Module 3

CO3 – Convert Galvanometer into ammeter and voltmeter

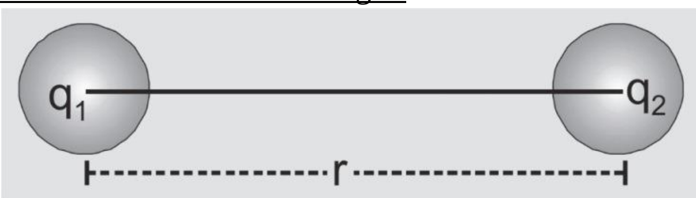
M3.01 – Explain Coulomb's law, Electric field, Electric potential etc.

Electric Charge (q)

- Electric charge is the physical property of matter that causes it to experience a force when placed in an electromagnetic field.
- There are two types of charges – Positive charge and Negative charge.
- The force between a positive charge and a negative charge is attractive.
- The force between two positive charges or two negative charges is repulsive.
- The SI unit of charge is Coulomb (C).
- The smallest or the elementary charge is the charge of an electron or a proton and its value is 1.6×10^{-19} C
- All charges are integral multiples of the elementary charge

Coulomb's law

- Coulomb's law states that the force of interaction between two electric charges is directly proportional to the product of the charges and inversely proportional to the square of the distance between the two charges.



- According to Coulomb's law, the electrostatic force between the charges q_1 and q_2 separated by a distance 'r' is given by,

$$F \propto q_1 q_2 \text{ and } F \propto \frac{1}{r^2}$$

$$F \propto \frac{q_1 q_2}{r^2}$$

$$F = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r^2}$$

- $\frac{1}{4\pi\epsilon_0}$ is the constant of proportionality, where ϵ_0 is the permittivity of free space
- $\epsilon_0 = 8.85 \times 10^{-12}\ C^2 N^{-1} m^{-2}$

Electric Field (E)

- The region around a charged particle within which another charge experiences an electric force is called electric field.
- If a charge q experiences a force F when placed at a point in an electric field, then the electric field intensity (E) at that point is defined as,

$$E = \frac{F}{q}$$

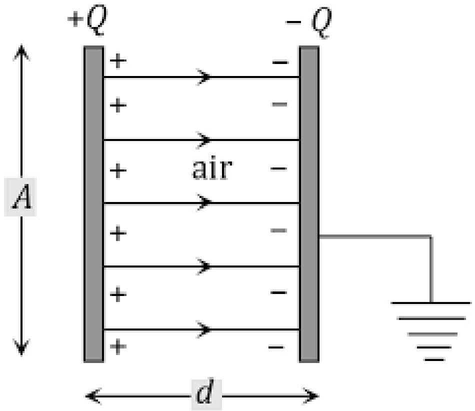
- SI unit of electric field intensity is N/C

Electric Potential

- The electric potential at a point in an electric field is defined as the work done in moving a unit positive charge from infinity to that point.
- The unit of electric potential is volt (V).
- The difference in electric potential between two points is called the potential difference or voltage between the two points.
- Electric charges always flow from higher potential to lower potential.

Capacitor

- Capacitor is a system of two conductors placed close to each other with an insulating medium in between them.
- One of the conductor is given a positive charge (+Q) and the other conductor is given an equal negative charge (-Q).
- The potential difference between positively charged conductor and the negatively charged conductor is called potential of the capacitor (V).



- For a given capacitor, the charge Q on the capacitor is proportional to the potential difference V between the two conductors.

$$Q \propto V$$
$$Q = CV$$

- The proportionality constant C is called the capacitance of the capacitor.
- The capacitance of a capacitor is the measure of how much charge a capacitor can store.
- The capacitance C of a capacitor depends on the shape, size, separation between the conductors and the nature of the insulating medium between the conductors.
- The SI unit of capacitance is farad (F).
  1 farad = 1 coulomb/volt
  1 microfarad = 10^{-6} farad
  1 picofarad = 10^{-12} farad

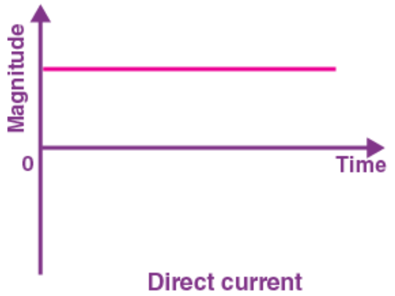
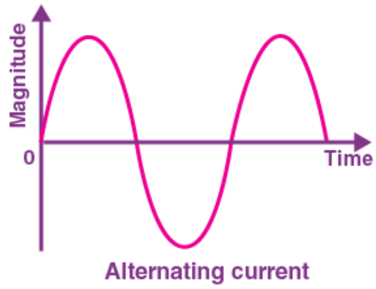
Electric Current

- The rate of flow of charges is called electric current.
- If q is the quantity of charge flows across an area in t seconds, then electric current (I) is given by,

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

- The SI unit of electric current is Ampere (A).

Distinguish between Direct current (DC) and Alternating current (AC)

Direct Current (DC)	Alternating Current (AC)
The current whose direction and magnitude remains constant is called direct current or DC.	The current whose direction and magnitude changes with time is called Alternating current or AC.
The frequency of DC supply is zero	The frequency of AC supply in India is 50 Hz
Obtained from Cell or Battery	Obtained from AC generator
	

M3.02 - Discuss Ohm's law and apply it to calculate the effective resistance in electrical circuits

Ohm's Law

- Ohm's law states that, at constant temperature, the current (I) flowing through a conductor is directly proportional to the potential difference (V) across its ends.

$$I \propto V$$
$$V \propto I$$
$$V = IR$$

- The constant R is called the resistance of the conductor.
- The resistance represents the opposition offered by the conductor to the flow of current through it.
- Unit of Resistance is ohm (Ω).

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

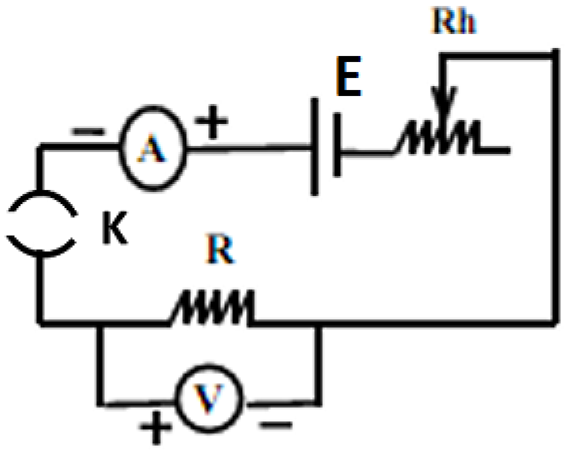
- For a good conductor, the value of resistance is low.
- The reciprocal of resistance is called conductance (S).
- The SI unit of conductance is ohm^{-1} (mho)

$$S = \frac{1}{R} = \frac{I}{V}$$

Verification of Ohm's Law

- Ohm's law can be verified using the circuit shown below.
- A conducting wire of resistance R is connected to a cell of emf E through a key K and rheostat Rh.

- The ammeter A measures the current through the circuit and the voltmeter V measures the potential difference across the resistance R.
- When the key K is closed, current flows through the circuit.
- The rheostat is adjusted to get a particular value of potential difference across the resistance. The corresponding ammeter reading is also noted. This process is repeated to get the value of current for different potential differences.
- In each case the ratio of V/I is calculated and found to be constant. This constant value gives the resistance R of the conductor.



Specific Resistance or Resistivity (ρ)

- The resistance (R) of a conductor is directly proportional to the length of the conductor (L).

$$R \propto L$$

- The resistance of a conductor (R) is inversely proportional to the area of cross section of the conductor (A).

$$R \propto \frac{1}{A}$$

$$R \propto \frac{L}{A}$$

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

- The proportionality constant 'ρ' is called the specific resistance or resistivity of the material of the conductor.

$$\rho = \frac{RA}{L}$$

- The resistivity of a material is a measure of how strongly a material opposes the flow of electrical current.
- The unit of Specific resistance or Resistivity is ohm m (Ωm).

Specific conductance or Conductivity (σ)

- The reciprocal of specific resistance or Resistivity (ρ) is called the specific conductance or conductivity (σ) of a material.

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

$$\sigma = \frac{L}{RA}$$

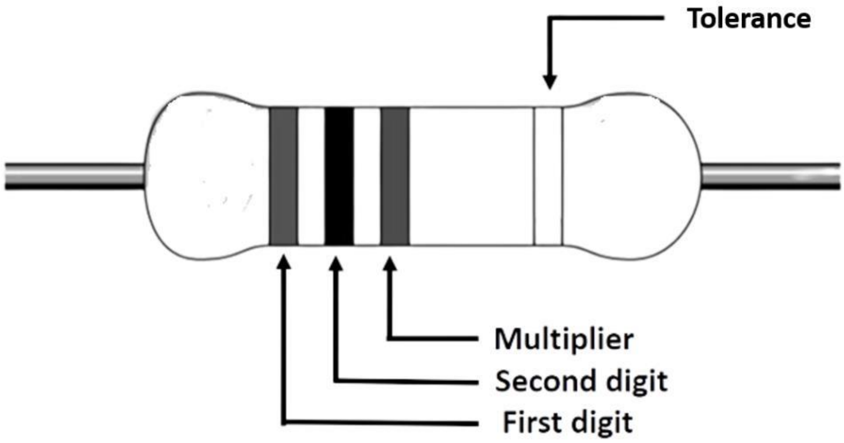
- The unit of specific conductance or Conductivity is ohm^{-1}m^{-1} (Ω^{-1}m^{-1})

Factors affecting the resistance of a conducting wire.

