equation is in accordance with the law of conservation of energy i.e., the energy of the incident photon (hv) = energy spent in taking the electron just out of the photosensitive surface (W_o) + kinetic energy of the photoelectron.
  - Since, $W_0 = h\nu_0 = \frac{hc}{\lambda_0}$.

  Hence, Einstein's photoelectric equation may be written as:

$$hv = h\nu_0 + \frac{1}{2}mv_m^2$$

Scan to know more about this topic

Photoelectric Effect and Wave Theory of Light or $$\frac{hc}{\lambda} = \frac{hc}{\lambda_0} + \frac{1}{2}mv_m^2$$

- The photoelectrons are ejected with velocities ranging from 0 to v_m.
- The work function is the minimum amount of energy spent in taking the photoelectron out of the metallic surface. In general, energy spent in doing so may be more than W_0 then the rest energy is imparted to the emitted photoelectron as its kinetic energy.
- If the collector of the photocell is given negative potential, the photoelectrons moving towards it are retarded. The negative potential of the collector, which just stops the photoelectrons with maximum velocity, from reaching the collector is called **stopping potential**. It is denoted by V_0. In such a case, $\frac{1}{2}mv_m^2 = eV_0$. So, Einstein's photoelectric equation may be written as:

$$h\nu = W_0 + eV_0$$

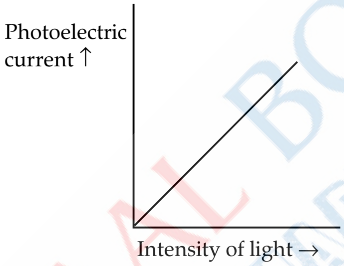
- The photoelectric emission is instantaneous, i.e., the photoelectron is ejected as soon as the photon is absorbed.
- Einstein has proposed his theory of the photoelectric effect in 1905 and was awarded the Nobel prize.
- Einstein's photoelectric equation was experimentally verified by R.A. Millikan. From the equation,

$$h\nu = W_0 + K_m$$

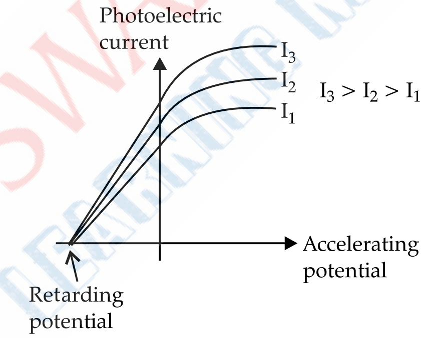
where, K_m is the maximum kinetic energy, we can write

$$K_m = h\nu - W_0 = h\nu - hv\nu$$

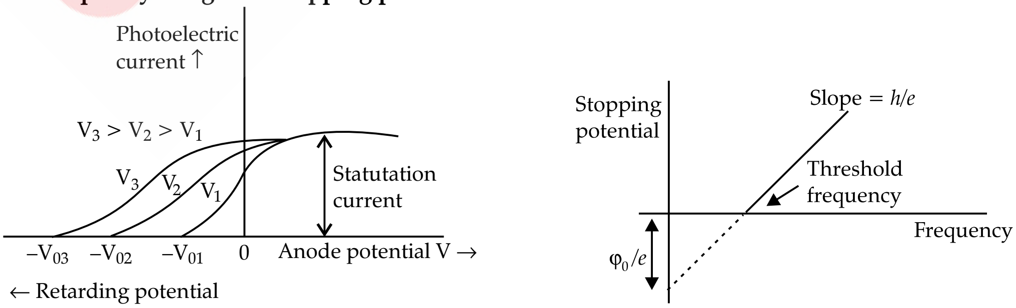
- **Effect of intensity of light on photoelectric current:**



- **Effect of potential on photoelectric current:**



- **Effect of frequency of light on stopping potential:**



- The Photoelectric effect confirms the particle or quantum nature of light.
  - Photoelectric effect occurs, when the energy of the incident photon is of the order of work function i.e., $h\nu_0 = W_0$.
  - The electron ejected in photoelectric effect completely absorbs the incident photon.
  - All of the incident photons do not cause photoelectric emission.
- In the photoelectric effect, the electron is assumed to be bound i.e., the energy of the incident photon is of the order of the binding energy of the electron.

- For alkali metals, the **threshold frequency** lies in the visible region. For zinc, it lies in the ultraviolet region. Infrared radiations cannot eject photoelectrons, while *X*-rays will always do it.
- The kinetic energy of photoelectrons does not depend on the intensity of light.

Key Formulae

- $E = h\nu = \dfrac{hc}{\lambda}$
- $p = mc = \dfrac{h\nu}{c} = \dfrac{h}{\lambda}$
- $W_0 = h\nu_0 = \dfrac{hc}{\lambda_0}$
- $K_{max} = \dfrac{1}{2}mv_{max}^2 = h\nu - W_0 = h(\nu - \nu_0)$
- $K = \dfrac{1}{2}mv_m^2 = eV_0$

Key Terms

- **Stopping potential:** It is the minimum value of the negative potential that must be applied to the anode of the photocell to make the photoelectric current zero.
- **Threshold frequency:** The minimum value of the frequency of incident radiation below which the photoelectric emission stops altogether is known as threshold frequency.

Topic-2 de-Broglie Wavelength

Concepts covered: Matter waves, de-Broglie relation.

Revision Notes

- The de-Broglie wavelength of the particle of mass *m* and moving with velocity *v* is given by

$$\lambda = \frac{h}{mv} = \frac{h}{p}$$

- The de-Broglie wavelength of a particle of mass *m* and kinetic energy K is given by,

$$\lambda = \frac{h}{\sqrt{2mK}}.$$

- If a particle of mass *m* carrying charge q_0 is accelerated through potential V, then its de-Broglie wavelength is given by

$$\lambda = \frac{h}{\sqrt{2mq_0V}}.$$

For electron wave, putting the value of mass and charge of electron and the value of Planck's constant

$$\lambda_e = \frac{1.227}{\sqrt{V}}$$

- The de-Broglie wavelength associated with ordinary objects is of the order of 10^{-24} m.
- In practice, the matter waves can be detected only when the wavelength of the matter waves is much greater than the size of the particle.
- The de-Broglie wavelength is independent of the charge of the particle.
- Electron microscope works on the basis of de-Broglie waves.
- de-Broglie suggested that as light possesses dual nature, the same should be true for the particles.

