2. Electricity, Magnetism & Semiconductors

1. Concept of charge, Coulomb's inverse square law, electric field, electric field intensity, potential and potential difference.

Concept of charge

Charge is an intrinsic property of matter.
There are two types of charges:
1) Positive charge (proton)
2) Negative charge (electrons)

Properties of charge

1) Like charges repel each other
2) Unlike charges attract each other
eg. if we rub a glass rod with a piece of silk cloth the rod becomes positively charged & silk cloth becomes negatively charged.

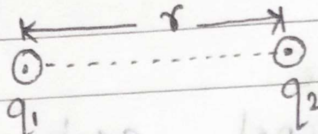
Conservation of electric charge

Electric charge can neither be created nor be destroyed it can only be transmitted from one body to another body.

The study of electric charges at rest is called electrostatics.
The study of electric charges in motion is called electromagnetics.

Calomb's Inverse Square Law

The force of attraction or the force of repulsion between two charges is directly proportional to the product of magnitude of charges & is inversely proportional to the square of distance between them, also the force between the two charges act along the line joining them



Let q_1 & q_2 be two charges separated by distance 'r'. According to Coulomb's law

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

Combining,

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

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

K is electrostatic force constant

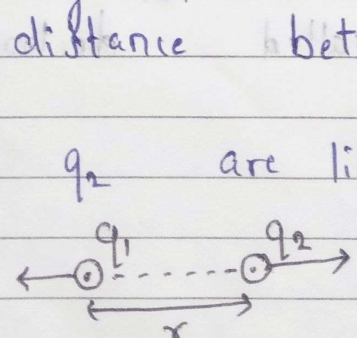
$$K = \frac{1}{4\pi\epsilon_0}$$

F is force

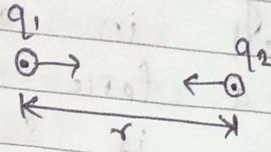
q_1, q_2 magnitude of charges

r distance between the charges

1) If q_1 & q_2 are like charges they repel



27 If q_1 & q_2 are unlike charges they will attract.



Electrostatic force constant

$$K = \frac{1}{4\pi\epsilon_0}$$

ϵ_0 is permitivity of free space

$\epsilon_0 = 8.854 \times 10^{-12}$ C^2/Nm^2

S.I unit of electric charge = coulomb (C)

S.I unit of electric force = newton (N)

charge on $e^- \rightarrow$ -ve

charge on proton $\rightarrow$ +ve

magnitude of charge is 1.602×10^{-19} C

When same charges q_1 & q_2 are kept at same distance 'r' in a medium whose permitivity is ϵ_m,

$$F_{med} = \frac{1}{4\pi\epsilon_m} \frac{q_1 \cdot q_2}{r^2}$$

For free space

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

$$\therefore \frac{F_{free\,space}}{F_{medium}} = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2} \Bigg/ \frac{1}{4\pi\epsilon_m} \frac{q_1 q_2}{r^2}$$

$$\frac{F_{free}}{F_{med}} = \frac{\epsilon_m}{\epsilon_0}$$

The ratio of ϵ_m/ϵ_0 is called relative permittivity or dielectric constant of the medium denoted by ϵ_r.

Unit charge or 1 coulomb charge

When two charges having equal strength are placed in air 1 m apart & they exert a force of 9×10^9 N Then each charge is said to be unit charge or 1C charge.

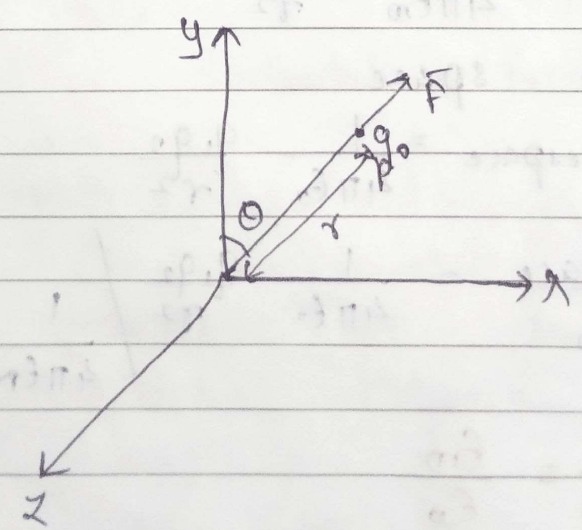
Relative permittivity (Dielectric constant)

Ratio of magnitude of force between the two charges placed some distance apart in vacuum to the force between the same charges placed same distance apart in the medium.

As relative permittivity (ϵ_r) is ratio of two similar quantities it is a dimensionless quantity.

