GOVERNMENT POLYTECHNIC
BHUBANESWAR

LECTURE NOTES

ON

ELECTRICAL ENGINEERING MATERIAL

(TH-4)

SEM:3RD SEM

Department of Electrical Engineering

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CHAPTER-1
CONDUCTIVITY OF METALS

INTRODUCTION:

The most important properties of metals are their high thermal and electrical conductivities. Silver has the highest electrical conductivity. Copper comes next and is similar to silver from the point of view of atomic structure ; both belonging to the same group of periodic table. The conductivity of copper is less than that of silver. Since supplies of copper are not abundant in nature, aluminium which is light and has a high conductivity is rapidly becoming more important as a conductor material. Gold which has a conductivity higher than that of aluminium but lower than that of silver or copper does not find use in electrical industry because it is expensive.Metals having complex structures such as As, Sb, Bi, Sn, Hg have lower conductivities which lie between those of ideal metal (very high conductivity) and of insulators (negligible conductivities).

Resistivity

The resistivity of a substance is the resistance of a cube of that substance having edges of unit length, with the understanding that the current flows normal to opposite faces and is distributed uniformly over them.

The electrical resistivity is the electrical resistance per unit length and per unit of crosssectional area at a specified temperature.

The SI unit of electrical resistivity is the ohm.metre (Ω.m). It is commonly represented by the Greek letter ρ, rho.

Although the SI resistivity unit, the ohms metre is generally used, sometimes figures will be seen described in terms of ohms centimetres, Ω.cm.

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

Where:
R is the electrical resistance of a uniform specimen of the material measured in ohms l is the length of the piece of material measured in metres,cm
A is the cross-sectional area of the specimen measured in square metres, m^2

FACTORS AFFECTING THE RESISTIVITY OF ELECTRICAL MATERIALS

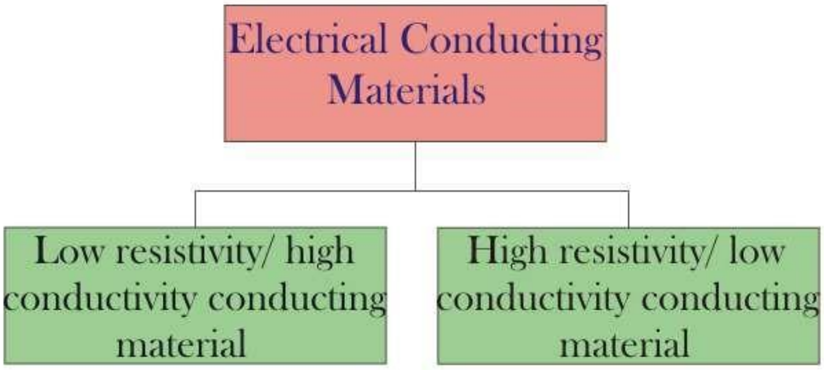
1. Temperature : The electrical resistance of most metals increases with increase of temperature while those of semiconductors and electrolytes decreases with increase of temperature. Many metals have vanishing resistivity at absolute zero of temperature which is known as superconductivity.
2. Alloying : A solid solution has a less regular structure than a pure metal. Consequently, the electrical conductivity of a solid solution alloy drops off rapidly with increased alloy content. The addition of small amount of impurities leads to considerable increase in resistivity.
3. Cold Work : Mechanical distortion of the crystal structure decrease the conductivity of a metal because the localized strains interfere with electron movement.
4. Age Hardening : It increases the resistivity of an alloy.

Classification of Electrical Conducting Materials:

Electrical conducting material are the basic requirement for electrical engineering products. The electrical conducting material can be classified as below-
Based on Resistivity or Conductivity

- Low resistivity or high conductivity conducting material
- High resistivity or Low conductivity conducting material

A classification chart of conducting materials based on resistivity or conductivity is shown in figure below-



Low Resistivity or High Conductivity Conducting Material

Material having low resistivity or high conductivity are very useful in electrical engineering products. These material used as conductors for all kind of windings required in electrical

machines, apparatus and devices. These material are also used as conductor in transmission and distribution of electrical energy.
Some of low resistivity or high conductivity materials and their resistivity are given in table below – • Silver

- Copper
- Gold
- Aluminum

High Resistivity or Low Conductivity Conducting Material

Materials having High resistivity or Low conductivity conducting are very useful for electrical engineering products. These material are used to manufacture the filaments for incandescent lamp, heating elements for electric heaters, space heaters and electric irons etc.
Some of materials having High resistivity or Low conductivity are listed below:

- Tungsten
- Carbon
- Nichrome or Brightray – B
- Nichrome – Vor Brightray – C
- Manganin

Based on Area of Application

- Materials used as conductor for coils of electrical machines
- Materials for heating elements
- Materials for lamp filaments
- Material used for transmission line
- Bimetals
- Electrical Contact Materials
- Electrical Carbon Materials
- Material for Brushes used in Electrical Machines
- Materials used for fuses

Properties of low resistivity materials:

1. Conductivity (σ) :

The conductivity (σ) is the reciprocal of electrical resistivity of the material. The units of conductivity are mhos/cm. It is the property of a material due to which the electric current flows easily through the material. In other words it provides an easy path to the flow of electric current through the material.

2. Low temperature coefficient:

The change in resistance with change in temprature should be low. This is necessary to avoid variation voltage drop and power losses with change in temperature,
2. Tensile Strength :

Strength of a material is defined as the ability to resist load without failure. Tensile strength is therefore tie ability of the material resist a stretching (tensile) load without fracture. Therefore the tensile strength gives an indication of the conductor limit within which it has to be used and beyond which excessive deformation or fracture takes place. It is expressed in load per unit cross sectional area. (tonnes / cm^2).

3. Ductility :

It is the ability of the material to be deformed plastically without rupture under tensile load. A ductile material can be drawn out into a fine wire without fracture and can also be bent, twisted or changed in shape without fracture. Gold, silver, copper, aluminium, nickel, tin, lead etc., are ductile materials.

4. Corrosion Resistance :

Corrosion is a gradual process in a material due to electro-chemical attack. Due to the chemicals present in the atmosphere and if the material is exposed, the metal is generally converted into an oxide, salt or some other compound, thus the metal- does not serve the purpose it is intended to. It may also occur in elevated temperature in media which are inert when near or below the room temperature.