Scan to know more about this topic

Wave Nature of Electron-de-Broglie Relation

Mnemonics

Concept : de-Broglie wavelength of particle

Mnemonics: We **P**ut **C**onfidence **ON M**cdonald's **P**roducts.

Interpretation:

W : Wavelength
P : Planck's
C : Constant
ON : on
M : momentum of
P : particle

(de-Broglie wavelength, $\lambda = \frac{h}{p}$)

Key Formulae

➢ The de-Broglie wavelength of the neutron having kinetic energy K electron volt is given by

$$\lambda_n = \frac{0.286}{\sqrt{K}}\ \text{Å}$$

➢ For same wavelength, the ratio of accelerating potential is as follows,

- $\frac{V_p}{V_\alpha} = \frac{m_\alpha q_\alpha}{m_p q_p} = \frac{4\times2}{1\times1} = 8.$
- $\frac{V_p}{V_d} = \frac{m_d q_d}{m_p q_p} = \frac{2\times1}{1\times1} = 2.$
- $\frac{V_d}{V_\alpha} = \frac{m_\alpha q_\alpha}{m_d q_d} = \frac{4\times2}{2\times1} = 4.$

➢ $\frac{h}{2\pi} = 1.054 \times 10^{-34}$ Js

➢ Expression for the wavelength associated with charged particles accelerated through a potential difference V;

- Electron: $\lambda_e = \frac{12.27}{\sqrt{V}}$ Å
- Proton: $\lambda_p = \frac{0.286}{\sqrt{V}}$ Å
- Deuteron: $\lambda_\alpha = \frac{0.202}{\sqrt{V}}$ Å
- α-particle: $\lambda_\alpha = \frac{0.101}{\sqrt{V}}$ Å.

➢ The de-Broglie wavelength of a particle of mass m and kinetic energy K

$$\lambda = \frac{h}{V(2m\text{K})}$$

➢ If a particle of mass m is accelerated through potential V, then its de-Broglie wavelength

$$\lambda = \frac{h}{V(2mqV)}$$

UNIT – 8: ATOMS AND NUCLEI

CHAPTER-12

ATOMS

Concepts covered: Alpha particle scattering experiment, Rutherford's model of atom, Bohr's model, Hydrogen spectrum.

Revision Notes

- **Scattering of α-particles:** The scattering of α-particles from the thin metallic sheets was observed by Rutherford in 1906. He found that when a beam of α-particles was incident on a photographic plate, a sharp image was obtained. But, when the same beam passes through a thin metal foil, the image becomes diffused. He suggested that it happens, due to the scattering of α-particles.
  - In 1911, Rutherford successfully explained the scattering of α-particle on the basis of the nuclear model of an atom.
  - Number of α-particles scattered through angle θ is given by:

$$N(\theta) \propto \frac{Z^2}{\sin^4\left(\frac{\theta}{2}\right)K^2}$$

where, K is the kinetic energy of the α-particle and Z is the atomic number of the metal.

- **Rutherford's model of the atom:** Atom is a sphere of diameter about 10^{-10} m. The whole of its positive charge and most of its mass is concentrated in the central part, called the nucleus.
  - The space around the nucleus is virtually empty with electrons revolving around the nucleus in the same way as the planets revolve around the Sun.
  - The electrostatic attraction of the nucleus provides centripetal force to the orbiting electrons.
  - Total positive charge in the nucleus is equal to the total negative charge of the orbiting electrons.

Scan to know more about this topic

Rutherford's nuclear model of atom

- **Drawbacks of Rutherford's model of the atom:**
  - **Stability of the atom:** The electrons orbiting around the nucleus radiate energy. As a result, the radius of the orbit of the electron should continuously decrease and ultimately the electrons should fall into the nucleus. But it does not happen. Atom has a stable structure.
  - **Nature of energy spectrum:** According to Rutherford's model, the electrons can revolve around the nucleus in all possible orbits. Hence, the atom should emit radiations of all possible wavelengths. However, in practice, the atoms are found to have a line spectrum or discrete spectrum.
- **Bohr retained the following features of Rutherford's model:**
  - Atom consists of a positively charged nucleus around which electrons revolve in circular orbits.
  - Majority of the mass and whole of the positive charge of the atom is concentrated in the nucleus.
  - Size of the nucleus is very small as compared to the size of the atom.
- **Bohr's postulates:** Bohr added the following postulates to the Rutherford's model of the atom:
  - The electrons revolve around the nucleus only in certain permitted orbits, in which the angular momentum of the electron is an integral multiple of $h/2\pi$, where 'h' is the Planck's constant.
  - Electrons do not radiate energy while revolving in the permitted orbits i.e., the permitted **orbits are stationary,** non-radiating orbits.
  - The energy is radiated only when the electron jumps from an outer permitted orbit to some inner permitted orbit. (Absorption of energy take place when electron jumps from an inner orbit to the outer orbit).

Scan to know more about this topic

Bohr's Model of atom

  - If the energy of the electron in n^{th} and m^{th} orbits be E_n and E_m respectively, then when the electron jumps from n^{th} to m^{th} orbit the radiation frequency ν is emitted, such that:

$$E_n - E_m = h\nu.$$

  This is called Bohr's frequency equation.

- The diagrammatic description of the energy of the electron in different orbits around the nucleus is called the energy level diagram.
  The energy of the orbital electron in the n^{th} orbit is given by:

$$E_n = -\frac{13.6}{n^2}\text{eV}$$

$$E_2 = -\frac{13.6}{2^2}\text{eV} = -3.4 \text{ eV}$$

$$E_3 = -\frac{13.6}{3^2}\text{eV} = -1.51 \text{ eV}$$

and
$$E_\infty = -\frac{13.6}{\infty^2} = 0$$

  As n increases, E_n decreases. So that when n is large, the values of E_n for orbits become very-very close to each other.
- **Excitation Potential:** The potential through which an electron needs to be accelerated so that it acquires energy equal to the excitation energy is called **excitation potential**. If the excitation energy is 10.2 eV, then the excitation potential will be 10.2 V.
- **Ionisation potential:** The potential through which an electron needs to be accelerated so that it acquires energy equal to the excitation energy is called **excitation potential.** If the excitation energy is 10.2 ev, then the excitation potential will be 10.2V. The potential through which an electron needs to be accelerated so that it acquires energy equal to the ionisation energy is called ionisation potential.
  - For the Lyman series, $n_i = 1$ and $n_0 = 2, 3, 4.....$
    The wavelength of the radiation is given by,
    $$\frac{1}{\lambda} = R_H\left[\frac{1}{1^2} - \frac{1}{n_0^2}\right]$$
    These lie in the ultraviolet region.
  - The Balmer series of the radiations corresponds to $n_i = 2$ and $n_0 = 3, 4, 5, ...$ The wavelength of the radiation is given by,
    $$\frac{1}{\lambda} = R_H\left[\frac{1}{2^2} - \frac{1}{n_0^2}\right]$$
    These lie in the visible region.
  - For Paschen series, $n_i = 3$ and and $n_0 = 4, 5, 6.....$ The wavelength of the radiation is given by,
    $$\frac{1}{\lambda} = R_H\left[\frac{1}{3^2} - \frac{1}{n_0^2}\right]$$
    These lie in the infrared region.
  - For Brackett series, $n_i = 4$ and $n_0 = 5, 6, 7.....$
    The wavelength of the radiation is given by,
    $$\frac{1}{\lambda} = R_H\left[\frac{1}{4^2} - \frac{1}{n_0^2}\right]$$
    These lie in the far infrared region.
  - p-fund series of radiation corresponds to $n_i = 5$ and $n_0 = 6, 7, 8, 9.....$ The wavelength of the radiation is given by:
    $$\frac{1}{\lambda} = R_H\left[\frac{1}{5^2} - \frac{1}{n_0^2}\right]$$
    These lie in infrared region.
- The radius of n^{th} orbit of hydrogen is approximately $0{\cdot}53\ n^2\text{Å}$.
- The speed of an electron in the ground state of a hydrogen atom is $c/137$,
  where, c = speed of light in a vacuum.
- Observation of faint spectral line very near to the blue line of hydrogen spectrum leads to the discovery of deuterium.
- In the Bohr's model of the atom, an electron can revolve around the nucleus in a stable orbit without emitting radiations if its orbit has a whole number of de-Broglie waves.
- Rydberg constant is the same for different hydrogen-like atoms.
- The speed of the electron in the n^{th} orbit is $\frac{1}{n}\times\frac{c}{137}$,
  where, c = speed of light in vacuum.

- If the mass of the electron becomes n times the present value, the Rydberg constant will also become n times the present value.
- For the given value of the principal quantum number, the shape of the subshell depends on the azimuthal quantum number l. Also $l = 0, 1, 2, \ldots, (n-1)$.
- The total energy of the orbital electron is negative.
- Balmer series was the first to be discovered in the hydrogen spectrum.
- The quantization of the energy states of an atom was demonstrated by the Franck-Hertz experiment. This experiment demonstrated the existence of discrete energy levels in the atom.
- The binding energy of the electron in the ground state of hydrogen is called Rydberg.

$$1 \text{ Rydberg} = 13.6 \text{ eV.}$$

- Each state of the atom is quantized in regards to the size, shape, and orientation of the electron orbits.
- **Quantum numbers:**
  - Principal quantum number n is also called total quantum number.

$$E_n - E_m = h\nu$$
$$n = 1, 2, 3, \ldots \infty$$

  - It determines the general size, the velocity as well as the energy of the orbital electrons.

$$K \rightarrow n = 1$$
$$L \rightarrow n = 2$$
$$M \rightarrow n = 3$$
$$N \rightarrow n = 4$$

- From Bohr's theory of hydrogen atom, an electron can orbit around the nucleus indefinitely without radiating energy, provided the orbit is circular.
- The energy of the electron in the n^{th} orbit of the hydrogen-like atom is:

$$E_n = \frac{Z^2}{n^2} \times 13.6 \text{ eV}$$

- Bohr's theory assumes that the angular momentum of the orbital electron is quantized.
- Angular momentum of the electron in the n^{th} orbit of the hydrogen atom is

$$L = \frac{nk}{2x}.$$

- Ionisation potential for hydrogen is 13.6 eV.
- H_α line of every series is the longest and the series limit is the shortest.
- Ionisation energy $= 13.6\frac{Z^2}{n^2}$ eV.

Mnemonics

Concept : Series of Hydrogen spectra.
Mnemonics: (a) **L**eela **B**ought **P**astry for **B**abu and **P**apa.
Interpretation:
L : Lyman series for $n_i = 1$
B : Balmer series for $n_i = 2$
P : Paschen series for $n_i = 3$
B : Brackett series for $n_i = 4$
P : p-fund series for $n_i = 5$

(b) 1 is **U**nimportant, **2** is **v**ery important and **rest** are **I**mportant
Interpretation:
1 : $n_i = 1$ i.e., Lyman series
U : Ultraviolet range
2 : $n_i = 2$ i.e., Balmer Series.
V : Visible range
Rest : $n_i = 3, 4, 5$ i.e., Paschen, Brackett and p-fund series
I : Infrared range.

Key Formulae

- The orbital radius of the electron is: $r_n = 4\pi\varepsilon_0 \frac{n^2h^2}{4\pi^2 me^2}$
- The orbital velocity of electron is: $v_n = \frac{1}{4\pi\varepsilon_0} \cdot \frac{2\pi e^2}{nh}$

- Orbital frequency is given by, $$f = \frac{1}{T} = \frac{v}{2\pi r} = \frac{me^4}{4\varepsilon_0^2 n^3 h^3}$$
- The total energy of the orbital electron is, $$E = -\frac{me^4}{n^2h^2\varepsilon_0^2}$$
$$K.E. = -\frac{me^4}{8n^2h^2\varepsilon_0^2}$$
$$P.E. = -\frac{me^4}{4n^2h^2\varepsilon_0^2}$$
- The velocity of the orbital electron may be written as:
$$v_n = \frac{1}{4\pi\varepsilon_0}\left[\frac{2\pi e^2}{h}\right]\left(\frac{1}{n}\right)$$
- The kinetic, potential and total energies of the electron with r as the radius of the orbit are respectively:
$$K.E. = \frac{1}{2}\left[\frac{1}{4\pi\varepsilon_0}.\frac{Ze^2}{r}\right];\ P.E. = -\frac{1}{4\pi\varepsilon_0}.\frac{Ze^2}{r} \text{ and } E \propto -\frac{1}{2}\left[\frac{Z}{4\pi\varepsilon_0}\times\frac{e^2}{r}\right]$$
Therefore, they are related to each other as,
$$K.E. = -E \text{ and } P.E. = 2E.$$
- The energy of orbital electron in the n^{th} orbit is given by,
$$E_n = -\frac{13.6}{n^2}\text{ eV}$$
- Wavelength in each series: $$\frac{1}{\lambda} = \left[\frac{1}{n_i^2} - \frac{1}{n_f^2}\right]$$
- Impact parameter: $$= \frac{1}{4\pi\varepsilon_0}\frac{Ze^2\cot\frac{\theta}{2}}{E}$$