Electric field

The space around a point charge where another charge experiences force of attraction or repulsion



Consider a positive charge 'q' at a point 'O'.

The electric field due to this charge at some point 'P' is defined as electric force experienced by a positive test charge q_0 placed at point 'P'.

$$E = \frac{F}{q_0}$$

S.I unit of electric field is N/C. It is a vector quantity. The directions of electric field is same as direction of electric force

$$E = \frac{\frac{1}{4\pi\epsilon_0}\frac{q q_0}{r^2}}{q_0} = \frac{1}{4\pi\epsilon_0}\frac{q}{r^2}$$

$$E = \frac{1}{4\pi\epsilon_0}\frac{q}{r^2}$$

Advantages of using electric field over Coulomb's law to determine electric force between charges.

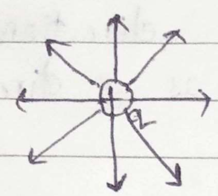
1) Electric field is associated with position so electric field at a given point in space due to some given charge or group of charges is fixed.

2) It is easy to determine electric force experienced by given charges in that region as electric field of given region in space is known.

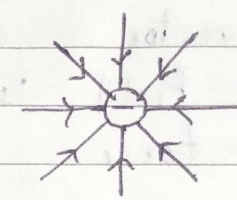
2) When charges are moving electric fie & Coulomb's law do not describe elec forces in similar manner.

Coulomb's law tells effect of motion of charge is felt immediately by other charges. But this is not supported by experimental observations.

Electric lines of force



a) Electric lines of force due to +q charge



b) Electric lines of force due to -q charge

Characteristics of electric lines of force

1) Direction of field lines indicate the direction of electric field.

2) Electric field lines start on positive charge & end on negative charge.

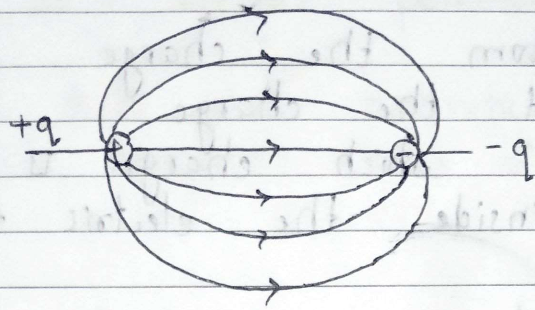
3) Electric lines of force never intersect each other

4) No. of electric lines of force per unit cross-sectional area at a point is directly proportional to the magnitude of electric field at that point.

5) While representing electric field by field lines the number of field lines are drawn in proportion to magnitude of charge so that density of lines truly represent magnitude of field at given point.

6) There are no lines of force inside the conductor.

Electric field lines due to system of two charges of equal magnitude.



Electric field intensity

It is defined as the electric force on a unit positive charge placed at that point in the electric field.

$$E = \frac{V}{d}$$

Electric field intensity is used to measure the strength of electric field.

In radial electric field intensity decreases as distance from central charge increases.

$$E = \frac{1}{4\pi\epsilon_0} \frac{Q}{\epsilon_r d^2}$$

If $\epsilon_r = 1$

$$E = \frac{1}{4\pi\epsilon_0} \frac{Q}{d^2}$$

$$E = 9 \times 10^9 \frac{Q}{d^2}$$

$$\therefore \frac{1}{4\pi\epsilon_0} = 9 \times 10^9 \ Nm^2/C^2$$

S.I unit of electric field intensity = N/C
Alternative unit = V/m

Factors affecting electric field intensity at a point
1) Distance from the charge
2) Strength of the charge
3) Medium in which charge is placed
4) Position inside the electric field.

Electric Potential
Work done in bringing a unit positive charge from infinity to that point.

$$V = \frac{1}{4\pi\epsilon_0} \frac{Q}{r}$$

Alternative defination:
Electric Potential energy per unit charge
Unit of electric potential = Volt (V)

Electric Potential Difference
Electric potential difference (P.D) or voltage between points A & B is defined as the amount of work done to move unit positive charge from point A to B.
Consider two points A & B in an electric field of point charge +Q.
let V_A = electric potential at point A
V_B = electric potential at point B
$V_{AB} = V_B - V_A = W_{AB}$

$V_B - V_A$ = Potential difference
W_{AB} = Work done in moving unit positive charge from A to B

If charge 'q' is moved from A to B then

$$V_{AB} = \frac{W_{AB}}{q}$$

Unit of electric potential is volt (V)

2.2. Magnetic field and magnetic field intensity & its units, magnetic lines of force, magnetic flux.

Magnetic field

The space surrounding the magnet where the magnetic force of attraction or repulsion is experienced.