5. Solderability :

Solder is a fusible alloy used to join the surfaces of metals. The property is useful at places where the two pieces of metals are to be joined as in the case of wires.

High resistivity materials:

Materials having high resistivity or low conductivity are very useful for some electrical engineering products and applications. These material are used to manufacture the filaments for incandescent lamp, heating elements for electric heaters and furnaces, space heaters and electric irons etc.

The following properties are required in high resistivity or low conductivity conducting material–

- Low Temperature Coefficient: High resistivity materials are often used as shunts in electrical measuring instruments, in making wire-wound precision resistances and resistance boxes. For such precision applications, an important requirement is that the material of the element should have a negligible temperature coefficient of resistance as otherwise the accuracy of measurements will be affected.

- High Melting Point: In applications like loading rheostats and starters for electrical motors the material of the resistance element should be able to withstand high temperatures for a long time without melting. The consideration of the resistance temperature coefficient in these cases is also important but comparatively higher values than those mentioned in the above paragraph are permissible. The consideration of high melting point is important also for resistance materials used in electrical heating devices like room heaters, furnaces, etc.
- No Tendency for Oxidation: Materials used as high resistance elements in heating appliances should be able to withstand high temperature for a long time without oxidation. This is because if an oxide layer is formed on the heating element the amount of heat radiation will reduce.
- Ductility: High resistance materials are required to be made in the shape of very thin wires in the case of precision wire-wound resistors and the shape of thick wires in the case of the elements used in ovens, heaters, starters, etc. High resistance materials to be used for such applications should, therefore, be capable of being drawn into wires of different sizes and further be capable of being coiled.

- High mechanical strength: High resistivity materials to be used for applications, where the wire must be very thin, are required to have high tensile strength as otherwise, they may break during the drawing of the wire or during the assembly and subsequent operation.

High Resistivity Material and their Applications:

Tungsten

Tungsten is produced by very complicated processes from rare ores or from tungstic acids. Some facts about tungsten are listed below-

- Very hard.
- Resistivity is twice to aluminum.
- High tensile strength.
- Can be drawn in the form of very thin wire.
- Oxidize very quickly in the presence of oxygen.
- Can be used up to 2000^{o}C in the atmosphere of inert gases (Nitrogen, Argon etc.) without oxidation.

Properties of Tungsten

Properties of tungsten are listed below-

- Specific weight : 20 gm/cm^3
- Resistivity : 5.28 μΩ -cm
- Temperature coefficient of resistance : 0.005 / ^{o}C
- Melting point : 3410^{o}C
- Boiling point : 5900^{o}C

- Thermal coefficient of expansion: 4.44×10^{-9} / °C

Uses of Tungsten

1. Used as filament for incandescent lamp.
2. As electrode in X- ray tubes.
3. The great hardness, high melting and boiling points make it suitable for use as electrical contact material in certain applications. It is having high resistance for destructive forces produces during operation of electrical contacts.

Carbon:

Carbon in widely used in electrical engineering. Electrical carbon materials are manufactured from graphite and other forms of carbon.

Properties of Carbon

- Resistivity : 1000 – 7000 μΩ – cm
- Temperature coefficient of resistance : – 0.0002 to – 0.0008 /°C
- Melting point : 3500°C
- Specific gravity : 2.1gm $/cm^3$

Uses of Carbon

Carbon is having following applications in electrical Engineering

1. Used for making pressure sensitive resistors, which are used in automatic voltage regulators.
2. Used for manufacturing the carbon brushes, which are used in DC machines. These carbon brushes improve the commutation as well as reduce the wear and tear.
3. For making filament of incandescent lamp.
4. For making electrical contacts.
5. For making resistors.
6. For making battery cell elements.
7. Carbon electrodes for electric furnaces.
8. Arc lighting and welding electrodes.
9. Component for vacuum valves and tubes.
10. For makings parts for telecommunication equipment.

Platinum:

- Though pure platinum is very good metal but its use is limited due to its high cost, high-temperature coefficient of resistance (0.003 Ω/Ω/per °C). It is a heavy, grayishwhite, non-corroding noble metal which is malleable and ductile, but poorly fusible and resistant to most chemicals. The properties of platinum are as follows:

Specific Weight — 21400 kg/ m^3
Melting Point — 1775°C
Boiling Point — 4530°C
Thermal Coefficient of Expansion — 9 x 10^{-4} per °C
Resistivity — 0.1 μΩ-m

- Platinum can be drawn into thin filaments and strips and is used in different electrical devices, for example, as the heating elements in electrical laboratory ovens and furnaces (at extra high temperatures above 1,300°C it begins to atomize), in platinum-platinum-rhodium thermocouples working at temperatures up to 1,600°C.
- Multiple drawing of a bimetallic platinum-silver wire, after which the surface layer of silver is dissolved in nitric acid (that does not act on the platinum), is the way extra-thin elements of about one-micron diameter are made for suspending movable parts in electric meters and other sensitive instruments.
- Other applications of platinum are insoluble anodes, thermocouples, electrical contacts, corrosion-resistant laboratory accessories, electrical furnace windings, catalytic gas igniters, grids in special-purpose vacuum tubes, etc.

Mecury:

It is good conductor of electricity and heat.
It is a heavy silver white metal.
It is only metal which is in liquid state at room temp.

Properties:
Specific Weight — 13.55g/ cm^3
Boiling Point — 357°C
Thermal Coefficient of Expansion — 0.00027 °C
Resistivity — 0.95 μΩ-m

Uses:
It is used in mercury vapour lamp, mecury are rectifier gas filled tube etc.

Application of Low Resistivity or High Conductivity of Conducting Material:

Material having low resistivity or high conductivity are very useful in electrical engineering for manufacturing electrical engineering machines or equipment's. These material used as conductors for all kind of winding required in electrical machines, apparatus and devices. These material are also used as conductor in transmission and distribution of electrical energy

Silver (Ag):

Silver is the best conductor of electricity. It is having highest conductivity. It is moldable and weld able. The main drawback of it that it is very costly, which limits its practical use in electrical machines / equipment. However, it is still used in precious equipment used for research where cost of equipment does not matter.

Properties

1. Resistivity : 1.58 μΩ -cm
2. Temperature coefficient of resistance at 20^{o}C: 0.0038/^{o}C
3. Melting point: 962^{o}C
4. Specific gravity: 10.49 gm /cm^{3}

Copper (Cu):

The extensively used, high conductivity material as conductor for electrical machines or equipment, is copper. Malleability, weld ability and solder ability are most important properties of copper. Copper in pure form is having good conductivity. But the conductivity of standard grade copper is reduced due presence of impurities.