Key Terms

- **Impact parameter:** It is defined as the perpendicular distance of the velocity vector of the α-particle from the centre of the nucleus, when it is far away from the atom.
- **Stationary orbits:** While revolving in the permissible orbits, an electron does not radiate energy. These non-radiating orbits are called stationary orbits.
- **Excitation energy:** The excitation energy of an atom is defined as the energy required by its electrons to jump from the ground state to any one of the excited states.
- **Ionization energy:** It is defined as the energy required to knock an electron completely out of the atom.
- **Ionization potential:** It is that accelerating potential which gives to a bombarding electron, sufficient energy to ionise the target atom by knocking one of its electrons completely out of the atom.

CHAPTER-13

NUCLEI

Topic-1 Composition and Size of Nucleus

Concepts covered: Atomic Mass and Nuclear Density, Isotopes, Isobars and Isotones.

Revision Notes

- Composition of atomic nuclei includes protons and neutrons in which nucleus of hydrogen atom has only single proton.
- The charge on a proton inside nucleus is $+1.6 \times 10^{-19}$ C with mass as 1836 times of electron.
- Neutrons are uncharged particles with its mass slightly more than that of a proton.
- Neutrons and protons together are known as nucleons.
- The number of protons in nuclei of an element is similar to number of electrons in neutral atom of that element.
- All nuclei of a given element may not have similar number of neutrons.
- The size of nucleus was estimated initially through Rutherford scattering experiment where incident alpha particles on deflection by target nucleus having distance not exceeding 1014 m were shown.
- If R is nuclear radius, relationship between R and A is $R = R_0A^{1/3}$ where $R_0 \cong 1.2 \times 10^{-15}$ m $\cong$ 1.2 fm and is known as nuclear radius parameter.
  Density of nucleus is approximately 2.3×10^{17} kg m^{-3}
- **Isotopes:** The atoms of an element having the same atomic number (Z) but a different mass number (A) are called isotopes. They are the nuclei of the same element having a different number of neutrons but the same number of protons. Their chemical properties are similar but they differ in physical properties such as mass. Examples of isotopes are:
  - ${}_1H^1, {}_1H^2, {}_1H^3$
  - ${}_8O^{16}, {}_8O^{17}, {}_8O^{18}$
  - ${}_{17}Cl^{35}, {}_{17}Cl^{37}$
  - ${}_{92}U^{235}, {}_{92}U^{238}$
- **Isobars:** The atoms having the same mass number but a different atomic number are called isobars. They are atoms of different elements. Examples of isobars are:
  - ${}_1H^3, {}_2He^3$
  - ${}_2Li^7, {}_4Be^7$
  - ${}_{18}Ar^{40}, {}_{20}Ca^{40}$
  - ${}_{32}Ge^{76}, {}_{34}Se^{76}$
- Atoms having the same number of neutrons are called **isotones**. Examples of isotones are:
  - ${}^{16}_{8}O, {}^{14}_{6}C, {}^{15}_{7}N$
  - ${}_7N^{17}, {}_8O^{18}, {}_9F^{19}$

Mnemonics

Concept : Number of protons & neutrons in isotope, isobar and isotone.
Mnemonics: Prakash **Tope**wala had a **T**utti-Frutti **bar,** played a nice **tone.**
Interpretation:
P : Protons are same
Tope : Isotope
T : Total number of protons & neutrons are same
bar : Isobar
N : Neutrons are same
tone : isotone
(Number of protons are same in isotopes.
Total number of protons & neutrons are same in isobars.
Number of neutrons are same in isotones.)

Topic-2 Binding Energy and Nuclear Reactions

Concepts covered: Mass energy relation, Mass defect, Binding energy per nucleon, Nuclear Reactions, Nuclear fission, Nuclear fusion.

Revision Notes

- Using Einstein's mass-energy relation ($E = mc^2$), the energy equivalent to a mass of 1 amu is given by:

$$1 \text{ amu} = 1.660565 \times 10^{-27} \times \frac{(2.9979 \times 10^8)^2}{1.6021892 \times 10^{-19}} \text{ eV}$$

$$= 931.486 \times 10^6 \text{ eV}$$

- Mass defect is the difference in the sum of the masses of the neutrons and protons in the nucleus and that of nucleus of ${}_ZX^A$. It has Z protons and (A – Z) neutrons. Suppose its mass is M. Let the mass of the neutron be m_n and that of proton be m_p, then the mass defect is given by

$$\Delta m = [Zm_p + (A - Z)m_n] - M$$

- The energy that keeps the neutrons and protons bound to the nucleus is called **binding energy**.
- If Δm be the mass defect of a nucleus, then its binding energy is given by Δmc^2,

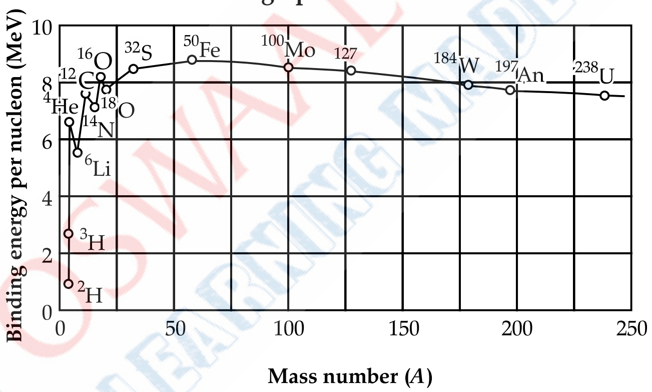
  where, c = speed of light.