Retentivity

The ability of a material to remain magnetized after removal of magnetizing force is called retentivity.

Magnetic field strength / intensity (H):

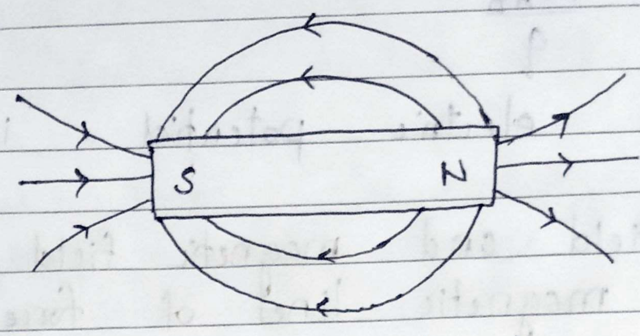
It is ratio of magnetic field in vacuum (B_0) to the absolute permeability (μ_0)

$$H = \frac{B_0}{\mu_0}$$

$\mu_0 = 4\pi \times 10^{-7}$ tesla or mA^{-1}

Unit of magnetic field intensity is A/m or $N/m^2 T$ or N/Wb

Magnetic lines of force



magnetic lines of force

Magnetic lines of force is defined as the path or curve along which the unit north pole moves in the magnetic field.

Characteristics of magnetic lines of force

1) They always originate from North pole & terminate on south pole.
2) Direction of magnetic field B at any point is along the tangent to the lines of force at that point.
3) The magnitude of magnetic field is represented by the number of field lines per unit cross sectional area.
4) Magnetic lines of force are denser near the north or south pole indicating large value of magnetic field.
5) The magnetic lines of force are rarer at far off points compared to poles.
6) The lines of force never intersect each other.
7) All the lines of force have same strength.

Magnetic field lines of earth

Magnetic south pole of earth is located near its geographical north pole & vice versa.

Magnetic flux (ϕ)

The number of magnetic field lines passing normally through the surface area.

$$\phi = BS\cos\theta$$

θ = Angle between magnetic field B & normal to surface area 'S'.

S.I unit of magnetic flux weber (Wb

Magnetic flux density or magnetic induc

Magnetic flux density at a point in a magnetic field is defined as magnetic flux per unit area at that point.

S.I unit 'tesla' or 'Wb/m^2'.

Relations between magnetic flux density (& magnetic field intensity (H).

$$B \propto H$$

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

$$B = \mu H$$

$$B = \mu_0 \mu_r H$$

~~At~~ μ_r is relative permeability.

2.3. Electric current, Ohm's law, specific resistance, laws of series & ||el combination of resistance, conversion of galvanometer into ammeter & voltmeter, Heating effect of electric current.

Electric Current

Electric current is the rate of flow of charge.

If Q is the total charge flowing through conducting wire in time 't' electric current is given as,

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

If total charge Q contains 'n' number of e^- each having charge e

$$Q = ne$$

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

SI unit of current - ampere (A)

1 ampere

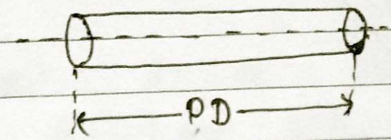
If 1 coulomb of charge flows through the conducting wire in one second then electric current is said to be 1 ampere.

$$1 \text{ ampere} = \frac{1 \text{ coulomb}}{1 \text{ second}}$$

Ohm's law

When potential difference is applied across the ends of the conductor the free e present in the conductor gets accelerated

This motion is opposed due to their collisions with ions in the conductor.



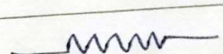
Resistance

Opposition to the flow of electrons

SI unit ohm (Ω)

Resistor:

Electronic device used in a circuit in order to resist the flow of electric current.

symbol : 

1 Ω

When 1 V potential difference is applied across the conductor & one ampere current flows through a conductor then resistance of a conductor is 1 Ω.