Properties

1. Resistivity : 1.68 μΩ -cm
2. Temperature coefficient of resistance at 20^{o}C: 0.00386 /^{o}C
3. Melting point: 1085^{o}C
4. Specific gravity: 8.96gm /cm^{3}

Gold (Au):

Gold is a precious and costly metal. It is having good conductivity. Gold is having highest malleability and ductility among all metals. Due to high cost, its practical use is limited to precious instruments used for research.

Properties

1. Resistivity : 2.21 μΩ -cm
2. Temperature coefficient of resistance at 20^{o}C: 0.0034 /^{o}C
3. Melting point: 1064^{o}C
4. Specific gravity: 19.30gm /cm^{3}

Aluminum (Al):

Aluminum is an element which is a silver-white, light weight, soft, non-magnetic and ductile metal. Aluminum is the third most abundant element (after oxygen and silicon) and most abundant metal found in earth's crust. The main ore of aluminum is bauxite. Aluminum is having low density, high ductility, good corrosion resistance and good conductivity, which makes it suitable to use as electric conductor for transmission and distribution of electricity.
Properties

1. Resistivity: 2.65 μΩ -cm
2. Temperature coefficient of resistance at 20°C: 0.00429 /°C
3. Melting point: 660°C
4. Specific gravity: 2.70 gm /cm^3

Steel:

It contains iron with a small percentage of carbon added to it.
Iron itself is not stronger but when carbon is added to it .
Due to addition of carbon tensile strength of steel increases.
Its resistivity is 8-9 times higher than copper.
It is easily affected by moisture of zinc coating is provides on its surface.

Uses:

Galvanised steel wires are used as over head telephone wires and earth-wires.

Application of Low resistivity copper alloy:

Brass (60% copper and 40% zinc)

- It is the generic term for a range of copper-zinc alloys with differing combinations of properties, including strength, machinability, ductility, wear-resistance, hardness, colour, hygienic, electrical and thermal conductivity, and corrosion-resistance.
- Brasses set the standard by which the machinability of other materials is judged and are also available in a very wide variety of product forms and sizes to allow minimum machining to finished dimensions. Brass does not become brittle at low temperatures like mild steel.
- Brass also has excellent thermal conductivity, making it a first choice for heat exchangers (radiators). Its electrical conductivity ranges from 23 to 44% that of pure copper.

Bronze (copper, tin and third element like phosphorus, beryllium, silicon and cadmium)

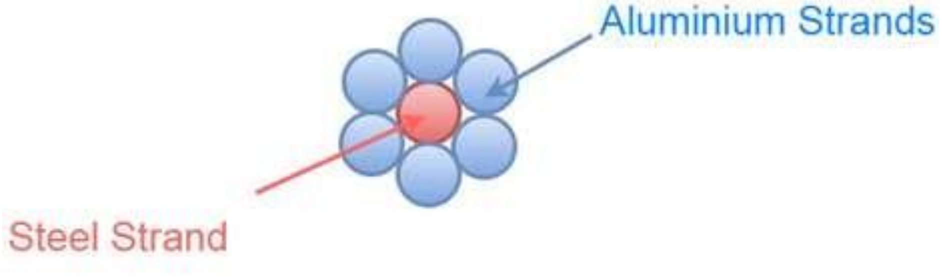
- These alloys are made from copper and tin, and were the first to be developed, about four thousand years ago. They were so important that they led to a period in time being named the Bronze Age.
- When copper and added with phosphorus called phosphorus bronze, with silicon silicon bronze, like wise beryllium bronze and cadmium bronze.
- It is used for making current carring spring, slide contacts etc.
- It is free from corrosion.

Beryllium-Copper

- It is similar in mechanical properties to many high strength steels but, compared to steels, it has better corrosion resistance (approximately equivalent to nickel silvers), higher electrical conductivity (16-65% IACS) and higher thermal conductivity (210W/m^{o}C). It is also non-sparking and non-magnetic. Beryllium-copper should only be specified where its unique combination of properties can be fully exploited.
- Because of the excellent fatigue resistance, beryllium-copper is widely used for springs, pressure responsive diaphragms, flexible bellows, connectors, contacts and relays, which are all subject to cyclical loading.
- The anti-galling, strength and good corrosion resistance led to the widespread use of beryllium-copper for down-hole drilling tools for the oil and gas industry.
- It is used for making current carring spring, brush holder, sliding contacts etc.

Stranded conductors:

Stranded conductors are very much popular in electrical power system for transmission and distribution line. A stranded conductor is consists of several thin wires of small cross sectional area called strands as shown in figure below-



Stranded Conductor

- As shown in figure above, at the center of stranded conductor, we are using steel conductor which provided the high tensile strength to conductor. In the outer layers of **stranded conductor**, we use aluminum conductors, which provide the conductivity to stranded conductor.

- Basic, reason of using stranded conductor is to make the conductor flexible. If we use a single solid conductor. It does not have sufficient flexibility and it is difficult to coil a solid conductor. Hence, it becomes difficult to transport a single solid conductor of long length over the distance. To eliminate this drawback, conductor is formed by using several thin wires of small cross section. These thin wires are called strands. By making the conductor stranded, it becomes flexible. Which makes **stranded conductor** suitable to be coiled easily to transport it over long distance.
- It is used in high voltage line.
- The **stranded conductor** is having sufficient flexibility, which makes stranded conductor suitable to be coiled easily to transport it over long distance.
- For a stranded conductor of same cross sectional area, the flexibility of conductor increase with increase of number of strands in conductor.
- The stranded conductor is formed by twisting the strands together in layers.
- The strands of each layer are laid in helical fashion over the preceding layer. This process is called stranding

Bundle conductors:

- The adoption of bundled conductors in extra high voltage transmission enables stranded conductors to be employed and gives an increased current carrying capacity compared with a single conductor of equivalent crosssectional area.

- Since the voltage stress at conductor surface is reduced by using bundled conductors, corona loss is smaller and the line is less liable to cause radio interference.