1	Material of the wire	Materials like silver, copper, aluminium has low resistance compared to other materials.
2	Length of the wire	Resistance increases with increase in length
3	Thickness or area of cross section of the wire	Resistance decreases with increase in thickness or area of cross section
4	Temperature	Resistance increases with increase in temperature

Carbon Resistors

- Resistors have extensive use in electrical and electronic circuits as voltage dividers, voltage droppers and to limit the passage of current through various parts of the circuits
- The most commonly used type of resistors are carbon resistors.
- Carbon resistors are made from a mixture of fine carbon fragments and a non-conducting ceramic powder.
- Carbon resistors are small in size and are inexpensive.
- Carbon resistors are cylindrical in shape with their resistance values are given using colour codes.



Resistance value of Carbon resistors using colour code

- There are four colour bands in a carbon Resistor
- The first two rings give the first two significant figures of the resistance value in ohms.
- The colour of the third ring indicates the decimal multiplier.
- The last ring represents the variation of the resistor value in percentage.
- To memorize the table **- B**.**B**. **ROY** of **G**reat **B**ritain had a **V**ery **G**ood **W**ife.

Letter as an aid to memory	Colour	Figure	Multiplier	Colour	Tolerance
B	Black	0	10^0	Gold	5%
B	Brown	1	10^1	Silver	10%
R	Red	2	10^2	No Colour	20%
O	Orange	3	10^3		
Y	Yellow	4	10^4		
G	Green	5	10^5		
B	Blue	6	10^6		
V	Violet	7	10^7		
G	Grey	8	10^8		
W	White	9	10^9		

Question

Find the value of carbon resistor with colour bands Yellow, Violet, Brown, Gold.

Answer

Yellow – 4

Violet – 7

Brown – 10^1

Gold - ± 5%

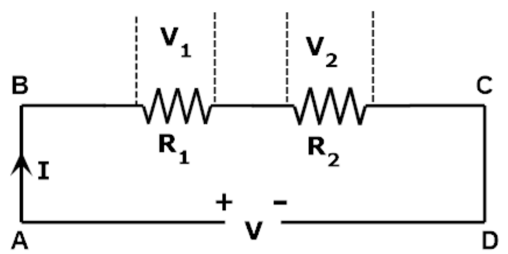
Resistance = $47 \times 10^1 \pm 5\%\ \Omega$

Series and Parallel combinations of resistors

- The combination of resistors can be classified into two types as (a) Series combination and (b) Parallel combination.
- The effective resistance or equivalent of a combination of resistors is that single resistance which produces the same effect of the combination of the resistances.

(a) Series Combination

- Consider two resistances R_1 and R_2 connected in series with a voltage V.



- In series connection, the current through the resistors are same but the voltage across the resistors are different.
- The total voltage, $V = V_1 + V_2$ -------- (1)
- If R_s is the effective resistance of the series combination, then according to Ohm's law

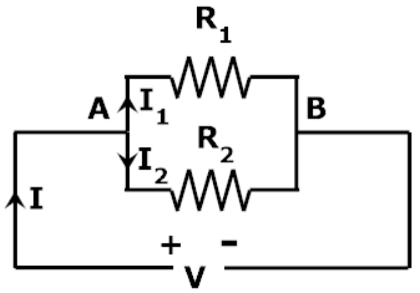
$$V = IR_s,\ V_1 = IR_1 \text{ and } V_2 = IR_2$$

- Substituting the voltages in Eqn (1)

$$IR_s = IR_1 + IR_2$$
$$IR_s = I(R_1 + R_2)$$
$$\mathbf{R_s = R_1 + R_2}$$

(b) Parallel Combination

- Consider two resistances R_1 and R_2 connected in parallel with a voltage V.



- In parallel connection, the voltage across the resistors are same but the current through the resistors are different.
- The total current $I = I_1 + I_2$-------- (1)
- If R_p is the effective resistance of the parallel combination, the according to Ohm's law

$$I = \frac{V}{R_p},\ I_1 = \frac{V}{R_1} \ \ and\ I_2 = \frac{V}{R_2}$$

- Substituting the currents in Eqn (1)

$$\frac{V}{R_p} = \frac{V}{R_1} + \frac{V}{R_2}$$
$$\frac{V}{R_p} = V\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$
$$\boldsymbol{\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2}}$$

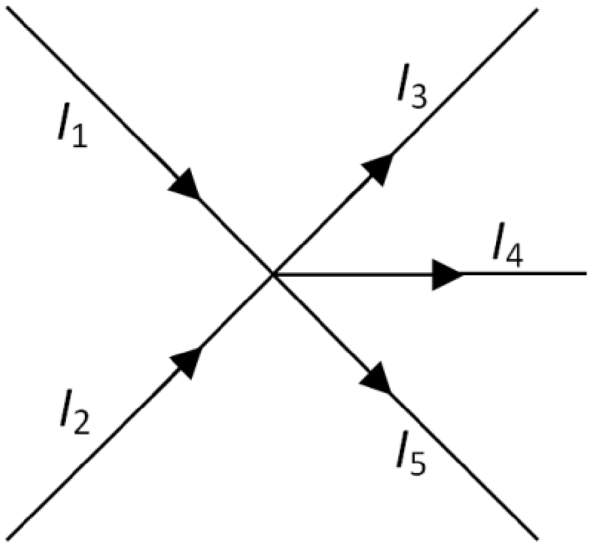
M3.03 - Apply Kirchhoff's laws to explain the working of a meter bridge

Kirchhoff's circuit laws

- There are two Kirchhoff's laws – Kirchhoff's first law (Junction rule) and Kirchhoff's second law (Loop rule)

Kirchhoff's first law (Junction rule)

- Kirchhoff's first law is a statement of law of conservation of charge
- Kirchhoff 's first law states that the algebraic sum of the currents meeting at a junction is zero.
- In other words, the total current entering a junction is equal to the total current leaving the junction.



- According the Kirchhoff's first law,

$$I_1 + I_2 - I_3 - I_4 - I_5 = 0$$

or

$$I_1 + I_2 = I_3 + I_4 + I_5$$

$$Total\ current\ entering\ the\ junction = Total\ current\ leaving\ the\ junction$$

Kirchhoff's second law (Loop rule)

- Kirchhoff's second law is a statement of law of conservation of Energy.
- Kirchhoff 's second law states that the algebraic sum of the potential differences around any closed loop in a circuit is zero.
- The potential difference across a resistance is taken positive when traversed in the direction of the current.
- The potential difference across a cell is taken positive when traversed from the positive terminal to negative terminal inside the cell.

Example:

- Applying Kirchhoff's second law for the loop PQRSTUP

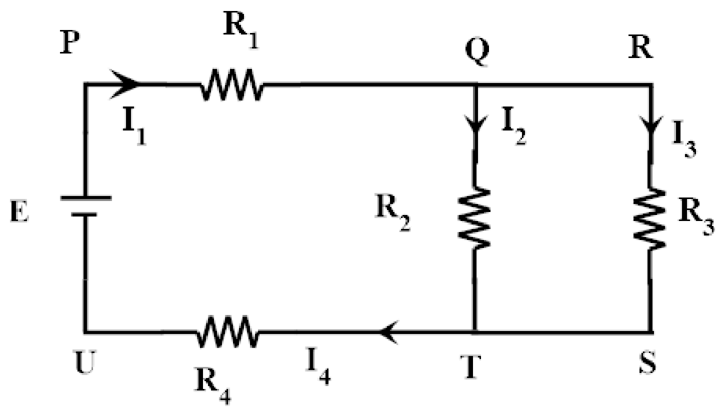
$$I_1R_1 + I_3R_3 + I_4R_4 - E = 0$$

- Applying Kirchhoff's second law for the loop PQTUP

$$I_1R_1 + I_2R_2 + I_4R_4 - E = 0$$

- Applying Kirchhoff's second law for the loop QRSTQ

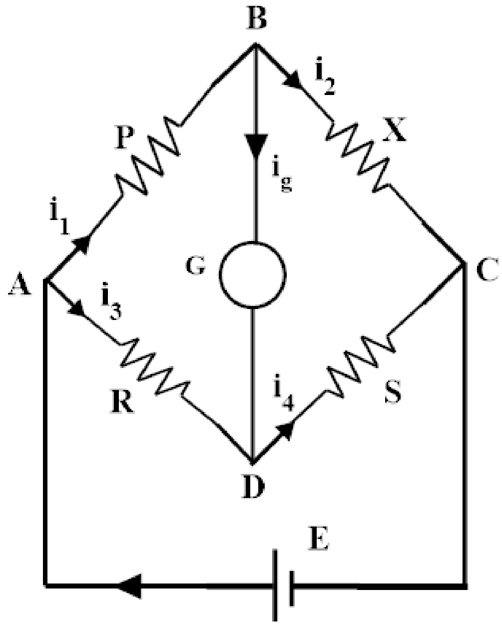
$$I_3R_3 - I_2R_2 = 0$$



Wheatstone's Bridge

- Wheatstone's bridge is a network of four resistances which can be used for the measurement of resistance.

Circuit diagram of Wheatstone's Bridge



Circuit Details

- Consider four resistances P, X (unknown), R and S connected in the form of a bridge.
- A cell of emf 'E' is connected between the terminals A and C.
- A galvanometer is connected between the terminals B and D.