Statement of Ohm's law:

The current (I) flowing through a conductor is directly proportional to the potential difference (V) across its two ends if its physical conditions remains the same.

$$V \propto I$$

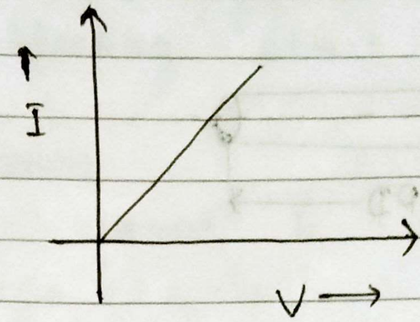
$$V = RI$$

, V is potential difference

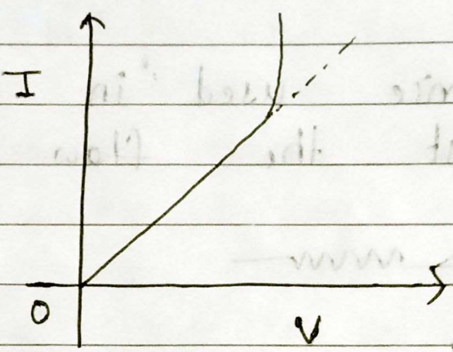
R is resistance

I is current

If variation of current with potential difference is linear the conductor is ohmic conductor



If variation of current with potential difference is non-linear the conductors are non-ohmic conductor.



Specific Resistance (Resistivity)

Consider a conductor having length 'l' & area of cross-section 'A'. Consider potential difference of V volts is applied across the two ends of conductor

Then $R \propto \frac{1}{A}$, $R \propto l$

$\therefore R \propto \frac{l}{A}$

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

ρ is called specific resistance or resistivity of wire

Rearranging,

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

SI unit of ρ is $\frac{\Omega m^2}{m} = \Omega m$

If $A = 1\,m^2$, $l = 1\,m$ then $\rho = R$

Resistivity: Resistance offered by the material of conductor having unit length & unit cross-sectional area

Resistivity is the characteristics of the material of wire.

Conductivity

Reciprocal of resistivity

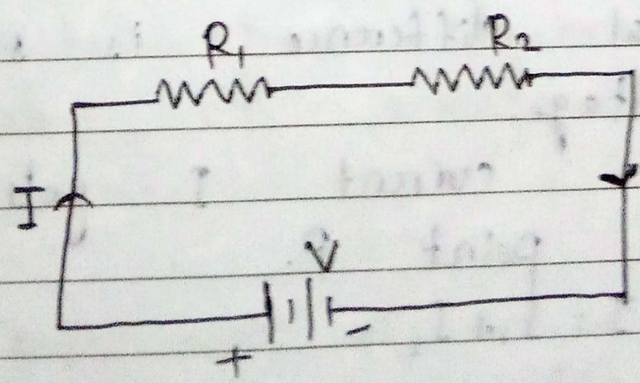
$$\sigma = \frac{1}{\rho}$$

SI unit mho/m or $ohm^{-1}\,m^{-1}$

laws of series & parallel combination of resistance

17 Resistors in series

let us consider two resistors R_1 & R_2 connected in series (one after another) Source of potential difference V is applied across the combination



Resistors in series

let R_s = equivalent resistance of series combination.

Here current flowing through both resistors is same.

$\therefore \quad I_1 = I_2 = I$

If V_1 = P.D across resistor R_1

V_2 = P.D across resistor R_2

Using ohm's law,

$V_1 = IR_1$ & $V_2 = IR_2$

$V = V_1 + V_2$

$= IR_1 + IR_2$

$IR_s = I(R_1 + R_2)$

$R_s = R_1 + R_2$

This is equivalent resistance of resistors connected in series.

law of resistance is series

Equivalent resistance offered by two or more resistors connected in series combination is algebraic sum of resistances of individual resistors.

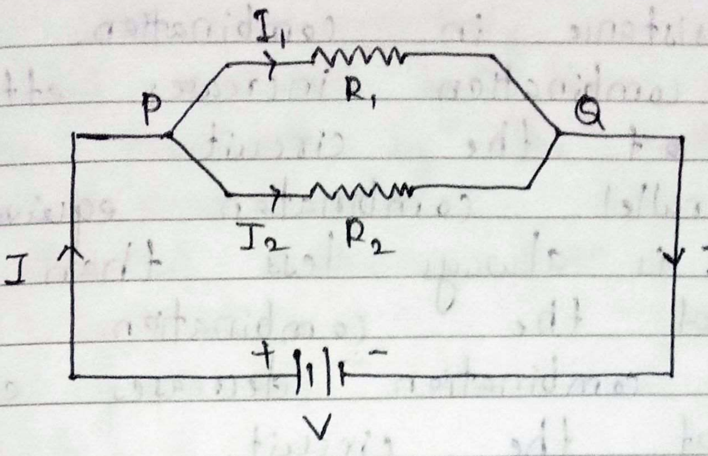
27 Resistor in Parallel

let R_1 & R_2 be two resistors connected in parallel.

Potential difference is same as applied voltage.

Total current I gets divided into I_1 & I_2 at point P.