Superconductors:

- A superconductor is a material that can conduct electricity or transport electrons from one atom to another with no resistance. This means no heat, sound or any other form of energy would be released from the material when it has reached "critical temperature" (T_c), or the temperature at which the material becomes superconductive. Unfortunately, most materials must be in an extremely low energy state (very cold) in order to become superconductive.
- It has been stated that the resistivity of most metals increases with increase in temperature and vice-versa. There are some metals and chemical compounds whose resistivity becomes zero when their temperature is bought near 0^{o} kelvin (273^{o}C). At this stage such metals are said to have attained superconductivity.

Types

Superconductors are classified into Type I and Type II materials.

Type-I

- Type-I superconductors are generally pure metals.
- These are also called as Soft Superconductors.
- These are also called as Low-temperature Superconductors.
- Slight impurity does not affect the superconductivity of type-I superconductors.
- Due to the low critical magnetic field, type-I superconductors have limited technical applications.
- Examples: Hg, Pb, Zn,etc.

Type-II

- Type-II superconductors are generally alloys and complex oxides of ceramics.
- These are also called as Hard Superconductors.
- Slight impurity greatly affects the superconductivity of type-II superconductors.
- Due to the high critical magnetic field, type-II superconductors have wider technical applications.
- Examples: NbTi, Nb_3Sn, etc.

Application of superconductor Materials:

Electrical Machines: It is possible to manufacture electrical generators and transformer with the efficiency about 99% with the help of super conducting materials and the size of machine will also be small.

Power cables: If super conductor materials used in power cables it will enables the transmission of power for long distance without power loss or drop in voltage.

Electromagnets: By using super conductor materials we can use solenoid which doesn’t produce heat during operations. It has been possible to design electromagnets using superconductivity for use in laboratories and for low temperature device.

Future scopes: It must be realized that the above applications require the conductor to be maintained at temperature very close to $0\,^{o}$K.

CHAPTER-2 SEMICONDUCTING MATERIALS

SEMICONDUCTOR:

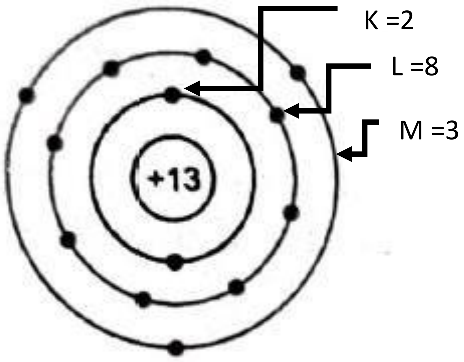
- Semiconductors are materials which have a conductivity between conductors (generally metals) and insulators (such as glass).
- A semiconductor is neither a good conductor nor a good insulator.
- Typical semiconductor materials are Germanium and Silicon each of which have four valence electrons.

ELECTRON ENERGY AND ENERGY BAND THEORY:

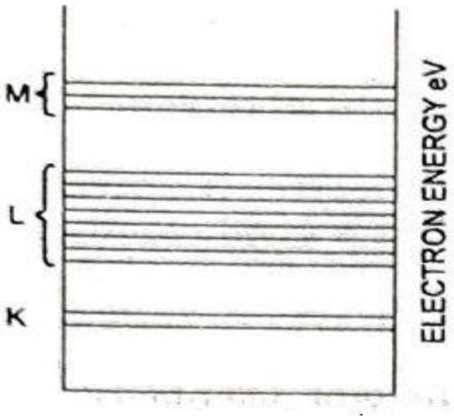
An electron revolving around the nucleus of an atom has potential energy,centrifugal energy, rotational energy and magnetic energy, all of which together determine the total energy or the energy level of an electron. This valueis measured in electron volts(eV).

The electron volt is defined as that amount of energy gained or lost whenan electron moves with or against a potential difference of one volt.

$$1\, eV = 1.602 \times 10^{-19} Joule$$



(a)The Bohr Model of an Aluminium atom

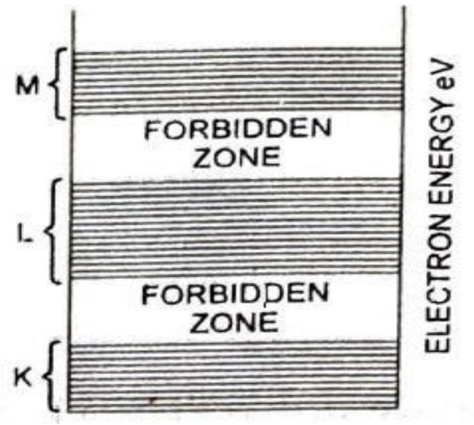


(b)**Energy Level of Al Atom**

Let us discuss the Bohr Model of an Al atom.

- The larger the orbit in which an electron revolves, the greater is its energy. Electrons with least energy are on the K level i.e., the orbit closest to the nucleus. Each succeeding level contains electrons with higher energies.
- If an individual atom is considered then all atoms in a given level shall possesses same energy. But atoms do not exist in isolation they are in large groups crowded together. The nuclei of neighbouring atoms exert forces of attraction on each other's electrons. So, no two electrons share exactly the same orbit and, therefore,the energy of no two electrons is the same.

- Each level or shell is therefore,divided into subshells, each subshell having a different energy level. Each electron occupies an energy level different from that of any other.
- The energy levels have been grouped into energy bands. The areas between them are called energy gaps; they are also called forbidden zones, since no electron can have an energy represented by these areas.



Energy Levels grouped as Bands

EXCITATION OF ATOMS:

When each electron in an atom is in its normal orbit, the atom is said to be in an unexcited state.

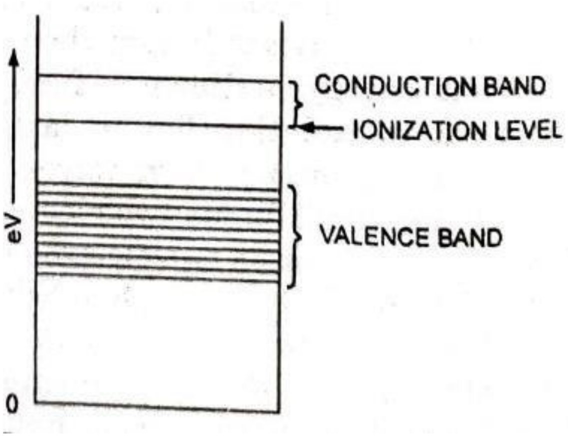
When the electron is in the higher energy level, the atom is said to be in an excited state.