  The binding energy may also be defined as the energy that needs to be supplied to the nucleus to split it into individual neutrons and protons.

Scan to know more about this topic

Binding Energy and Fission

- **Binding energy per nucleon vs. mass number graph:**



- Maximum and minimum binding energy per nucleon (E_{bn}) is 8.75 MeV for A= 56 and 7.6 MeV for A = 238.
- E_{bn} is lower for both light nuclei (A < 30) and heavy nuclei (A > 170).
- A very heavy nucleus, say A = 240, has lower binding energy per nucleon compared to that of a nucleus with A = 120. Thus if a nucleus A = 240 breaks into two A = 120 nuclei, nucleons get more tightly bound. This implies energy would be released in the process. Such process is known as fission.
- If two very light nuclei (A ≤ 10) join to form a heavier nucleus, the binding energy per nucleon of the fused heavier nuclel is more than the binding energy per nucleon of the lighter nuclei. This means that the final system is more tightly bound than the initial system. So, again energy would be released. Such a process is known as fusion.
- The process of splitting the heavy nucleus by bombarding it with neutron is called **fission**. The most commonly discussed fission is that of ${}_{92}U^{235}$. The process occurs as follows:

$${}_0n^1 + {}_{92}U^{235} \longrightarrow \left[{}_{92}U^{236}\right] \longrightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3{}_0n^1 + Q.$$

  So, when ${}_{92}U^{235}$, is bombarded with a neutron, the neutron enters the Uranium nucleus producing a compound nucleus ${}_{92}U^{236}$ which splits producing one atom each of Ba, Kr, and 3 neutrons. About 200 MeV energy is also released, i.e., Q = 200 MeV.

- Neutrons moving with a speed of about 2.2 kms^{-1} and having energy of the order of 0.025 eV are called thermal neutrons. They are so called because their velocity is of the same order as the velocity of the gas atoms at room temperature. Thus, thermal neutrons are slow moving neutrons.

- The combination of lighter nuclei to form a nucleus with the release of energy is called **fusion**. The simplest example is the fusion of Hydrogen atom to Helium which is as follows:

$$4\ {}_1H^1 \rightarrow {}_2He^4 + 2\ {}_{+1}e^0 + Q$$

$$4 \times \text{Hydrogen} \rightarrow \text{Helium} + 2\ \text{positron} + \text{energy}$$

Scan to know more about this topic

Nuclear Fusion

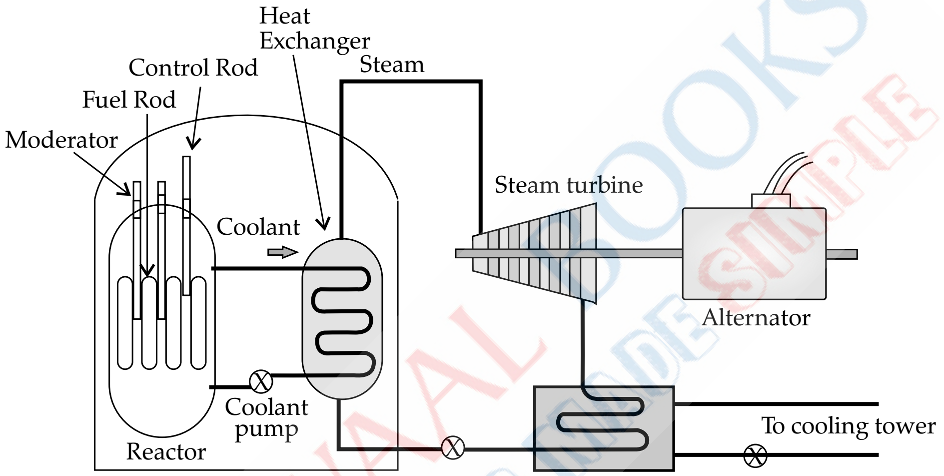
Similarly,

$${}_1H^2 + {}_1H^2 \rightarrow {}_2He^4 + Q$$
$${}_1H^2 + {}_1H^3 \rightarrow {}_2He^4 + {}_0n^1 + Q$$

- The protons cannot be kept bound to the nucleus by the gravitational force alone. It is found that another force called the nuclear force F_n, which is about 100 times greater than Coulomb's repulsive force keeps the nucleons together in the nucleus. Their relative values are:

$$F_g : F_e : F_n :: 1 : 10^{36} : 10^{38}.$$

- **Components of a nuclear reactor:**



  - **Fuel**
    Uranium is the basic fuel which undergoes fission.
  - **Moderator**
    Moderator slows down the neutrons released from fission so that they cause more fission. It is usually heavy water or graphite.
  - **Control rods**
    These are made with neutron-absorbing material such as cadmium, hafnium or boron and are inserted or withdrawn from the core to control the rate of reaction or to halt it.
  - **Coolant**
    Coolant is a fluid circulating through the core so as to extract the heat from it.
  - **Steam generator**
    Part of the cooling system which utilizes the heat extracted from the reactor to make steam for the turbine, in a secondary circuit.
- Enriched Uranium is better fuel for the reactor because it has a greater proportion of U^{235}.
- The percentage of mass which changes into energy during fission is of the order of 0·7%.
- In the fission of Uranium, the percentage of mass converted into energy is about 0·1%.
- Nucleons attract each other when they are separated by a distance of 10^{-14} m.
- A neutron can be added to or taken out of the nucleus of an atom without changing its chemical properties.
- Energy released in nuclear fission mostly appears as kinetic energy of the fission fragments.
- The mass of the Sun is decreasing at the rate of 4×10^9 per second.
- To produce an electron-positron pair, the energy of the γ-particle should be more than 1·02 MeV.

Key Terms

- **Moderator:** Any substance which is used to slow down fast-moving neutrons to thermal energies (≈ 0·0235 eV) is called a moderator.

- **Multiplication factor:** The multiplication factor of a fissionable mass is defined as the ratio of the number of neutrons present at the beginning of a particular generation to the number of neutrons present at the beginning of the previous generation.
- **Critical size:** The size of the fissionable material for which the multiplication factor $k = 1$ is called critical size and its mass is called critical mass.
- **Breeder reactors:** A breeder reactor is one that produces more fissionable nuclei than it consumes.