$\therefore \quad I = I_1 + I_2$



According to ohm's law,

$V = I_1 R_1$ $\qquad$ $V = I_2 R_2$

$I_1 = \frac{V}{R_1}$ & $I_2 = \frac{V}{R_2}$

If R_p is equivalent resistance in parallel combination

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

$$I = I_1 + I_2$$

$$\frac{V}{R_p} = \frac{V}{R_1} + \frac{V}{R_2}$$

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2}$$

law of resistances in parallel

Reciprocal of equivalent resistance offered by two or more resistors connected in parallel combination is equal to the algebraic sum of reciprocals of resistances of individual resistors.

Significance

In series combination equivalent resistance (R_s) is always greater than the

largest resistance in combination.
- Series combination increases effective resistance of the circuit.
- In parallel combination equivalent resistance is always less than smallest resistance of the combination.
- Parallel combination decreases effective resistance of the circuit.

Galvanometer

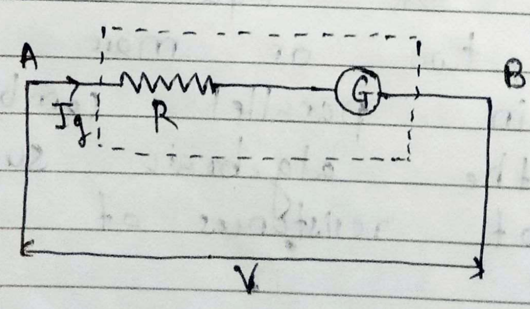
A galvanometer is a device which is used to detect small electric current flowing in the circuit.

Voltmeter:

Voltmeter is an instrument used to measure the potential difference across the two ends of a circuit element.

Conversion of galvanometer to voltmeter:

A galvanometer can be converted into a voltmeter by connecting a large resistance in series to the galvanometer



let G & R be the resistance of a galvanometer & a conductor connected in series with it respectively.

let V volt be the potential difference to be measured by the voltmeter & I_g be the current.

Potential difference betn point A & B:

$V = I_g R + I_g G$

$V = I_g (R + G)$

$R + G = \frac{V}{I_g}$

$R = \frac{V}{I_g} - G$

$\therefore R = \frac{V}{I_g} - G$

This is the required value of resistance which must be connected in series to the galvanometer to convert it into voltmeter of range 0-V volt.

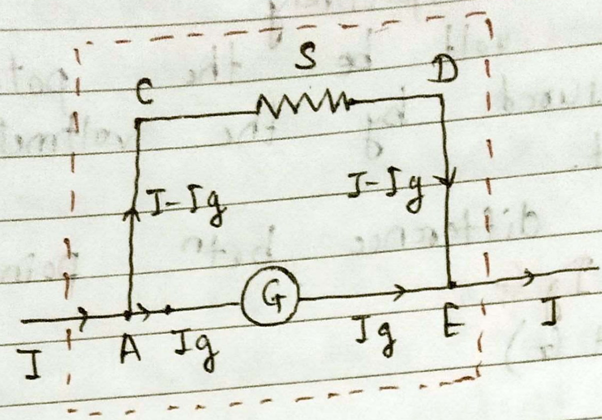
Voltmeter is a high resistance device. Resistance of an ideal voltmeter is infinite. A voltmeter is always connected in parallel to the circuit component across which voltage is to be measured.

Ammeter:

Ammeter is a device used to measure current.

Conversion of galvanometer into ammeter.

A galvanometer is converted into an ammeter by connecting a low resistance in parallel with galvanometer. This low resistance is called shunt resistance.



Ammeter

let I be the current passing through the circuit.

When current I reaches the junction A it divides into two components. let Ig be the current passing the galvanometer of resistance Rg through path AGE & remaining current (I-Ig) passes through along the path ACDE through shunt resistance S. The value of shunt resistance is so adjusted that current Ig produces full scale deflection in the galvanometer.

P.D across galvanometer is same as the P.D across shunt resistance.

$$V_{galvanometer} = V_{shunt}$$

$$I_g R_g = (I - I_g) S$$

$$S = \frac{I_g}{I - I_g} R_g$$

or $$I_g = \frac{S}{S + R_g} I$$

$$I_g \propto I$$

The deflection in the galvanometer measures is proportional to the current passing through it

$\theta \neq \frac{1}{G} I_g$ $\theta \propto I_g \Rightarrow \theta \propto I$

So, deflection in the galvanometer measures the current I passing through the circuit.

Shunt resistance is connected in parallel to galvanometer. Therefore resistance of ammeter can be determined by computing effective resistance,

$$\frac{1}{R_{eff}} = \frac{1}{R_g} + \frac{1}{S}$$

$$R_{eff} = \frac{R_g S}{R_g + S}$$

Heating effect of electric current

Heat is a form of energy. It is produced when electric current passes through a conductor.