To move an electron away from the nucleus requires additional energy. The additional energy can be obtained from any of the following sources:

1. Light,
2. Heat,
3. Electrostatic,
4. Magnetic,
5. Kinetic

- The quantum of energy, in electron volts, required to move an electron from one energy level to a higher energy level varies from material to material.For example, an atom of one type of material may require a quantum of energy corresponding to 1.9 eV, whereas another material may need 3.5 eV.
- When the required amount of light or heat energy is absorbed by a valence electron, it will leave the valence band and may move up to the ionization level.
- It is released from the attractive forces of the nucleus and is free to float around between the atoms and to conduct.
- An electron above the ionization level is said to be in the conduction band and is called a free electron.
- when an electron leaves the valence band, the remaining atom is no longer neutral but has a positive charge and is called a positive ion. The atom is said to be ionized.

- Its positive charge will attract a nearby free electron, which will give up its acquired energy. Thus, there is a constant interchange of electrons being given up and retrieved.



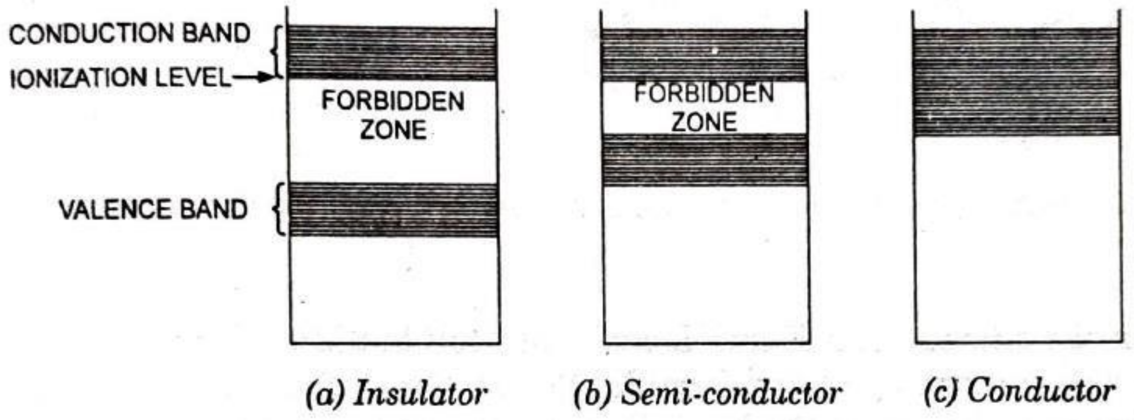
Energy band representation of Ionization level

INSULATORS, SEMICONDUCTORS AND CONDUCTORS:

INSULATORS: In an insulator, the valence electrons are tightly bound to the nucleus of the atom.The forbidden zone between the valence band and the conduction band is quite large. This indicates that electrons in the valence band require large amount of additional energy to move up and become free. As long as the valence electrons are unableto move upto the conduction band there can be no electron flow.

SEMICONDUCTORS: In the case of semiconductors the forbidden zone is reduced. Thus the valence electrons require less energy to free themselves from the attraction of the nucleus.

CONDUCTORS: In a conductor such as copper or aluminium, the valence electrons are very loosely bound to the nucleus. In a conductor there is no gap between the valence band and the conduction band. For the better conductors the conduction and valence bands may even overlap. Electrons from the valence ring may be moved into the conduction zone by a small amount of energy thus becoming free and are drawn back into the valence ring of an ionized atom, releasing their acquired energy as heat.The released heat then freesother electrons and the process goes on.

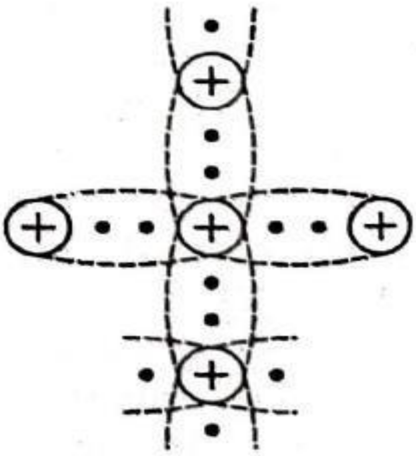


Energy and Ionization levels

COVALENT BONDS:

- A covalent bond results from sharing of pairs of valence electrons by two or more atoms.
- The atoms of materials having 4 or more than 4 electrons revolving in their outermost orbits must share their electrons with the neighbouring atoms because an atom must have at least 8 electrons in the outer most orbit in order to be stable.
- Each bond with two electrons is an electron pair bond.
- When atoms enter into covalent bonding, each atom has eight valence electrons and this, would result in making such a material a good insulator.
- But this structure is not a good insulator for several reasons:
    - First, a good insulator must have a perfect crystal structure. Covalent bonding, leads to the development of a polycrystal i.e. several individual crystals held together imperfectly. The extra atoms are not properly locked in place and there are missing atoms in some parts of the structure.
    - Second, due to impurities there may be extra electrons which cannot lock into the covalent bond structure.
    - Third, energy in the form of heat, light can cause structure disorder.

From the above reasons, the material does not have a perfect crystal structure and is, therefore, not a good insulator but a poor insulator or called as a semiconductor.
The temperature and the extent to which impurities exist in the structure of the material determine the degree of conduction.



Sets of covalent bond or sharing

INTRINSIC SEMICONDUCTORS:

If a crystal (silicon or germanium,) does not contain any impurity atoms i.e. if it contains only one type of atoms, it is called an intrinsic material.