Balancing Condition

- Applying Kirchhoff's junction rule at the Junction B
  $i_1 = i_2 + i_g$ -------- (1)
- Applying Kirchhoff's junction rule at the Junction B
  $i_3 + i_g = i_4$ -------- (2)
- Applying Kirchhoff's loop rule in the closed loop ABDA

$I_1P + I_gG - I_3R = 0$ -------- (3)

- Applying Kirchhoff's loop rule in the closed loop BCDB
  $I_2X - I_4S - I_gG = 0$ -------- (4)
- By varying the values of the resistances of the bridge, the current through the galvanometer can be made zero, $i_g = 0$. This condition is called the balanced condition of the bridge.
- Using balanced condition $i_g = 0$ in equation (1), (2), (3) and (4) we get,
  $i_1 = i_2$ -------- (5)
  $i_3 = i_4$ -------- (6)
  $I_1P = I_3R$ -------- (7)
  $I_2X = I_4S$ -------- (8)
- Dividing equations (7) by (8) and using equations (5) and (6)

$$\frac{I_1P}{I_2X} = \frac{I_3R}{I_4S}$$

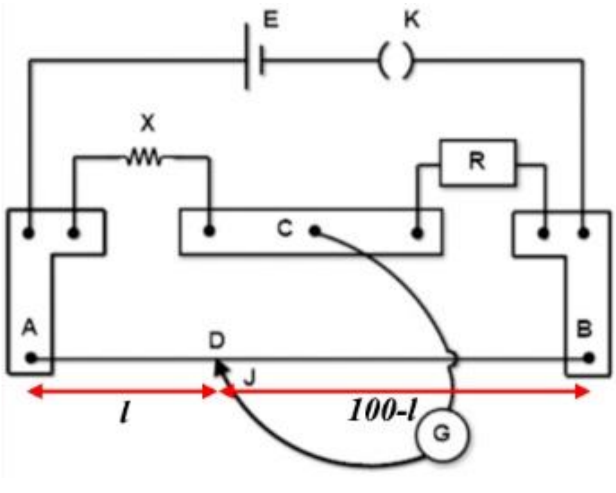
$$\frac{P}{X} = \frac{R}{S}$$

- This is the balancing condition of Wheatstone's bridge.
- Using the balancing condition, we can calculate the value of the unknown resistance 'X'.

Meter Bridge – Application of Wheatstone's bridge

- Meter bridge is a practical arrangement of Wheatstone's bridge used to measure unknown resistance.

Circuit diagram of Meter Bridge



Circuit details

- Meter bridge consist of a one meter long resistance wire fixed between the terminals A and B.
- A cell of emf E and a key are connected between the terminals A and B.
- A jockey is connected to the terminal 'C' through a galvanometer.

- The unknown resistance X is connected in the left gap and a known resistance R is connected in the right gap.

Principle

- Meter Bridge works on the principle of Wheatstone's Bridge
- If 'r' is the resistance per unit length of the resistance wire, at the balanced condition,

$$\frac{X}{R} = \frac{lr}{(100 - l)r}$$

$$X = \frac{Rl}{(100 - l)}$$

Procedure

- The key is closed.
- A suitable resistance is taken as the known resistance R.
- The jockey is moved from A towards B, until the galvanometer shows the zero deflection.
- The balancing length (AJ = l) is measured.
- Unknown resistance X is determined using the equation

$$X = \frac{Rl}{(100 - l)}$$

M3.04 - Discuss magnetic effect of electric current and apply it to explain the working of moving coil galvanometer, ammeter and voltmeter

Magnetic Field

- The region around a magnet or a moving charge within which another magnetic material or a moving charge experiences a magnetic force is called a magnetic field.
- Magnetic fields are represented using field lines.
- The number of field lines through a particular area represents the magnitude of the magnetic field.
- The SI unit of magnetic field is Newton/ (Ampere x metre). It is usually written as Tesla and abbreviated as T.

Magnetic Flux (Φ)

- Magnetic Flux (Φ) is the measure of total magnetic field passing through a given area.
- The magnetic flux (Φ) through an area A in a magnetic field is given by the expression

  $$\Phi = BA\cos\theta$$

  where θ is the angle between the direction of magnetic field and the perpendicular drawn to the area A.
- The SI unit of magnetic flux is weber (Wb).

Electromagnetic Induction

- The phenomenon in which electric current is generated in a circuit by varying magnetic fields is called electromagnetic induction.

Faraday's laws of electromagnetic induction

Faraday's first law of electromagnetic induction

- Faraday's first law states that whenever the magnetic flux associated with a circuit changes, an emf is induced in the circuit.

Faraday's second law of electromagnetic induction

- Faraday's second law states that the induced emf produced in the circuit is equal to the rate of change of magnetic flux through it.
- Induced emf is given by

$$E = \frac{d\Phi}{dt}$$

where Φ is the magnetic flux through the circuit.

Lorentz Force

- An electric charge q placed in an electric field experiences a force of magnitude qE in the direction of the field.
- In a magnetic field a moving charge q experiences a force of magnitude $qvB\sin\theta$, where v is the velocity of the charge, B is the magnetic field and θ is the angle between the magnetic field and direction of velocity.
- In the presence of both electric and magnetic fields, a moving charge experience both electric and magnetic force.
- The total force on the charge is the sum of electric and magnetic forces

$$F = F_{electric} + F_{magnetic} = qE + qvBsin\theta$$

- This total force is called Lorentz force.

Force on a current carrying conductor placed in a magnetic field

- The magnitude of the force acting on a current carrying conductor placed in an external magnetic field is given by the expression

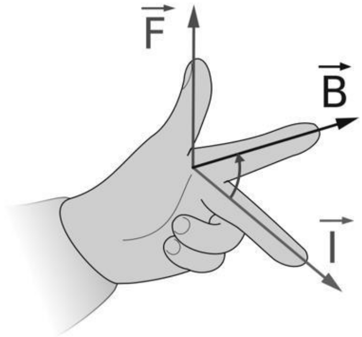
$$F = BiLsin\theta$$

where
B – Magnetic Field
i – Current through the conductor
L – Length of the conductor
θ – Angle between the direction of current and direction of magnetic field
- The direction of the force is perpendicular to both the direction of current and direction of magnetic field.

Fleming's Left hand rule.

- Fleming's left hand rule gives the direction of the force acting on a current carrying conductor placed in a magnetic field.

- Fleming's left hand rule states that if the thumb, forefinger and middle finger of the left hand are placed mutually at right angles, with the forefinger pointing in the direction of magnetic field and middle finger pointing in the direction of electric current, then the thumb gives the direction of the fore acting on the conductor,

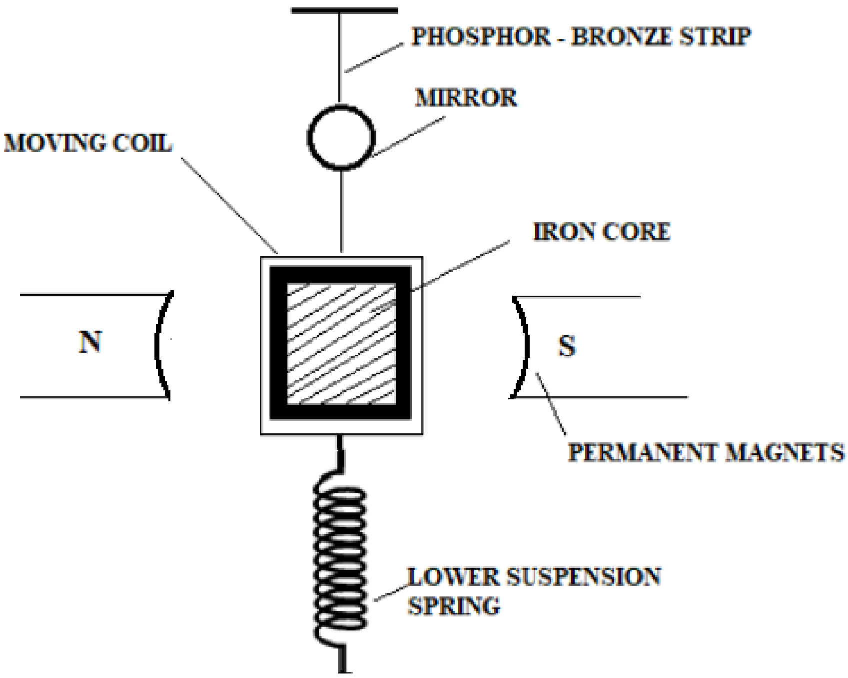


Moving Coil Galvanometer

- Moving coil galvanometer is used to detect the presence of small electric current and to give its direction.
- The moving coil galvanometer works on the principle that a current carrying conductor or coil placed in a magnetic field experiences a force.
- With simple modifications, it can be used to measure current and voltage.

Construction

- The galvanometer consists of a rectangular coil with many turns, suspended between the pole pieces of a magnet using a phosphor bronze wire.
- The pole pieces create a uniform radial magnetic field which is always parallel to the plane of the coil.
- A small mirror is attached to the suspension wire to measure the deflection of the coil.
- The current enters the coil through the suspension wire and leaves through the spring.