This was studied by Joule So the effect is known as Joule's heating effect.

Joule's law

The amount of heat (Q) produced in a conductor due to flow of current (I) is directly proportional to the square of current, resistance (R) of the conductor, time (t) for which current flows through the conductor.

$$Q \propto I^2 R t$$

$$Q = \frac{I^2 R t}{J}$$

J is called Joule's mechanical equivalent of heat. Value of J is 4.18 J/cal.

In SI unit amount of heat produced due to flow of current is given by

$$Q = I^2 R t$$

Electric Power

Electric power is defined as the rate at which work is done by the source of emf in maintaining the electric current in the circuit. SI unit = watt

let W = amount of work done

t = time

P = electric power

$$P = \frac{W}{t} \qquad P = \frac{V^2}{R} \qquad P = I^2 R \qquad P = \frac{E}{t}$$

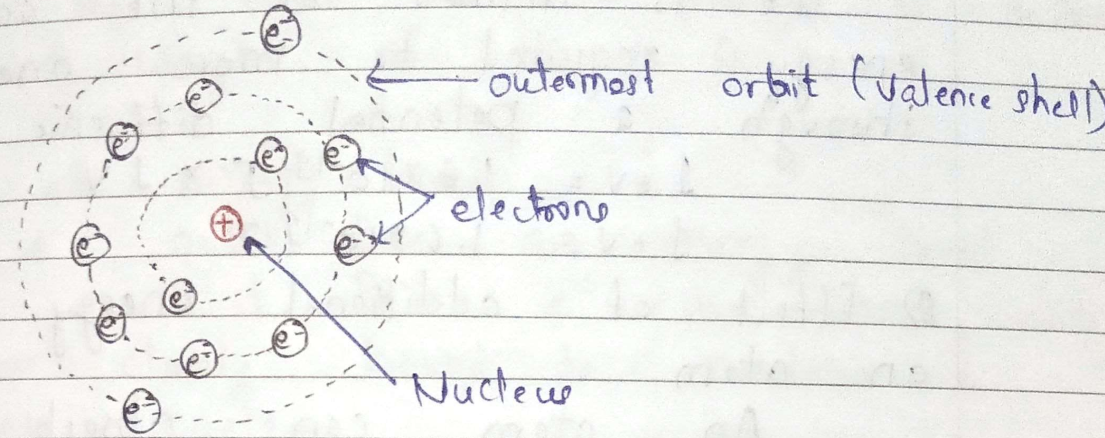
2.4. Conductors, Insulators & semiconductors, Energy bands, intrinsic & extrinsic semiconductors, minority & majority charge carriers.

Atom

Atom is the smallest indivisible particle of an element.

Atom contains protons (+vely charged), electrons (-vely charged) & neutrons (no charge)

These are called fundamental particles
Atom consists of nucleus at the centre with e^- revolving around it.



Structure of an atom

1) Nucleus of an atom consists of proton & neutrons.
2) Atoms are electrically neutral
∵ no. of proton = no. of e^-
3) Atoms can be converted to ions. If atom looses an e^- then it forms positive ion. If atom gains an e^- then negative ion.
4) Electron orbits or shells
A shell can contain maximum $2n^2$ number of electrons where n is the shell number.
5) Valence shell & valence e^-
Outermost shell is known as valence shell & e^- in it are called valence e^-
6) Energy levels of electron shells
Each shell has an energy level associated with it. This energy level represents amount of energy that is required to be supplied to extract an

electron from the shell

7) Energy level & electron volt (eV)

Energy levels are measured in electron volt.

It is defined as the amount of energy required to move one electron through a potential difference of 1 V.

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

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

8) Effect of additional energy absorbed by an atom.

An atom can absorb additional energy due to increase in temperature or from light focussed on it.

Due to absorbed energy, energy levels of e⁻ are raised & they move to higher orbits i.e orbits which are away from nucleus.

If energy is given to valence e⁻ then they will jump out of valence shell & become free. Such free e⁻ are not bound to nucleus of any atom. These free e⁻ constitute the flow of current through a material.

Atomic number

The number of protons in an atom is the atomic number of the atom.

Helium has 2 protons ∴ its atomic number is 2.

Atomic weight

It is approximately equal to the total number of protons & neutrons in the nucleus of an atom.

In He there are 2 protons & 2 neutrons so atomic weight of He is 4.

Concept of energy levels

Each e⁻ orbit has an energy level associated with it. The e⁻ in inner orbits are more closely bound to nucleus & possess less energy.