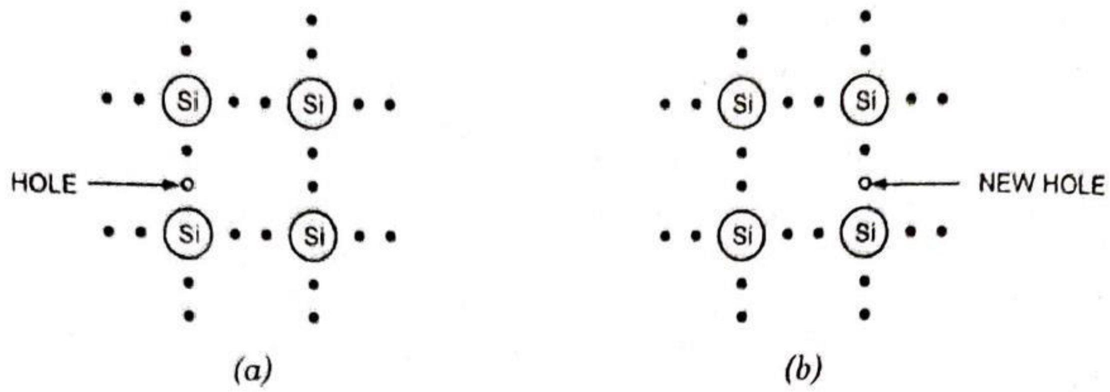
- At 0°K (i.e. - 273°C) temperature this intrinsic material will act as a good insulator .
- When operated at room temperature, however, enough thermal energy is provided to raise the valence electrons into the conduction band making them free as current carriers.
- When an electron is freed from the atom of an intrinsic material it breaks a covalent bond and leaves behind a vacancy (called a hole). The free electron and the hole form an electron-hole pair.
- The higher the temperature, the greater the number of free electrons and therefore, of holes. Thus, higher the temperature, the greater the thermal agitation giving rise to more electron hole pairs.
- A hole in effect means the loss of an electron and is therefore considered to be positively charged with the same charge as an electron.

When a voltage is applied to an intrinsic material at a temperature above 0°K. it acts as a conductor. The higher the temperature, the more the free electrons and therefore better the conduction.

The holes created by the free electrons are fixed in the atomic structure and do not actually move. However, they appear to move from the positive to the negative terminal. This is because when a hole is created by an electron breaking a covalent bond due to thermal energy, a valence electron from a neighbouring atom may have just enough energy to break its bond and jump over into this hole, thereby creating a new hole. As this occurs, it appears that the hole has moved from one atom to another (but in fact it is a valence electron which has moved in the opposite direction).

If a voltage is applied to a semiconductor containing free electrons and holes, current consisting of two parts will flow: free electronics moving in one direction and holes moving in the opposite direction. The total current is the sum of the two parts.

In an ordinary conductor, the amount of electron flow is determined by the applied voltage. However, in an intrinsic material the temperature is also a factor since increased heat generates more electron-hole pairs, thereby increasing the current flow. The higher the temperature of a semiconductor material, the lower its resistance and better its conduction. Thus intrinsic semiconductors have negative temperature coefficient.



Hole Movement Caused by Valence Electrons Jumping from Hole to Hole

EXTRINSIC SEMICONDUCTORS:

Pure (i.e. intrinsic) silicon or germanium exhibits characteristics closer to that of an insulator than a semiconductor. Therefore, an intrinsic semiconductor is of little use as a semiconductor except as a heat or light sensitive resistance. It is not used for transistor work.

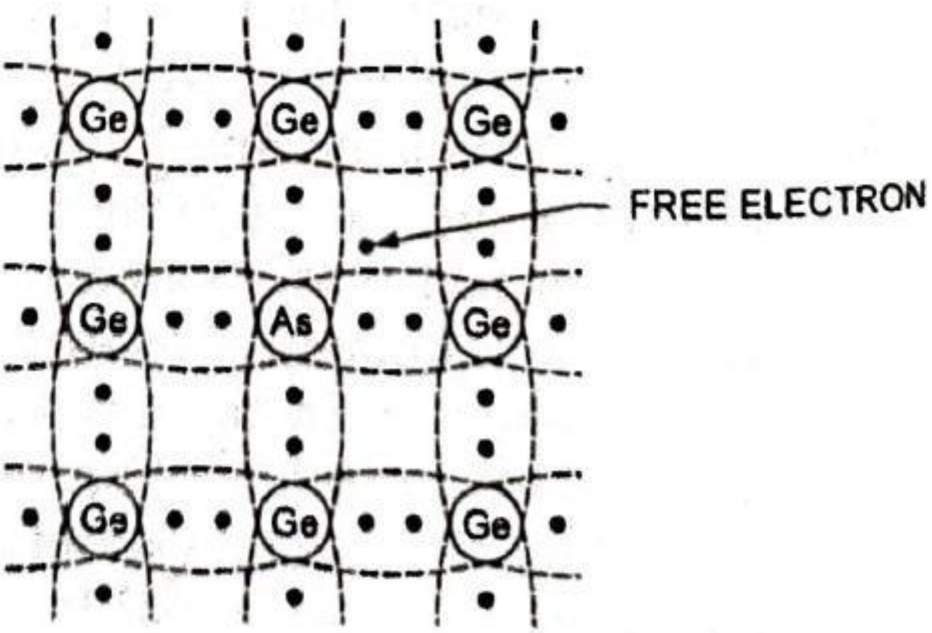
In order that the material may function properly as a semi-conductor, certain impurities are added in very carefully into the intrinsic semiconductor. The addition of impurities is called ***doping***. A material which has been doped (i.e. impurities are added) is called an ***extrinsic material.***

Extrinsic semiconductors are of two types: N-type and P-type.

N-TYPE MATERIALS:

One category of the impurities has five valence electrons and is called the pentavalent group. The impurities of this group are Antimony, Arsenic, and Phosphorus.

When a pentavalent impurity is added to an intrinsic material (germanium or silicon) only four of its valence electrons lock into the covalent bond formation of the atomic structure. The fifth valence electron of the impurity atom is free to wonder through the crystal.



Arsenic Impurity Atom Provides a Fifth Electron That Cannot Enter the Covalent Bond Structure

The impurity atom becomes ionized and has a positive charge when its fifth valence electron moves off. The impurity atom thus becomes a positive ion. The positive impurity ion so formed is not free but is firmly held in the crystal structure.

Since pentavalent atoms provide (or donate) an extra electron, they are called donor impurities. A material doped with a donor impurity has excess of electrons in its structure and is, therefore, known as negative or N-type material. The net charge of the N-type material is still neutral since the total number of electrons is equal to the total number of protons.

P-TYPE MATERIALS:

Another category of impurities has three valence electron and is called the trivalent group. Some of the impurities of this group are Aluminium, Gallium, and Indium.