Principle and working

- When current flows through the coil, a torque acts on it.
- In the radial magnetic field maximum torque is experienced
- The torque, $\tau = NIAB$
  N – Number of turns in the coil
  I – Current flowing through the coil
  A – Area of the coil
  B – Magnetic field
- Because of this torque, the coil rotates, and then a restoring torque is developed in the spring.

$$\tau_{res} = C\theta$$

  C – Couple per unit twist
  θ – Angle of deflection
- At equilibrium, $C\theta = NIAB$

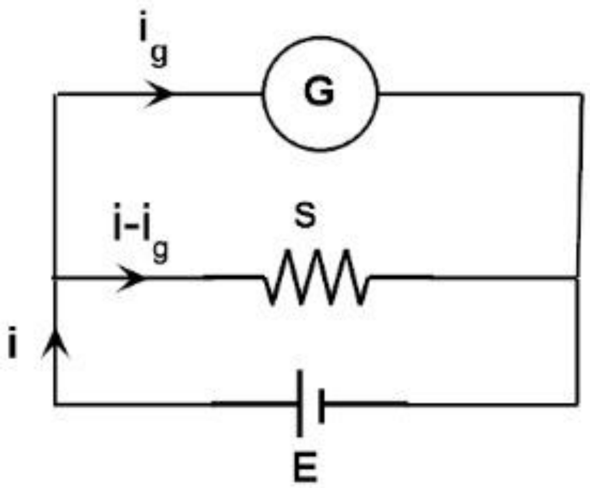
$$\theta = \frac{NIAB}{C} = \left(\frac{NAB}{C}\right) I = kI$$

  where k = $\left(\frac{NAB}{C}\right)$, us called the Galvanometer constant
  Therefore, $\theta \propto I$
- The angle of deflection θ is proportional to the current I
- The angle of deflection is measured using a lamp and scale arrangement.

Conversion of Galvanometer to Ammeter

- An ammeter is used to measure the value of current in a circuit.
- To use a galvanometer as an ammeter, a small resistance called shunt resistance is connected in parallel with the galvanometer

Circuit diagram



Equation for Shunt resistance (S)

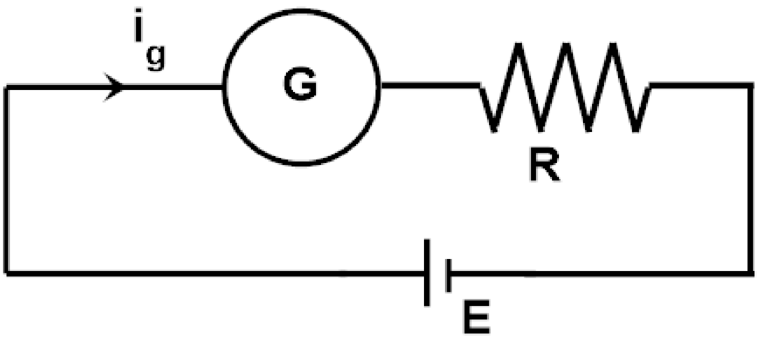
- The current to be measured is ‘i’.
- i_g is the current flowing through the Galvanometer with resistance G and ($i-i_g$) is the current flowing through the shunt resistance S

- Since the shunt resistance and Galvanometer are in parallel connection
Voltage across the shunt = Voltage across the galvanometer
$$(i - i_g)S = i_g G$$
- $The\ value\ of\ shunt\ resistance\ to\ be\ connected\ is\ S = \frac{i_g G}{(i - i_g)}$

Conversion of Galvanometer to Voltmeter

- Voltmeter measures the voltage across a given section of a circuit.
- <u>A galvanometer is converted into a voltmeter by a connecting a suitable high resistance in series with the galvanometer</u>

<u>Circuit diagram</u>



<u>Equation for Shunt resistance (S)</u>

- The voltage to be measured is 'E'.
- i_g is the current flowing through the Galvanometer with resistance G and the high resistance R
- Applying Kirchhoff's loop rule in the circuit
$$i_g G + i_g R = E$$
$$i_g(G + R) = E$$
$$G + R = \frac{E}{i_g}$$
The value of high resistance to be connected is $R = \frac{E}{i_g} - G$

Example 3.1

A wire of length 2 m and radius 0.1 mm has a resistance of 200 Ω. Find the specific resistance of the material.

Solution:

Given, L = 2 m , R = 200 Ω r = 0.1 mm = 0.1×10^{-3} m

Specific resistance = ρ $= \frac{\text{R A}}{\text{L}} = \frac{\text{R X π r}^2}{\text{L}}$

$= \frac{200\ X\ 3.14\ X(0.1\ X\ 10^{-3})\ 2}{2}$

$= 3.14 \times 10^{-6}$ Ωm

Example 3.2

Calculate the length of copper wire of cross-sectional area 0.01 mm^2 required to make a resistance of 3 Ω. Resistivity of copper = 1.7×10^{-8} Ωm.

Solution:

Given ρ = 1.7×10^{-8} Ωm

A = 0.01 mm^2 = 0.01×10^{-6} m^2 R = 3 Ω

Specific resistance = ρ $= \frac{\text{R A}}{\text{L}}$

$$L = \frac{R\ A}{\rho} = \frac{3\ X\ 0.01\ X\ 10^{-6}}{1.7\ X\ 10^{-8}} = 1.76\text{ m}$$

Example 3.3

A wire of resistance 50 Ω is recast into a wire of length double that of the original. What is the new resistance of the wire?

Solution:

Specific resistance = ρ $= \frac{\text{R A}}{\text{L}}$

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

For the Original wire, $R = \frac{\rho L}{A} = 50\ \Omega$

New length L’ = 2L

Since the volume (Area of cross section × Length) remains constant,

A’ L’ = A L

New area, $A' = \frac{A\,L}{L'} = \frac{A\,L}{2L} = \frac{A}{2}$

New resistance, $R' = \frac{\rho L'}{A'} = \frac{\rho\ 2L}{\frac{A}{2}} = 4 \text{ X } \frac{\rho L}{A'} = 4 \text{ x } 50 = 200\ \Omega$

Example 3.4

Two resistances 12 Ω and 6 Ω are connected in parallel and the combination is connected in series with an 8 Ω resistance. Find the effective resistance.

Solution:

The effective resistance of 12 Ω and 6 Ω in parallel is:

$$R_p = \frac{R_1\ R_2}{R_1 + R_2} = \frac{12\ X\ 6}{12 + 6} = 4\ \Omega$$

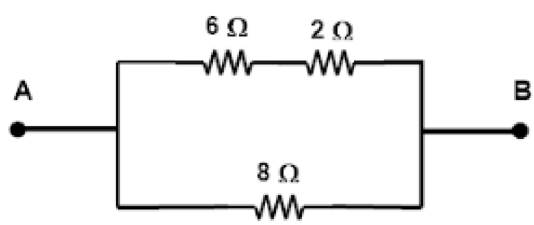
This 4 Ω is in series with the 8 Ω resistance.

Therefore, the effective resistance of the total combination,

$$R_{eff} = 4\ \Omega + 8\ \Omega = 12\ \Omega$$

Example 3.5

Find the effective resistance of the combination as measured across the terminals AB.



Solution:

The The 6Ω and 2Ω are in series. The effective resistance of this combination is:

$$R_S = 6\ \Omega + 2\ \Omega = 8\ \Omega$$

This 8 Ω resistance is parallel to 8Ω resistance.

Therefore, The effective resistance across the terminals AB:

$$R_{eff} = \frac{8 \times 8}{8+8} = 4\ \Omega$$

Example 3.6

Find the current I and the voltage across each resistance.

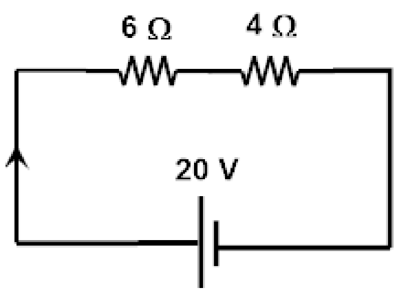
Solution:

The effective resistance of the combination is Reff = 6 Ω +4 Ω = 10 Ω

From Ohm's law V =IR

$$\text{Current}, I = \frac{V}{R} = \frac{20}{10} = 2\ A$$

The value of current through each resistance is 2A. Using Ohm's law,



Voltage drop across 6 Ω, $V_1 = 2 \times 6 = 12$ V

Voltage drop across 4 Ω, $V_2 = 2 \times 4 = 8$V

Example 3.7

A galvanometer has a 100 Ω and shows full scale deflection for 10 mA.

How can it be connectedto an ammeter of range 0 to 5 A?

Solution:

Given, G = 100 Ω

I_g = 10 mA =10 x 10^{-3} A i= 5 A

$$S = \frac{i_g\, G}{i - i_g} = \frac{10 \times 10^{-3} \times 100}{5 - 10 \times 10^{-3}} = 0.2\ \Omega$$

The given galvanometer can be converted into ammeter of range 0 to 5 A by connecting aresistance of 0.2 Ω in parallel with the galvanometer.

Example 3.8

A galvanometer of resistance 30 Ω shows full scale deflection for a current of 10 mA. How willyou connect it into a voltmeter of range 0 to 12 V?

Solution:

Given, G = 30 Ω   E = 12 V i_g = 10 mA = $10 X 10^{-3}$ A

$$R = \frac{E}{i_g} - G = \frac{12}{10 x 10^{-3}} - 30$$

$$= 1170\ \Omega$$

The galvanometer is converted into voltmeter by connecting a resistance 1170 Ω in series with it.

Example 3.9

Design a voltmeter of range 0 to 10 V. Given a galvanometer of resistance 50 Ω which shows fullscale deflection for 10 mA.

Solution:

Given, G = 50 Ω   E = 10 V   ig = 10 mA = 10×10^{-3} A

$$R = \frac{E}{i_g} - G = \frac{10}{10 x 10^{-3}} - 50$$

$$= 950\ \Omega$$

The voltmeter is made by connecting a resistance 950Ω in series with the given galvanometer.

Module 4

CO4 – Explain the basic principles of semiconductor physics, photoelectric effect, LASER action and nanoscience

M4.01 – Discuss the basic principles of semiconductor devices such as diodes and transistors.