Energy of shell 1 is lowest.

Energy of valence shell is highest.

Free electrons

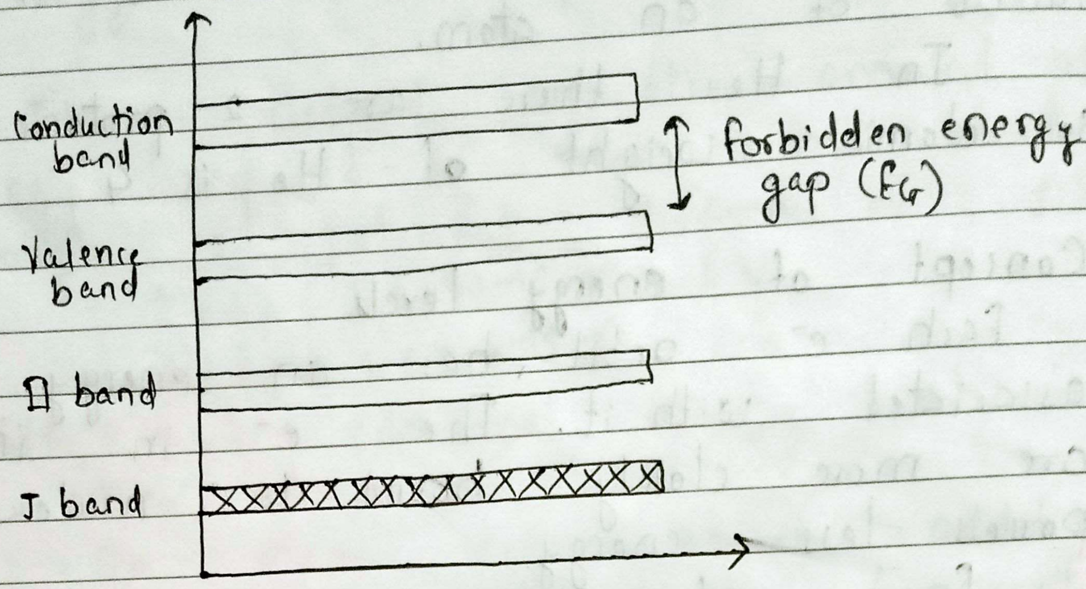
Valence e⁻ are loosely bound with nucleus. On applying external energy to them they can easily break away from nucleus & become free. Such e⁻ which are free from force of attraction of nucleus are called free electrons.

The electric current flows due to these free e⁻ & they are in conduction band.

Energy Bands

Energy bands in solids helps to study the variation in conductivity or resistivity.

Band theory in solids (formation of energy bands)



Valence band

Valence band corresponds to valence e^- present in different atoms of the materials

Conduction band

Conduction band has highest energy associated with it.

e^- in the conduction band are free e^-. These are actually responsible for the flow of current. More the number of electrons in the conduction band more will be the current flow.

Forbidden Energy Gap

The energy gap that separates the conduction & valence bands. No electrons normally exist in forbidden gap.

Depending upon the forbidden gap is large, small or non-existent materials are classified as insulators, semiconductor & conductors respectively.

Valence e^- can acquire energy & jump to the conduction band. The required energy can be supplied by increasing the temperature or focussing light on the material.

This is why conductivity increases with temperature in case of certain materials.

Classification of solids on the basis of band theory.

1) Conductors

Allow the current to flow
eg. metals like copper, aluminium etc.
There is no forbidden gap present between the valence & conduction band.

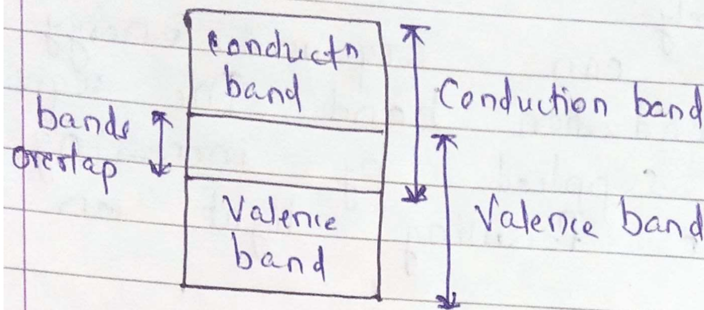
2) Insulator

Do not allow current to pass
eg. wood, plastic, glass
There is a large forbidden gap between the valence band & conduction band.