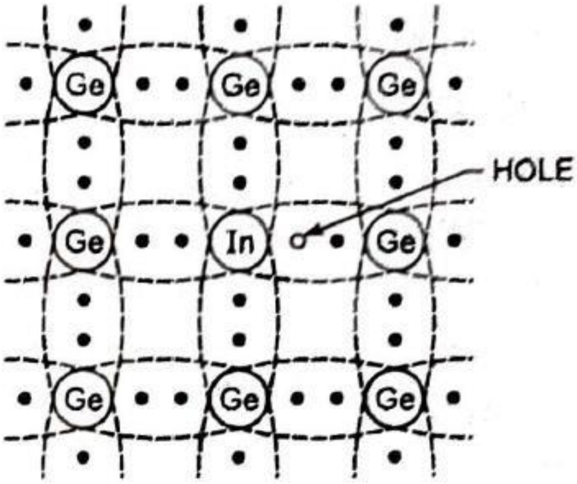
When added to intrinsic materials they lock into the crystal structure. Since the impurity has three valence electrons, there is a hole in the covalent bond structure created by the lack of an electron. The hole represents an incomplete covalent bond and exhibits a positive charge.

In order to complete the bond and form a stable eight electron structure a valence electron from a nearby atom gains sufficient energy to break its bond and jump into the hole due to attraction from it. Therefore, this type of impurity is known as acceptor.

The electrons available to fill the hole and complete the bond have been released by the atoms whose bonds have been broken and holes created. So the process will continue thus creating a mobility of holes.

The impurity atom becomes negatively ionized when it accepts an electron and the germanium (or silicon) atom which released one electron becomes positively ionized. The net charge of the material is still neutral, since the total number of protons equals the total number of electrons.

Intrinsic materials doped with a trivalent impurity are referred to as positive or P-type because the lack of electrons for the covalent bond structure causes an attraction to nearby electrons.



In P-Type Material an Indium impurity atom creates a Hole in The Covalent Bond Structure to provide an attraction for an electron

MAJORITY AND MINORITY CARRIERS:

In N-type materials conduction takes place through free electrons created by doping and a small number created by thermal generation. The small number of holes created by thermal generation move in the opposite direction. Since the number of free electrons is large they are called majority carriers. The holes being small in number are called minority carriers.

Similarly, in P-type materials holes are the majority carriers and electrons are the minority carriers.

SEMICONDUCTOR MATERIALS:

- The electrical characteristics of semiconductor materials fall between those of insulators and conductor.
- Thus, a semiconductor has a valence ring of four as compared to valence rings of eight electrons for the best insulators and one electron for the best conductors.
- Semiconductor materials have a narrow forbidden gap.

Of all the elements in the periodic table, eleven are semiconductors.

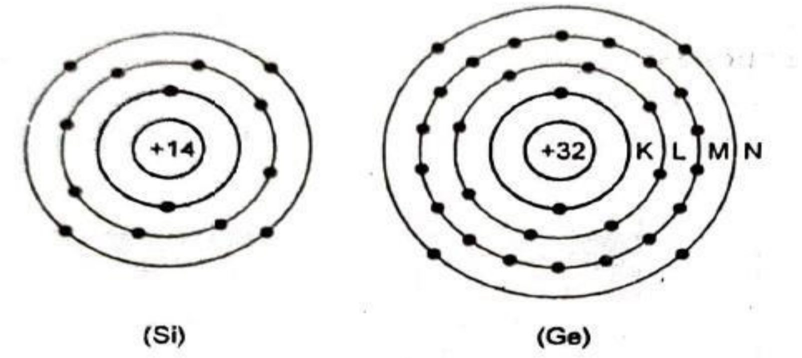
These elements are

1. Boron,
2. Carbon,
3. Silicon,
4. Germanium,
5. Phosphorus,
6. Arsenic,
7. Antimony,
8. Sulphur,
9. Selenium,
10. Tellurium,
11. Iodine

The two most widely used semiconductor materials are

- i. silicon (Si)
- ii. Germanium (Ge).

The atomic structure of Silicon and Germanium is shown below.

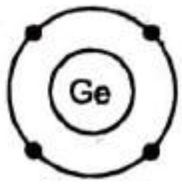


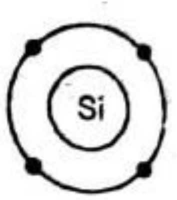
Shell Arrangements for Silicon and Germanium

In the silicon atom K and L shells are full but M shell contains only four electrons. According to $2n^2$ formula the M shell can contain18 electrons; however, the M shell in silicon is the valence shell and thus cannever contain more than eight electrons.

In the germanium atom the K, L and M shells are filled and the N shell is the valence shell containing four electrons.

since the valence electrons only are important from the chemical and electrical point of view, both germanium and silicon atoms can be represented by only outer shell.





The resistance of a semiconductor material can be controlled by changes in temperature and/or by adding impurities. The resistance of semiconductor materials can also be controlled by the following factors:

i. illumination,
ii. voltage,
iii. electric field.

Semiconductors can be classified as

i. Mono-crystals with an atomic lattice structure like carbon, silicon germanium; and poly-crystals with molecular lattice structure like selenium tellurium, antimony, arsenic, phosphorus;
ii. Oxides of such metals as copper, zinc, cadmium, titanium, molybdenum, tungsten;
iii. Sulphides, selenides and tellurides of lead, copper, cadmium and other elements; iv. Chemical compounds of certain elements of the third group of the Periodic Table like aluminium, gallium, indium with those of the fifth group like phosphorus, antimony, arsenic and also compounds of the fifth group elements like antimony with those of the second group like magnesium and zinc.

Applications of Semiconductor Materials

1. Rectifiers:

a) **Germanium and Silicon Rectifiers:** A P-type and a N-type material are joined together to form a junction called the P-N junction. When an external voltage is applied across the two materials a flow of current results if the positive and negative terminals of the voltage source are connected respectively to the extreme ends of the P and N materials. This is called forward biasing. If the applied voltage is reversed i.e. the positive of the supply voltage is connected to the N side and the negative of the supply voltage is connected to the P side, there is no flow of current. This is called reverse biasing. Thus the P-N junction offers high conductivity when forward biased and no conductivity when reverse biased.

Thus semiconductors can be used as rectifiers. Semiconductor P-N junction diodes have almost replaced thermionic values as rectifiers. Modern P-N junction rectifiers use germanium or silicon as the semiconductor material.

Germaniunm rectifiers were invented earlier than silicon rectifiers. Germanium and Silicon semiconductors find wide use in both high frequency and supply frequency circuits particularly as non-controlled rectifiers e.g. diodes and controlled rectifiers (e.g. transistors and silicon controlled rectifiers). Germanium and silicon rectifiers can operate at high current densities and reverse voltages with efficiencies of about 98%.