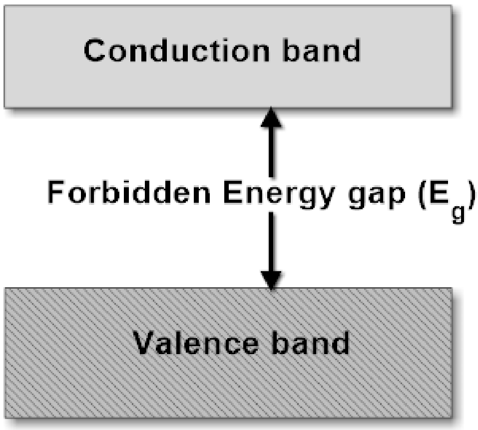
Electron volt (eV)

- Electron volt is a unit of energy used in solid state, atomic, nuclear and particle physics
- It is the energy gained by an electron when accelerated through a potential difference of one volt.

$$1\ eV = 1.6 \times 10^{-19}\ J$$

Energy Bands in Solids

- The range of energy possessed by the electrons in a solid is called the energy band.
- Valence band is the range of energy possessed by the valence electrons. It is the most occupied band.
- Conduction band is the range of energy possessed by the conduction electrons. It is the least occupied band.
- The energy difference between the bottom of the conduction band and the top of the valence band is called the forbidden energy gap.



Conductors

- A good conductor or a metal has approximately half-filled conduction band or else the conduction band overlaps with the valence band.
- Energy Bandgap (E_g) is zero
- Conductors have high conductivity ($10^2\ \Omega^{-1}m^{-1}$ to $10^8\ \Omega^{-1}m^{-1}$)
- Conductors have low resistivity ($10^{-2}\ \Omega m$ to $10^{-8}\ \Omega m$)
- Examples – Gold, Silver, Aluminium

Insulators

- In an insulating material, the valance band is filled and empty conduction band.

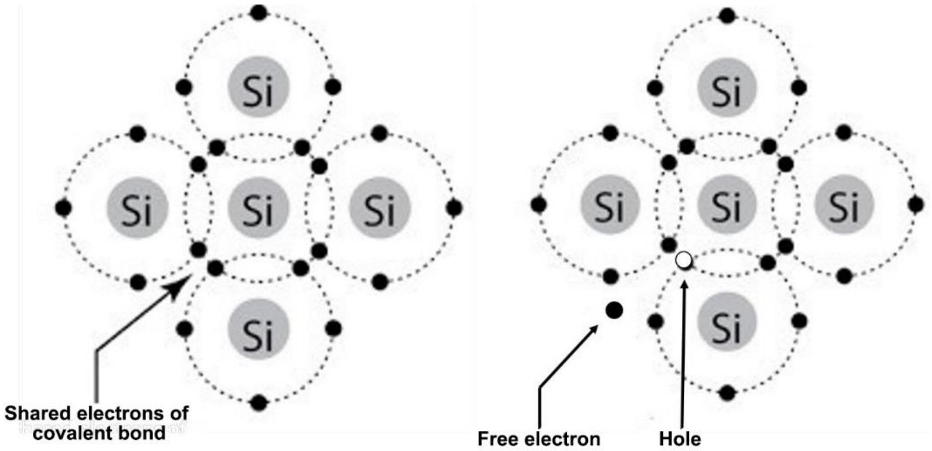
- There is a large forbidden energy band gap between the valance band and conduction band (> 3eV).
- Insulators have low conductivity ($10^{-11}\ \Omega^{-1}m^{-1}$ to $10^{-19}\ \Omega^{-1}m^{-1}$)
- Insulators have high resistivity ($10^{11}\ \Omega m$ to $10^{19}\ \Omega m$)
- Examples – Rubber, Mica

Semiconductors

- In a semiconductor, the valance band is filled like an insulator and the forbidden energy gap between valance band and conduction band is less than 3eV.
- Conductivity between Conductors and Insulators ($10^{5}\ \Omega^{-1}m^{-1}$ to $10^{-6}\ \Omega^{-1}m^{-1}$)
- Resistivity between Conductors and Insulators ($10^{-5}\ \Omega m$ to $10^{6}\ \Omega m$).
- Examples – Germanium, Silicon
- Semiconductors can be generally classified as intrinsic semiconductors and extrinsic semiconductors.

Intrinsic Semiconductors

- Extremely pure semiconductors without any impurities are known as intrinsic semiconductors.



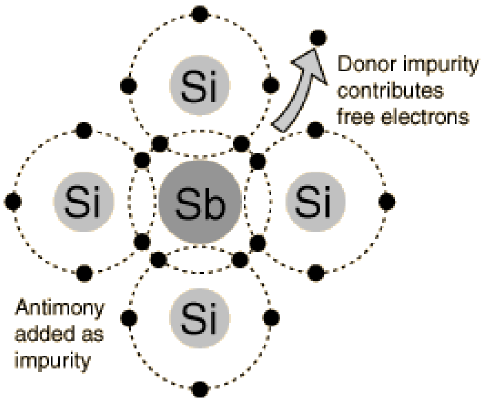
- At absolute zero (0 K), intrinsic semiconductors have completely filled valence band and empty conduction band.
- When the temperature is increased, the thermal energy is sufficient for the electrons in the valence band to jump into conduction band leaving oppositely charged vacancies known as holes in the valence band.
- Both the electrons and holes take part in the conduction.
- In an intrinsic semiconductor, the number of electrons is equal to the number of hole.
- Examples: Germanium (Ge) and Silicon (Si)

Extrinsic Semiconductors

- At room temperature the conductivity of intrinsic semiconductors is very low.
- The process of adding impurities to an intrinsic semiconductor so as to increase its conductivity is called doping.
- Doped semiconductors are called Extrinsic semiconductors
- There are two types of extrinsic semiconductors – n-type semiconductor and p-type semiconductor.

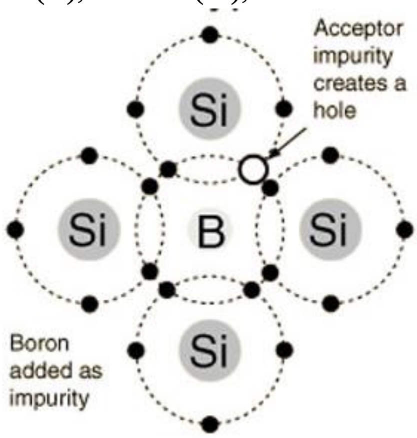
n-type semiconductors

- When a pentavalent impurity is added to an intrinsic semiconductor crystal, an n-type semiconductor is formed.
- For each impurity atom added, a free electron is created in the crystal.
- In an n-type semiconductor, electrons are the majority charge carriers and holes are the minority charge carriers ($n_e >> n_h$).
- The pentavalent dopant is donating one extra electron for conduction and hence it is known as donor impurity.
- In n-type semiconductors an extra energy level called donor energy level is produced just below the conduction band.
- Pentavalent impurities – Arsenic (As), Phosphorous (P), Bismuth (Bi) and Antimony (Sb)

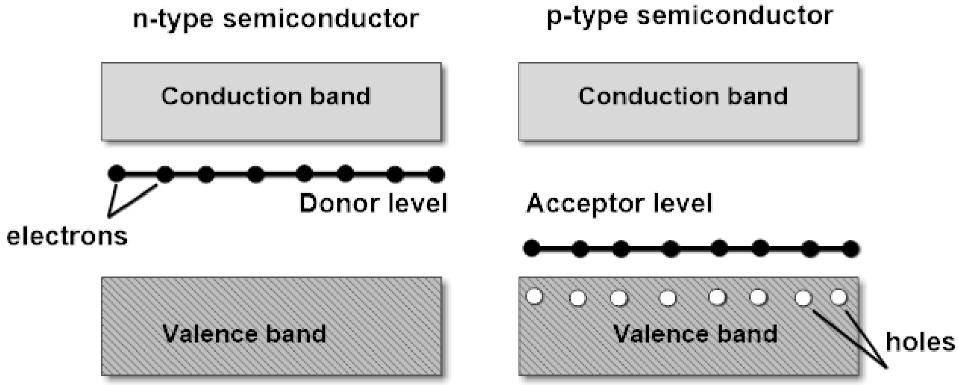


p-type semiconductors

- When a trivalent impurity is added to an intrinsic semiconductor crystal, an n-type semiconductor is formed.
- For each impurity atom added, a hole is created in the crystal.
- In a p-type semiconductor, holes are the majority charge carriers and electrons are the minority charge carriers ($n_h >> n_e$).
- The trivalent dopant accepts an extra electron and hence it is called acceptor impurity.
- In p-type semiconductors an extra energy level called acceptor energy level is produced just above the valence band.
- Trivalent impurities – Boron (B), Indium (In), and Gallium (Ga).