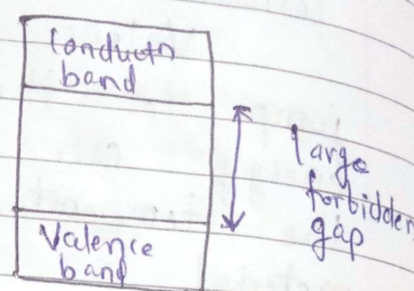
3) Semiconductor

These materials have conductivity that lies between that of a metal & insulators
eg. silicon & germanium.

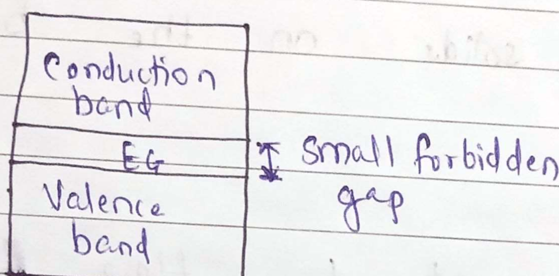
The band gap between valence band & conduction band is very small in semiconductor.



(a) for conductor



(b) for insulator.



(C) for semiconductor
Energy band diagrams

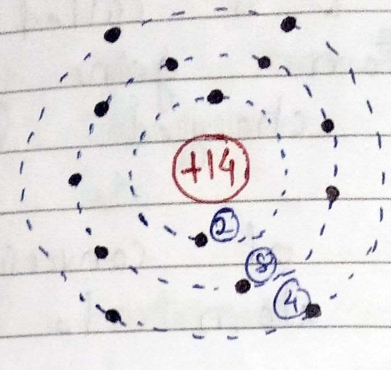
Semiconductor

Structure of silicon & germanium atoms.

1) Silicon

Silicon atom consists of 14 protons & 14 neutrons inside the nucleus & 14 revolving electrons.

First shell contains 2 e^-, second one contains 8 e^- while third shell which is valence shell contain 4 e^-.

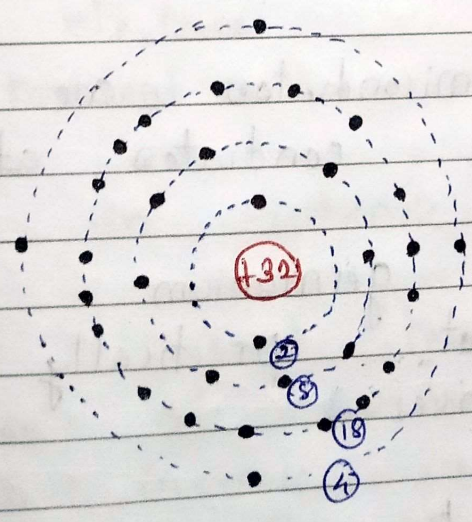


Structure of silicon atom

Germanium atom

It consists of 32 protons & 32 neutrons in the nucleus. The 32 e⁻ are distributed as follows:

2e⁻ in the first shell, 8 e⁻ in the second shell, 18 e⁻ in the third shell & 4 e⁻ in the valence shell.



Structure of germanium atom

Ionization

An atom is electrically neutral when number of protons is exactly equal to the number of electrons

When an atom looses an e^- it becomes positively charged & is called positive ion.

When an atom gains an e^- it becomes negatively charged & is called negative ion.

This process of conversion from an electrically neutral atom to an ion is called as ionization.

Intrinsic & Extrinsic semiconductor

Semiconductors

1. Intrinsic (Pure) : a) Silicon b) Germanium
2. Extrinsic (Impure) : a) p-type b) n-type

1. Intrinsic Semiconductors

These are semiconductor in their purest form.

Intrinsic semiconductors are insulators or very very poor conductors at room temperature

eg. silicon & germanium

These are not practically used for manufacturing devices.

2. Extrinsic Semiconductor

Extrinsic means impure

We can obtain the extrinsic semiconductors from intrinsic ones by adding impurities to them.

The process of adding impurity is called doping.

Due to doping conductivity of semiconductor increases.

Used in manufacturing of all the electronic components such as diodes, transistors etc.

Types of extrinsic semiconductors

1) n-type
2) p-type

Covalent bonds

Bonds formed by sharing of e^- is called covalent bond.

Both silicon & germanium atoms have four e^- in their valence shells they are referred to as tetravalent atoms

Trivalent means atoms having three valence electrons

Pentavalent - five valence electrons.

Conduction in intrinsic semiconductor

1) Effect of increased temperature (Thermal generation of carriers)

With increase in temperature many valence e^- will absorb thermal energy, break the covalent bond & go into conduction band.

These e^- are called conduction e^-

Generation of hole

When ~~an~~ e^- breaks a covalent bond & becomes free a vacancy is created