Mnemonics

Concept : Fission and Fusion process.
Mnemonics 1: **F**ishes are **s**upplied to **U**SA **f**rom **B**angladesh and **K**enya.
Interpretation:
F : Fission
s : splits
U : Uranium
f : to form
B : Barium
K : Krypton
(Fission splits Uranium to form Barium and Krypton)

Mnemonics 2: **F**arookh bought **u**ltra **H**i-**F**i **H**D TV.
Interpretation:
F : Fusion
u : unites
H : Hydrogen
F : To form
H : Helium
(Fusion unites Hydrogen to form Helium.)

❑❑

UNIT – 9: ELECTRONIC DEVICES

CHAPTER-14

ELECTRONIC DEVICES

Topic-1 Energy Bands

Concepts covered: Energy bands, Semiconductors and insulators, Intrinsic and extrinsic semiconductors.

Revision Notes

- A pure semiconductor is called an intrinsic semiconductor. To raise the electric conductivity, generally, the semiconductors are doped with either pentavalent impurity such as antimony (Sb), arsenic (As), or trivalent impurity such as indium (In), gallium (Ga). The process is called doping. The semiconductor is called an extrinsic semiconductor.
- The electrons and holes in the intrinsic semiconductors are called intrinsic charge carriers. Those generated in the extrinsic semiconductors are called extrinsic charge carriers.
- When we dope a semiconductor with a pentavalent impurity such as antimony (Sb) or arsenic (As), the extrinsic semiconductor so obtained is known as n-type.

  It has a large number of free electrons, which are known as majority (charge) carriers, the number of holes is small and they are known as minority (charge) carriers.
- The impurity atom in the n-type semiconductor is called a donor. The donor impurity atoms generate a new energy level just below the conduction band.

Scan to know more about this topic
Extrinsic semiconductors

- When we dope a semiconductor with a trivalent impurity such as indium (In), or gallium (Ga), the extrinsic semiconductor so obtained is known as *p*-type.

  It has a large number of holes, which are known as majority (charge) carriers. The number of free electrons is small and they are the minority (charge) carriers.
- The acceptor impurity atom in the *p*-type semiconductor is known as the acceptor atom.
- The presence of the impurity atoms generates a new energy level just above the valence band.
- At higher temperatures, the conductivity of the semiconductor increases because of the increase in the number density of the charge carriers.
- The number of free electrons in a semiconductor varies with temperature as $T^{3/2}$.
- The conductivity of a semiconductor is given by,

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

- Electron mobility is higher than that of the holes.
- The mobility of electrons as well as of holes in the semiconductor decreases with the increase in temperature but it is independent of the number density of the electrons or holes.
- As the temperature rises, many electrons from the valence band jump to the conduction band and then vacancies are created in the valence band. Each vacancy is known as a **hole**. As the sample is electrically neutral, the number of free electrons in the conduction band is equal to the number of holes in the valence band.
- At absolute zero, the semiconductor behaves as a perfect insulator.
- The doping of semiconductors with a small amount of impurity, drastically increases the conductivity.
- At low temperatures, the free electrons are present in the valence band of the semiconductor. As the temperature rises, electrons cross over to the conduction band.
- Let n_e = Number density of free electrons in the condition band, n_h = Number density of holes in the valence band, n_i = Number density of the intrinsic charge carriers.

  For intrinsic semiconductors: $n_e = n_h = n_i$

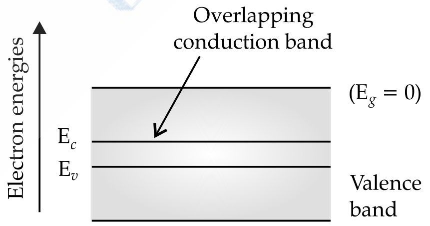
  For doped semiconductor: $n_e \times n_h = n_i^2$

  For *n*-type semiconductor: $n_e >> n_h$

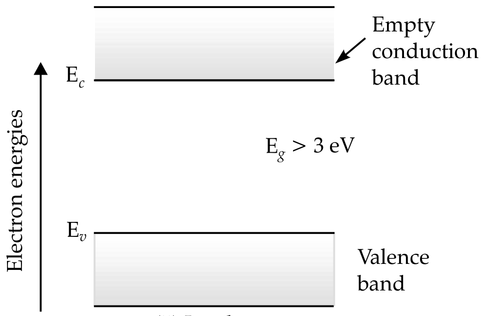
  For *p*-type semiconductor: $n_e << n_h$.
- **Valance and conduction band:** The energy band which includes the energy levels of the valence electrons is called the valence band. The energy band above the valence band is called the conduction band.
- **Forbidden energy band:** The gap between the conduction band and the valence band is known as forbidden energy band where no electron can stay.
- **Energy band diagram for metal insulator and semiconductor:**

Scan to know more about this topic

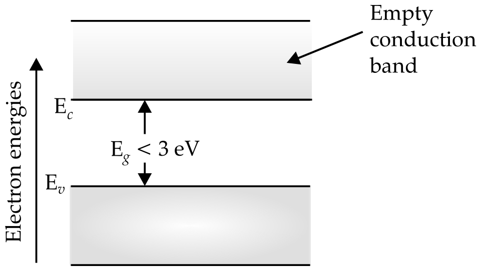
Energy band Theory



(i) Conductors



(ii) Insulators



(iii) Semiconductors

Key Terms

- **Valence band:** The highest energy band filled with valence electrons is called the valence band.
- **Conduction band:** The lowest unfilled allowed energy band next to the valence band is called the conduction band.
- **Fermi energy:** The highest energy level in the conduction band filled up with electrons at absolute zero is called Fermi level and the energy corresponding to the Fermi level is called Fermi energy.

Topic-2

Semiconductor Diodes and their Applications

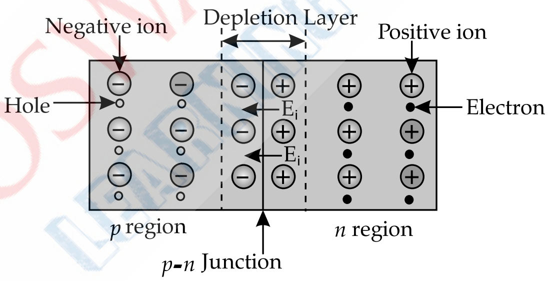
Concepts covered: Semiconductor diode, I-V characteristics in forward and reverse bias, Diode as a rectifier; Special types of junction diodes: LED, Photodiode, Solar cell.