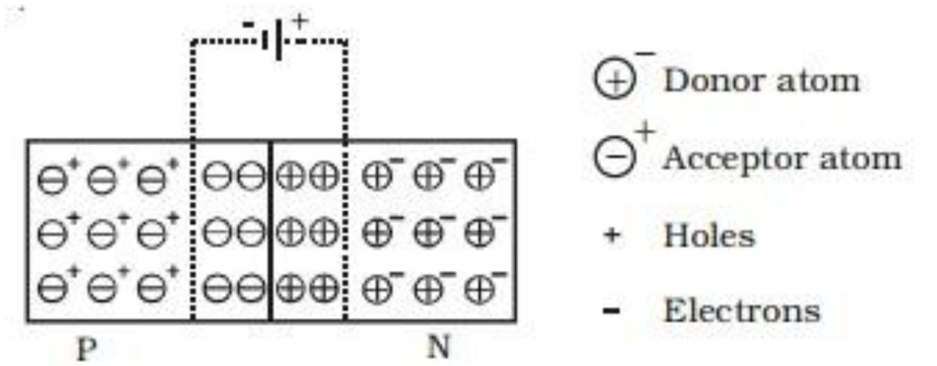


Band structures of Extrinsic semiconductors



p-n Junction

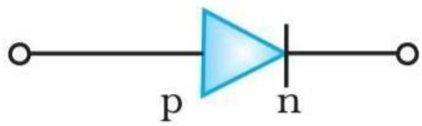
- A junction formed when a p-type semiconductor and n-type semiconductor are brought together is called a p-n junction.
- Two important processes occur during the formation of a p-n junction: diffusion and drift.
- Due to concentration differences, holes diffuse from p-side to n-side and electrons diffuse from n-side to p-side.



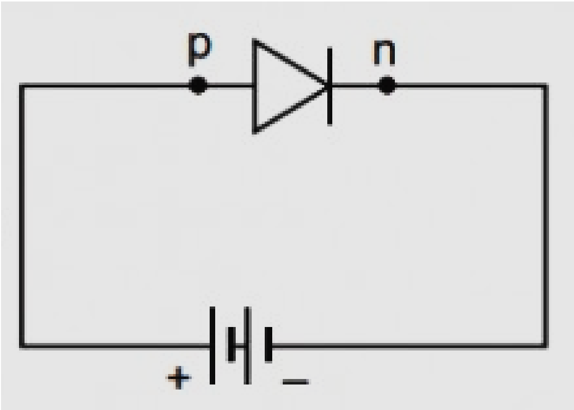
- Due to diffusion, a layer of negative charge is developed at the p-region of the junction and a layer of positive charge is developed at the n-region of the junction. This positively and negatively charged region is called depletion region.
- The potential difference between the depletion region is called potential barrier.
- The thermally generated electrons on the p-region moves towards the n-region and the thermally generated holes on the n-region moves towards the p-region due the potential barrier. This motion is called drift.
- The value of potential barrier is 0.6 to 0.7 V for a p-n junction made up of silicon and is approximately 0.3 V for a germanium p-n junction.

p-n Junction diode

- A semiconductor diode is a p-n junction with metallic contacts provided at the ends for the application of an external voltage.

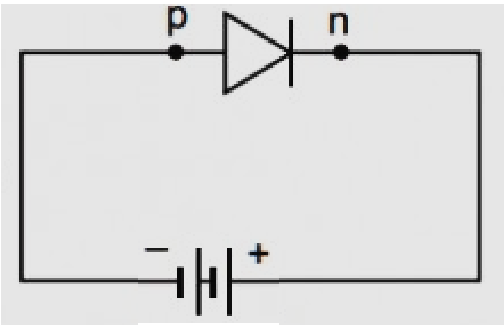


p-n Junction diode under forward bias

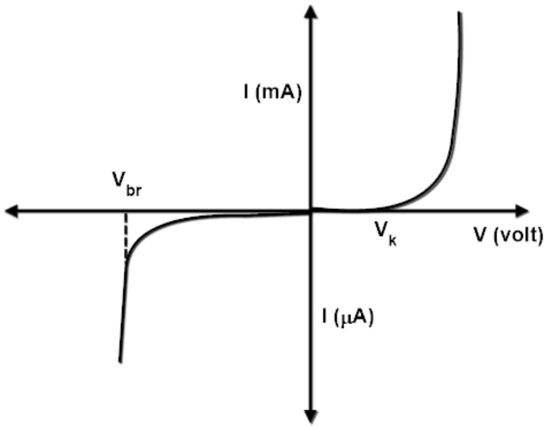


- In forward bias, the positive terminal of the battery is connected to the p-side and the negative terminal to the n-side of the p-n junction diode.
- Due to the applied voltage, electrons from n-side cross the depletion region and reach p-side and holes from p-side cross the junction and reach the n-side. This process under forward bias is known as minority carrier injection.
- Due to forward bias, the width of the depletion region reduces.
- Due to forward bias, the value of potential barrier decreases.
- The junction offers a very low resistance called forward resistance and the current increases sharply with forward voltage.
- The current increases slowly till the forward bias voltage reaches 0.3 V for Ge and 0.7 V for Si p-n junction. These voltages are called knee voltage (V_k).
- After knee voltage, there is an exponential rise in the forward current.

p-n Junction diode under Reverse bias



- In forward bias, the positive terminal of the battery is connected to the n-side and the negative terminal to the p-side of the p-n junction diode.
- When a diode is reverse biased, due to the attraction from the reverse biasing, holes and electrons move away from the junction.
- Due to reverse bias, the width of the depletion region increases.
- Due to reverse bias, the value of potential barrier increases.
- The junction offers a very high resistance called reverse resistance.
- If the reverse-bias voltage across a p-n junction diode is increased, at a particular voltage the reverse current suddenly increases to a large value. This phenomenon is called breakdown of the diode and the voltage at which it occurs is called the breakdown voltage (V_{br}).



Application of diodes

1) **Diode as rectifier**

- Rectifier is a device which converts AC to DC.
- p-n junction diode offers very low resistance in the forward bias and very high resistance in the reverse bias.
- If an alternating voltage is applied across a diode the current flows only in that part of the cycle when the diode is forward biased. This property is used to rectify alternating voltages and the circuit used for this purpose is called a rectifier.

2) **Diode as a voltage regulator (Zener diode)**

- A diode meant to operate in the breakdown region under reverse bias is called a Zener diode.
- Once the breakdown occurs, the potential difference across the diode does not increase even if the applied battery potential is increased. Such diodes are used to obtain constant voltage output. The current through the diode changes but the voltage across it remains essentially the same.

3) **Photodiodes used for detecting optical signal (photodetectors)**

- A Photodiode is a special purpose p-n junction diode fabricated with a transparent window to allow light to fall on the diode.
- It is operated under reverse bias.
- Under illumination electron-hole pairs are generated due to the absorption of photons.
- Due to electric field of the junction, electrons and holes are separated before they recombine.
- Electrons are collected on n-side and holes are collected on p-side giving rise to an emf.
- When an external load is connected, current flows.
- The magnitude of the photocurrent depends on the intensity of incident light (photocurrent is proportional to incident light intensity).

4) **Light emitting diodes (LED) which convert electrical energy into light**

- An LED converts electrical energy to light energy.
- It is a heavily doped p-n junction in forward bias.
- The diode is encapsulated with a transparent cover

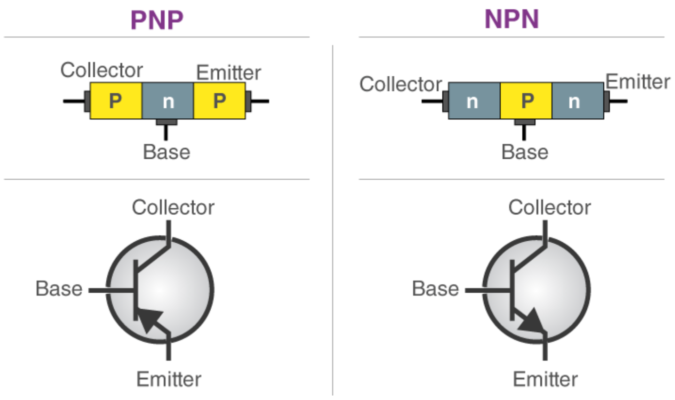
- When an electron makes a transition from conduction band to valance band photons with energy equal to or slightly less than the band gap is emitted.
- The compound semiconductor Gallium Arsenide – Phosphide is used for making LEDs of different colours.

5) Photovoltaic devices which convert optical radiation into electricity (Solar Cell)

- A solar cell is basically a p-n junction which generates emf when solar radiation falls on the p-n junction.
- It works on the same principle (photovoltaic effect) as the photodiode, except that no external bias is applied, and the junction area is kept much larger for solar radiation to be incident.

Transistors

- A transistor is a three terminal device.
- There are two types of transistors: n-p-n transistor and p-n-p transistor.
- A transistor is formed by sandwiching a thin layer of a p-type semiconductor between two layers of n-type semiconductors (n-p-n transistor) or by sandwiching a thin layer of an n-type semiconductor between two layers of p-type semiconductors (p-n-p transistor).
- Depending upon the size and doping concentration the different regions in the transistor are designated as Emitter, Base and Collector.
- Emitter is of moderate size and heavily doped. It supplies a large number of majority carriers for the current flow through the transistor. This is the segment on one side of the transistor.
- Base is the central segment. It is very thin and lightly doped.
- Collector is moderately doped. It is larger in size than emitter, which is larger than base. This segment collects a major portion of the majority carriers supplied by the emitter.



- Suitable potential differences should be applied across the two junctions to operate the transistor. This is called biasing the transistor.
- In normal operation of a transistor, the emitter–base junction is always forward-biased whereas the collector–base junction is reverse-biased.
- A transistor can be operated in three different modes: common emitter configuration or CE configuration (here the emitter region is grounded), common collector configuration or CC configuration (here the collector region is grounded) and common base configuration or CB configuration (here the base region is grounded).

Applications of Transistors

1) **Transistor as a switch**

- When the transistor is used in the cut off or saturation state it acts as a switch.
- If the input voltage is very low the transistor is said to be in cut off state and it does not conduct (switched off)
- If the input voltage is very high the transistor is said to be in saturation state and it conducts (switched on)
- Thus a low input switches the transistor off and a high input switches it on.

2) **Transistor as an amplifier**

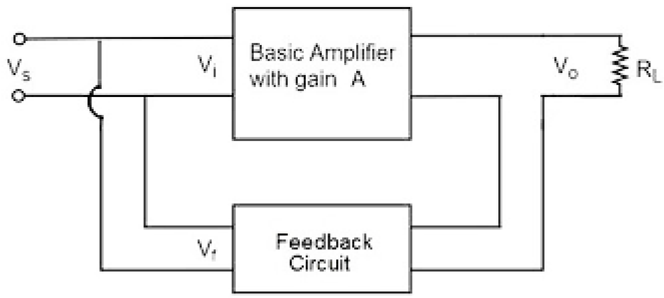
- Amplifiers are used to amplify alternating signals.
- Transistors can act as amplifiers while they are functioning in the active region or when it is correctly biased.
- If the transistor is properly biased, the collector (output) current I_C is directly proportional to the base (input) current I_B and the transistor act as a current amplifier.

$$I_C \propto I_B$$
$$I_C = \beta I_B$$

$where\ \beta\ is\ the\ current\ gain.$

3) **Transistor as an oscillator**

- Oscillator is a device used to convert dc voltage into ac voltage.
- When a portion of the output power of an amplifier is returned back (feedback) to the input in phase with the starting power it acts as an oscillator.
- The feedback can be achieved by inductive coupling (through mutual inductance) or LC or RC networks.



M4.02 – Explain photoelectric effect and its applications.

Photoelectric effect

- When light of sufficient wavelength is incident on some metal surface, electrons are ejected from the metal. This phenomenon is called the photoelectric effect.
- The electrons ejected from the metal are called photoelectrons.

Laws/Properties/Experimental observations of Photoelectric effect

1) **The photoelectric effect is frequency dependent:**

- There is a particular frequency above which the photoemission of electrons happens. This frequency is called as threshold frequency (υ_0).

2) **The photoelectric current is intensity dependent:**

- The number of photoelectrons generated determines the photocurrent.
- If the incident wave frequency is higher than or equal to the threshold frequency the photocurrent generated is proportional to the intensity of radiation.

3) **Photoelectric effect is an instantaneous process:**

- There is no time lag between the incidence of radiation and emission of photoelectrons for the incident wave with sufficient frequency.

Einstein's Explanation to Photoelectric effect

- Einstein explained photoelectric effect using Planck's quantum theory.
- According to quantum theory, light consists of small packets of energy called quantum or photon.
- If 'h' is the Planck's constant, 'c' is the velocity of light, 'υ' is the frequency and 'λ' is the wavelength of the incident photon. The energy (E) of a photon is given by,

$$E = hv = \frac{hc}{\lambda}$$

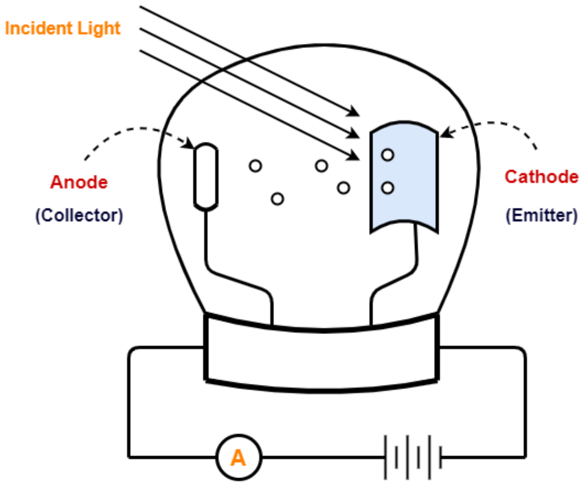
- According to Einstein, when a photon of energy $E = hv$ is incident on a metal surface, its energy is used for two purposes.
    1. Energy required to remove electron from the metal surface called photoelectric work function ($h\upsilon_0$).
    2. Kinetic energy of the emitted photo electrons. If m is the mass of the electron and v is its velocity, then kinetic energy $K.E. = \frac{1}{2}mv^2$
- Therefore, Einstein's photoelectric equation can be written as

$$Energy\ of\ the\ incident\ photon = Photoelectric\ work\ function + Kinetic\ Energy$$

$$hv = hv_0 + \frac{1}{2}mv^2$$

Photocells

- Photocells are sensors used to detect light or the intensity of light.
- Photocells convert light energy into electrical energy by employing photoelectric effect.
- The main parts of the photocell are an evacuated glass tube, which contains two metal electrodes namely Anode (Collector) and Cathode (Emitter).
- The metal electrodes are kept at a potential difference by an external battery or source through a rheostat and a commutator.
- In series to the source an ammeter or a galvanometer is connected.
- The emitter electrode or cathode C is plated with materials which shows photoelectric effect.
- When light of suitable frequency is incident on the emitter electrode through the transparent evacuated glass tube, photoelectric effect happens, and photoelectrons are emitted from the emitter electrode or cathode.
- These photoelectrons pass through the anode terminal and to the positive of the battery through the ammeter and produces a current.
- This current is termed as photocurrent.



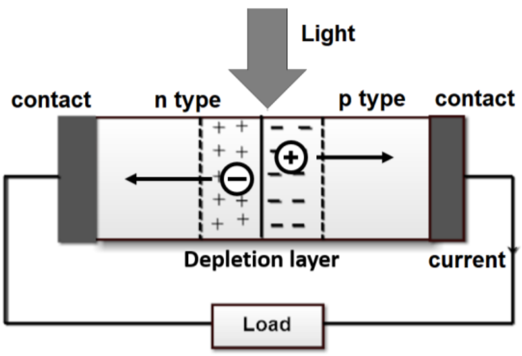
Photoelectric Cell

Applications of Photoelectric Effect

- Photoelectric cell is used as an illumination meter to measure the illuminating power of light sources.
- A burglar alarm can be constructed with a photoelectric cell.
- Photoelectric cell is used in relay circuits.
- Photoelectric cell is used to reproduce sound recorded in a talkie film.
- An array of photoelectric cell is used in television cameras for the conversion of light into electric signals.
- Photoelectric cells are used in automatic cameras to detect the ambient light and adjust the lenses to get clear photographs.

Solar cell

- Solar cells are semi-conductor devices which use sunlight to produce electricity.
- An unbiased p–n junction is used for charge carrier separation.
- The generation of emf/voltage by a solar cell is due to the three basic processes: generation, separation and collection of mobile charge carriers.
- When light falls on the p-n junction electron-hole pairs are generated on the depletion region (generation).
- The electron moves towards the n side and hole moves towards the p side due to the potential barrier (separation).
- Electrons and holes are collected by the contacts on the n and p side (collection)
- If the ends of the contacts are connected to a load, these charge carriers flow through the conducting wire to the load and create a current.



Applications of Solar cells

- Solar cells along with storage batteries are used in many electrical appliances
- Solar cells are used as energy source in satellites and space stations
- Solar cells are used in calculators
- Solar cells are used to power the electric vehicles.

M4.03 – Discuss the principles of LASER action and explain the working of semiconductor laser and He – Ne laser.

- **LASER** is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.

Absorption, Spontaneous emission and Stimulated emission

Absorption

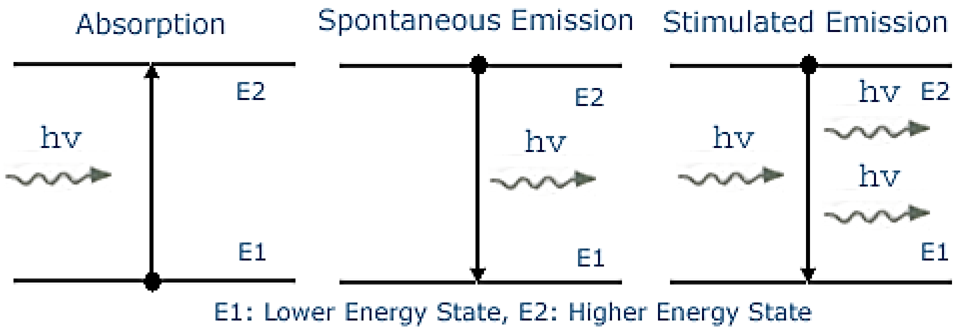
- An atomic system can exist in different energy levels.
- The energy level of an atom with lowest energy is called ground state and levels of higher energy are called exited states.
- An atom in the ground state can absorb energy and undergo transition to exited states. This process is called absorption.
- An atom in exited state can come down to ground state by emitting a photon in two ways: Spontaneous emission and Stimulated emission.

Spontaneous emission

- Since the atoms prefer to stay in the ground state, the excited atoms return to the ground state without any external stimuli by emitting a photon of same frequency as that of the originally absorbed photon. This process is called spontaneous emission.
- The direction and phase of the spontaneously emitted photons are random.
- Spontaneous emission cannot produce lasing action.

Stimulated emission

- A photon striking an exited atom can induce a transition from exited state to the ground state by emitting another photon. This process is called stimulated emission.
- The major feature of the stimulated emission is that the emitted radiation has the same phase and frequency as that of the stimulating photon.
- Stimulated emission can produce lasing action.



Basic operation of LASER

- A laser is basically an optical oscillator.

- It consists of an amplifying medium placed inside a suitable optical resonator or cavity.
- Generally, the laser action involves the following processes:

Pumping

- Pumping is the process of excitation of ground state atom to excited state.
- There are different pumping methods employed in various lasers.