Revision Notes

- The electronic device consisting of a *p-n* junction is called a **diode**. It has two terminals. One is anode and the other is cathode. The terminal connected to the *p*-type crystal is called anode and that connected to the *n*-type crystal is called cathode.
  - Potential difference created across the *p-n* junction due to the diffusion of electrons and holes is called the potential barrier.
  - The potential barrier across a germanium *p-n* junction is about 0.3 V and that across the silicon p-n junction is about 0.7 V.
  - A thin layer on both sides of the *p-n* junction which is devoid of the majority charge carriers is called depletion layer of thickness 10^{-6} m.

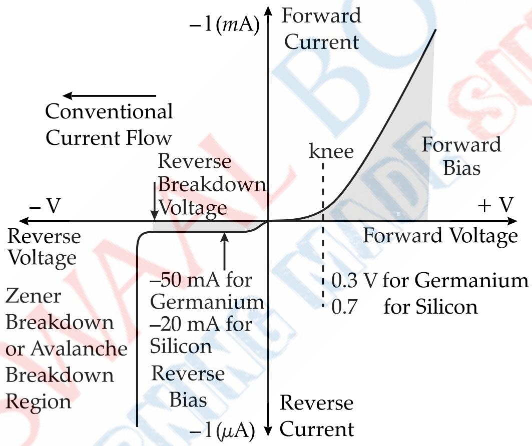
Scan to know more about this topic

Formation and properties of Junction Diode

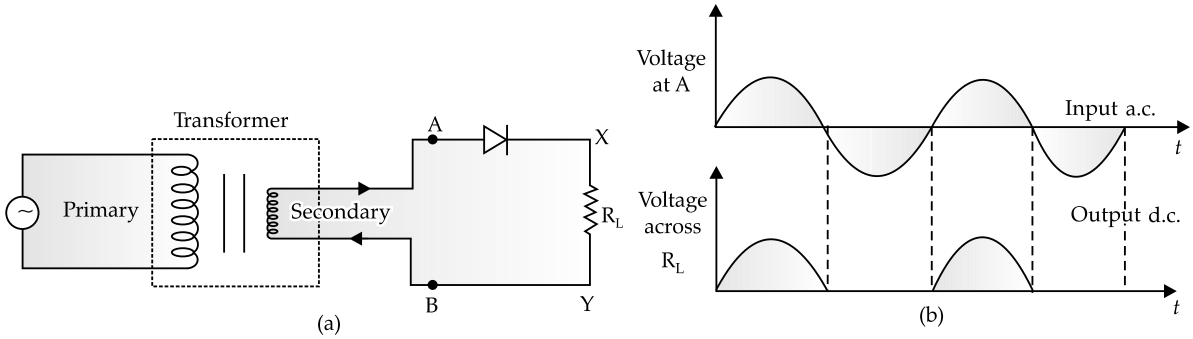


  - The knee potential does not depend on the current through the junction.
  - Semiconductor devices are current-controlled devices.
  - The semiconductor devices are temperature-sensitive devices.
  - The electric field due to potential barrier across the junction is of the order of 5 × 105 V/m.
  - Both *n*, as well as *p*-type semiconductors, are neutral.
  - The output of the rectifier is d.c. mixed with a.c.
  - The diode converts a.c. to d.c. during both half cycles of a.c., produces an output of a full-wave rectifier.
  - The *p-n* junction can be presumed as a capacitor, in which the depletion layer acts as a dielectric.
  - After the breakdown, the reverse current does not depend on the reverse voltage.
- **Rectifier:** The process of converting alternating current into the direct current is called rectification and the device used for this process is called a rectifier.
- **Dynamic resistance:** The dynamic or a.c. resistance of a diode is the ratio of small change in applied voltage ΔV to the corresponding change in current ΔI.
- **Depletion region:** The small region in the vicinity of the junction which is depleted of free charge carriers and has only immobile ions is called the depletion region.

- **Characteristics of Diode**
  - Diodes are two terminal devices like resistors and capacitors.
  - In diodes, the current is not linearly related to voltage, like in a resistor.
  - Diodes only consume power and do not produce power like battery and hence those are called passive devices.
- **I – V characteristics of diode in forward and reverse bias**
  - When positive and negative terminals of an external battery are connected to anode and cathode of a diode, the diode is said to be forward biased.
  - In forward bias, the depletion layers shrinks and large current flows due to majority carriers crossing the junction.
  - Forward current in *p–n* junction diode starts increasing strongly after knee point.
  - Using forward bias to *p-n* junction diode results in low impedance path (ideally 0) for junction diode.
  - When positive and negative terminals of an external battery are connected to cathode and anode of a diode, the diode is said to be reverse biased.
  - In reverse bias, the depletion layers widens and very little current, known as reverse saturation current, flows in reverse direction due to minority carriers crossing the junction.
  - Using reverse bias to *p-n* junction diode results in high impedance path (ideally ∞) for junction diode.