Population inversion

- Population inversion is the necessary condition to achieve lasing action.
- In atomic system, under normal conditions, the number of atoms in the ground state is much higher than that in the exited states.
- By supplying energy from outside, atoms in the ground state undergo transition to exited states.
- As a result of this, the number of atoms in the exited state becomes higher than that at the ground state. This condition is called population inversion.

Amplification

- The optical cavity or resonator of laser usually consists of two mirrors between which the amplifying medium is located.
- Under population inversion condition, a spontaneously emitted photon can induce exited atom to emit an identical photon. These two photons will stimulate two more and so on.
- Since the amplifying medium is placed inside an optical resonator, radiation produced in the amplifying medium bounces back and forth between the mirrors. In this way, it gets amplified.

Coherent emission

- The amplified waves in the cavity are in same phase so that the output laser light is coherent.
- The output laser light will have high directionality and high intensity.

Methods for producing Population inversion

1) Optical Pumping

- Optical pumping is a process in which light energy is used to excite electrons from a lower to higher energy level for attaining population inversion.
- Optical pumping is used in solid state laser
- Example: Ruby Laser

2) Electron excitation

- This is a type of electrical pumping.
- Direct electron excitation by gaseous discharge is used to produce the population inversion.
- This method is used in some of the gaseous ion lasers.
- Example: Argon laser.

3) Inelastic atom-atom collisions

- In this method a high voltage electric discharge acts as a pump source.
- However, in this method, a combination of two types of gases A and B are used.

- During electric discharge, gas A at ground state gets excited to higher energy state and becomes A*.
- The excited state A* collides with gas B at ground state and excites it to higher energy state B*. Thus population inversion condition is achieved in gas B.
- Helium-Neon (He-Ne) laser uses this method.

$$A^* + B = A + B^*$$

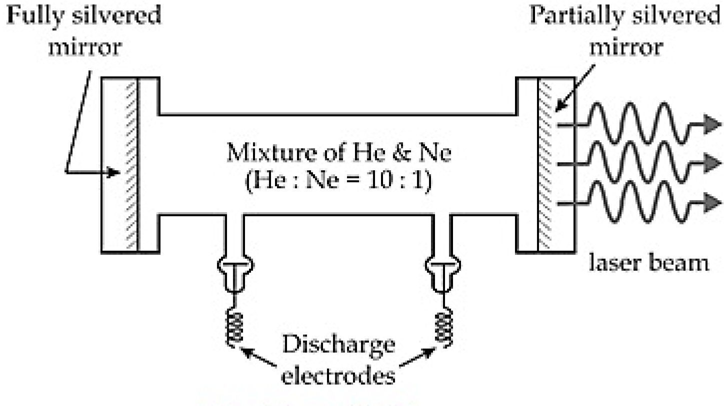
4) Chemical pumping

- In chemical pumping, chemical reactions are employed for achieving population inversion condition.
- In this method a molecule is caused to undergo a chemical change in which one of the products of the reaction is a molecule or an atom in an excited state.
- The lasers which employ chemical pumping are called chemical lasers.

Characteristics of LASER

- **Laser light is monochromatic:**
  The laser radiation is composed of a single colour or wavelength
- **Laser light is highly coherent:**
  The waves in the laser radiation are in same phase and frequency
- **Laser light is highly intense:**
  Since the number of waves per unit area is large and are in same phase, the laser light is highly intense.
- **Laser light is highly directional and has low divergence:**
  This is because of the fact that the laser light is highly coherent.

He-Ne LASER



He-Ne LASER

- Helium-Neon (He-Ne) laser is gas laser.

Construction

- The essential parts of He-Ne laser are shown in the figure.
- The working substance of this laser is a mixture of helium and neon gas in the ratio 10:1.
- The gas mixture is placed in a long discharge tube, typically 50 cm long and 0.5 cm diameter.
- The pressure inside the tube is nearly 1 mm of mercury.

- Discharge electrodes are attached to the discharge tube.
- The tube has a fully silvered mirror and partially silvered mirror (transparent) at its ends.

Working

- When the discharge is maintained in the tube by an electric field, electrons are produced.
- Electrons collide with atoms in the tube.
- The helium atoms are soon raised to higher energy states by electrons collisions.
- When the excited helium atoms collide with the neon atoms in the ground state, the excitation energy of helium is transferred to the neon atoms.
- In this way, a large number of neon atoms are raised to the excited states and population inversion is achieved.
- Under this condition, a spontaneously emitted photon can trigger laser action and an intense laser beam is emitted through the partially silvered mirror by amplification between the two mirrors.
- The output of He-Ne laser has a wavelength of 632.8 nm.

Semiconductor LASER

- The most compact laser is the semiconductor diode laser, also called as the injection laser.

Construction

- In its simplest form the diode laser consists of a p-n junction in a doped single crystal of a suitable semiconductor, such as gallium arsenide (GaAs).
- The junction layer is very thin of the order of micrometers in length.
- The end faces of the crystal are made partially reflective by polishing to form an optical resonator.

Working

- When a forward bias is applied to the diode, electrons are injected into the p side of the junction and holes are injected into the n side.
- The recombination of holes and electrons within the junction region result in recombination radiation.
- If the junction current density is large enough, a population inversion can be obtained between the electron levels and hole levels. Stimulated emission can then occur and thereby lasing action.
- The threshold current density for gallium arsenide injection laser is about 104 A/cm^2 and the emitted radiation is in the near infrared, about 830 to 859 nm.

Applications of LASER

- Laser can be used as tool for surgery (Ophthalmic surgery).
- Laser is used for precision cutting, drilling, and welding.
- Laser beam can be used as a carrier of information (telephone signal through optical fiber cables).
- Laser based methods are used to guide missiles and pilot-less fighter planes.
- Laser is used for range finding (measurement of distance of faraway objects).
- Laser is used in Holography or 3D imaging.

- Laser is used to initiate fusion reaction.
- Laser is used to read and write data in CD/DVD systems.
- Laser is used in printing technology (Laser printer).
- Laser is used in textile industry to perfectly cut many layers of cloths together.

M4.04 – Summarize the basic concepts of nanoscience and its importance

Significance of Nanomaterials

- The study of objects and phenomena at a very small scale (1-100 nanometers) is called nanoscience.
- In nanometer scale the material properties are size and shape dependent.
- The large surface area of nanomaterials enhances the properties such as reactivity, strength and electrical characteristics.
- Nanotechnology is the design, characterization, production and application of structures, devices and systems by controlling shape and size at nanometer scale.

Distinguishing properties of Nanomaterials

- A bulk material should have constant physical properties, but at the nanoscale size-dependent properties are observed.
- Percentage of atoms at the surface of a material is increased
- Increased surface area
- Aspect ratio or surface to volume ratio will increase considerably

Properties of bulk gold and nano gold particles

Properties	Bulk Gold	Nano Gold
Colour	Yellow	Red
Electrical conductivity	Conductive	Less Conductive
Magnetism	Non-Magnetic	Becomes Magnetic
Chemical reactivity	Chemically inert	Explosive, Catalytic

Characteristics of Nanomaterials

- Nano fiber is stronger than spider web
- Nano metal is 100 times stronger than steel
- Nano catalysts respond more quickly in reaction
- Nano plastics that conduct electricity.
- Nano coatings are frictionless
- Nano materials that change colour and transparency
- Nano scale powders better than metal for radiation protection.

Developments of Nanoscience to Technology

- Nanotechnology enables computational power. The computer simulations help for studying the drug discovery process.
- Nano-engineering is leading to better fuel cells and photovoltaic cells.
- Nano-engineered catalysts can be used extraction of oils.

- The replacement of carbon black in tyres by inorganic clays is a new technology (Leading to the production of environmentally friendly, wear-resistant tyres).
- LED s produced on nanoscale dimensions.
- Nanotechnology improves medical imaging.
- Nanomaterials will yield lighter, faster, safer durable, reliable bridges, pipelines etc.
- Nano coatings used in shipping industry.

Carbon nanotubes (CNTs)

- Carbon is tetravalent material so that it can form a sheet like structure.
- Carbon nanotube is an allotrope of carbon
- If the sheet of carbon atom network is folded like tube of nano scale diameter, it is called as carbon nanotube.
- There are two types of carbon nanotubes, namely single walled carbon nanotubes (SWCNTs) and Multi-walled carbon nanotubes (MWCNTs).
- The single walled carbon nanotube is a two dimensional hexagonal lattice of carbon atoms rolled up as a hollow cylinder.
- Multi-walled carbon nanotubes (MWCNTs) consisting of nested single-wall carbon nanotubes which are weakly bound together by van der Waals interactions in a tree ring-like structure.
- The length of the tube might be larger than the diameter of the CNTs.

Properties of carbon nanotubes

- Length to diameter ratio is about 10^6.
- Density is one sixth of steel
- Young's modulus is five times greater than steel
- Tensile strength is fifty times higher than steel
- High chemical stability
- Good thermal conductivity
- Tunable electrical conductivity

Applications of carbon nanotubes

- Medical applications:
  Nanotubes can help with cancer treatment
  Nanotubes can help with treating cardiovascular diseases
  Nanotubes play an important role in blood vessel cleanup
  Nanotubes are used in tissue engineering
- Used to make temperature resistant adhesive tape
- CNTs are used in modern bicycle parts since they had better hardness with less weight
- CNTs are used as epoxy resins in wind turbines, marine paints and a variety of sports gear such as skis, ice hockey sticks, baseball bats, hunting arrows, and surfboards.
- CNTs are used in shuttle badminton rackets so that they are light weight and strong.
- CNTs can be applied to camera and telescope systems to decrease the amount of light and thereby allow for more detailed images to be captured.