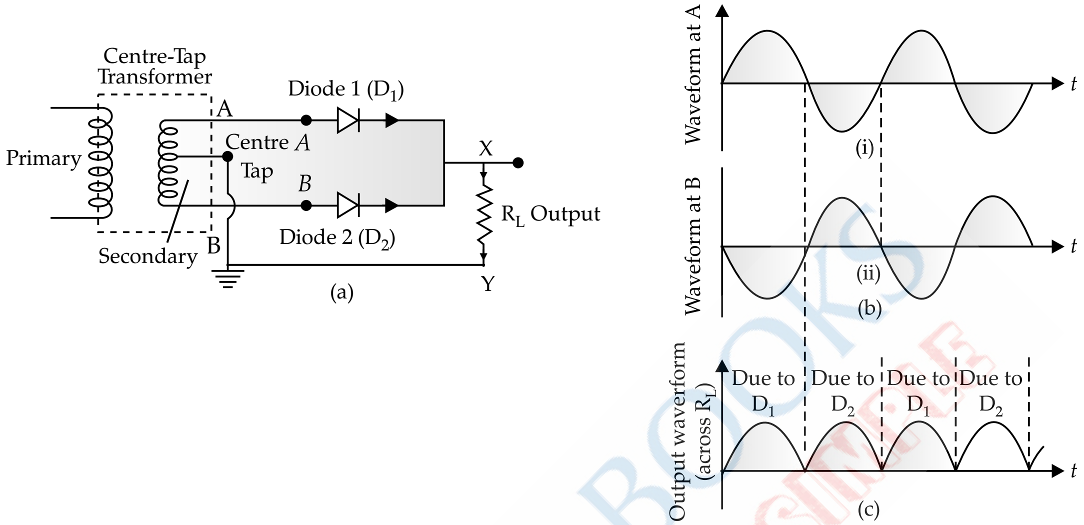


  - Beyond certain reverse voltage, diode breaks down with Avalanche breakdown mechanism or Zener breakdown mechanism and a large reverse current flows.
- **Diode as a Rectifier**
  - Rectifier is a circuit which converts a.c. supply into unidirectional d.c. supply.
- **Half wave Rectifier**
  - Single diode is used to rectify only one half cycle of a complete half cycle.
  - For positive half cycle the diode is forward biased, it conducts and a voltage drop appears across the load resistance.
  - For negative half cycle the diode is reverse biased and does not conduct. The voltage drop across the load is now zero. So, voltage waveform over the load resistor shows positive side of sinusoidal cycle while clamping off negative side of sinusoidal cycle.



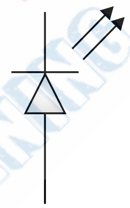
➢ **Full wave Rectifier:**

- To rectify a.c. for both half cycles, a center tap transformer with two diodes are used.
- During positive half–cycle, only the diode D_1 conducts while D_2 does not conduct. During negative half–cycle, only the diode D_2 conducts while D_1 does not conduct. So, rectified output is available for both the half–cycles.



➢ **Types of diodes:**

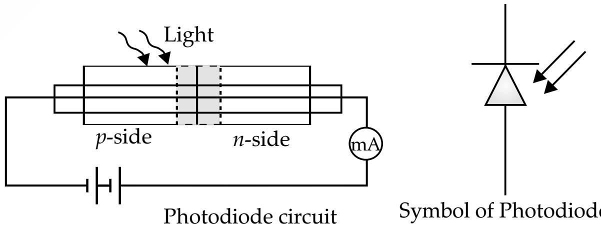
- **Light emitting diodes (LED):** These are the specially designed diodes, which give out light radiations when forward biased. LED's are made of special semiconductors such as gallium arsenic phosphide (GaAsP), gallium phosphide (GaP), etc.



Light emitting diode

- **Photodiode:** These are *p-n* diodes, in which electron and hole pairs are created by junction photoelectric effect i.e., the covalent bonds are broken by the radiations (light) absorbed by the electrons in the valence band.

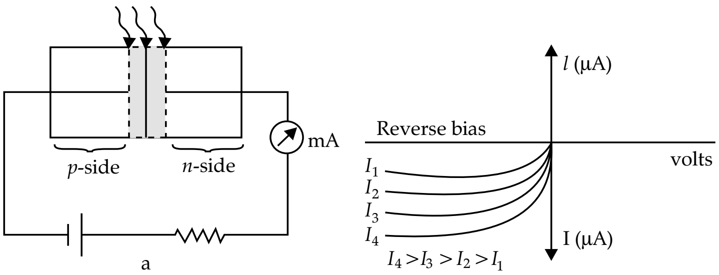
  The photodiode can be used for detecting light signals.



Photodiode circuit   Symbol of Photodiode

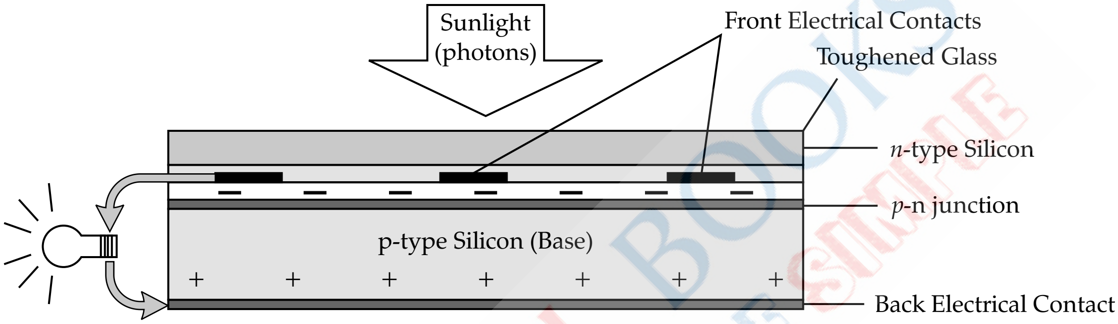
Photodiode circuit

- **I-V characteristics of a reverse biased illuminated photodiode for different illumination intensity $I_4 > I_3 > I_2 > I_1$.**

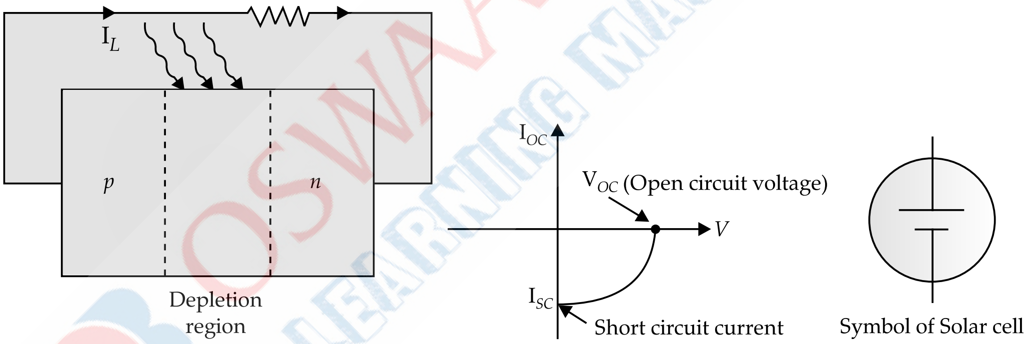


(a) **(b)**

- **Solar cells:** It is based on the photovoltaic effect. One of the semiconductor regions is made so thin that the light incident on it reaches the *p-n* junction and gets absorbed. This generates potential difference across the junction. It converts solar energy into electrical energy.



- **I-V characteristics of an illuminated solar cell:**



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