Advantages of Germanium Rectifiers:

i. It is easier and simpler to produce germanium nanocrystals. ii. Germanium has a melting point of 958°C and silicon 1,415°C.

iii. Molten silicon combines readily with all chemical elements and, is therefore, very difficult to purify and maintain free from impurity. All this would favour the use of germanium.

Disadvantages of Germanium Rectifiers:

i. They have limited working temperature from -50 to + 70 degrees C. Continuous operation at temperatures over + 60°C causes thermal ageing and deterioration of electrical characteristics.

ii. At low temperatures there is a considerable drop in the permissible reverse voltage.

Advantages of Silicon Rectifiers:

i. Silicon rectifiers can operate at temperatures up to 200°C. ii. Silicon diodes have an advantage over germanium diodes in high frequency electronic circuits as they are more sensitive to weak signals.

iii. Silicon rectifiers are available for very high PIV rating, of the order of 25kV and current rating of the order of 1000 amps.

Disadvantages of Silicon Rectifiers:

i. Frequency response is poor (i.e. at high frequency the depletion capacitance becomes prominent and this causes distortion of the rectified wave shape).

Silicon rectifiers are normally used in power rectifying devices and heavy current application silicon rectifiers find wider industrial application.

A silicon controlled rectifier (SCR) may be considered as a combination of two transistors one n-p-n type and the other p-n-p type. The regenerative action of the device depends on the current gain of the two separate transistors. The sum of the current gains of the two transistors should approach unity for this. Since Ge does not exhibit such property, only Si is used as base material for developing Silicon Controlled Rectifiers (SCRs).

b) **Copper-oxide and Selenium Rectifiers**: The earliest semiconductors to be used as rectifiers used copper-oxide or selenium. Copper oxide rectifier is a plate of 99.98 % pure copper on which a film of cuprous oxide is produced by a special process. One side of the plate is cleaned of cuprous oxide and an electrode is soldered directly to the copper. The second electrode is soldered to the cuprous oxide film. When positive potential is applied to the oxide layer and negative to the copper, it corresponds to forward biasing a P-N junction. By arranging the copper plate elements in stacks, rectifiers for many kinds of measuring circuits and instruments can be obtained.

Advantages of Copper oxide Rectifiers:

i. Copper oxide rectifiers are comparatively cheaper than Silicon rectifiers.
ii. Copper oxide rectifiers are available for low PIV and current rating.
iii. They are used in rectifier type instruments as in electronic multimeters.
iv. Frequency response is better (all the frequencies, the voltage drop across the device remains constant and there is no distortion in the rectified wave shape.)

Disadvantage of Copper oxide rectifiers is that it completely fail at sufficiently high reverse voltage.

Selenium rectifiers use more than 99.99% pure selenium. Purity is very important in respect of permissible current density and reverse voltage. Crystalline selenium which has a melting point of 220°C is used for making rectifiers. The barrier layer in the form of cadmium selenide is produced by a forming process.

Advantages of Selenium Rectifiers:

i. The selenium rectifier has a greater permissible current density and wider working temperature range as compared to copper oxide rectifier.
ii. Selenium rectifiers sometimes self-seal, if breakdown occurs at high reverse voltage, by fusion into the amorphous form of selenium which is an insulator

Selenium rectifiers find application, among other purposes, in battery charges and electroplating supplies.

Both copper oxide and selenium rectifiers are protected against moisture by giving their elements a coating of insulating varnish. Copper oxide rectifiers are often sealed in hermatic containers for this purpose.

2. **Temperature-sensitive Resisters or Thermisters:** Increasing the temperature of semiconductor materials causes their resistance to decrease. This property has found application in devices called thermisters.

   Thermisters are thermally sensitive resistors. They are made from oxides of certain metals such as copper, manganese, cobalt, iron, zinc. Often a mixture of several oxides is used because it can be arranged to give them the required properties.

   Thermisters find application in temperature measurement and control. They sense temperature variations and convert these variations into an electrical signal which is then used to control heating devices. Other applications of thermisters include measurement of radio frequency. Power, voltage regulation and timing and delay circuits.

3. **Photoconductive Cells:** The resistance of semiconductor material is low under light and increases in darkness. This phenomenon is used in photoconductive cells where a semiconductor material is connected in series with a voltage source. The resistance

of the semiconductor varies with the intensity of light and thus the current in the circuit is controlled.

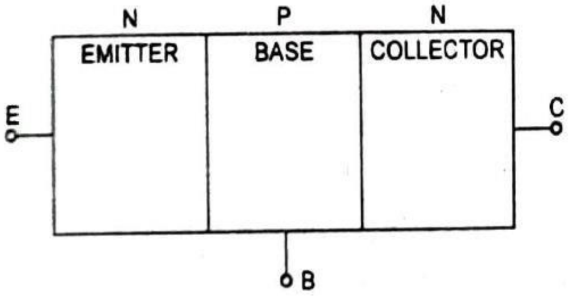
Photo conductive cells can be used in applications which require the control of a certain function or event according to the colour or intensity of light. Some of their applications are those of door openers, burglar alarms, flame detectors, smoke detectors and control for street lights.

4. **Photovoltaic Cells:** Photovoltaic cells are devices that develop an e.m.f. when illuminated. Thus they convert light energy directly into electrical energy. No outside source of electrical energy is required to produce current flow as a photoconductive device.

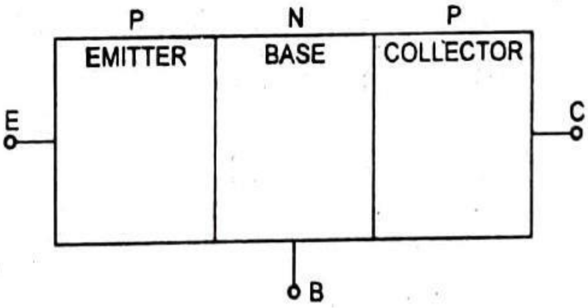
5. **Varisters:** The resistance of semiconductors varies with the applied voltage. This property is used in devices called varisters. Use of varisters is made in voltage stabilizers and motor speed control.

6. **Transistors:** The resistance of semiconductors depends to a large extent on the magnitude of electric field. The current in a semiconductor does not follow Ohms law and increases more rapidly than the voltage. This property has been used in the device called transistor.

A transistor is a two junction three terminal device, the two junctions being formed by joining P, N and P material or N, P and N materials. Transistors have replaced the vacuum and gas tubes in performing many jobs including amplification of signals and switching circuits.

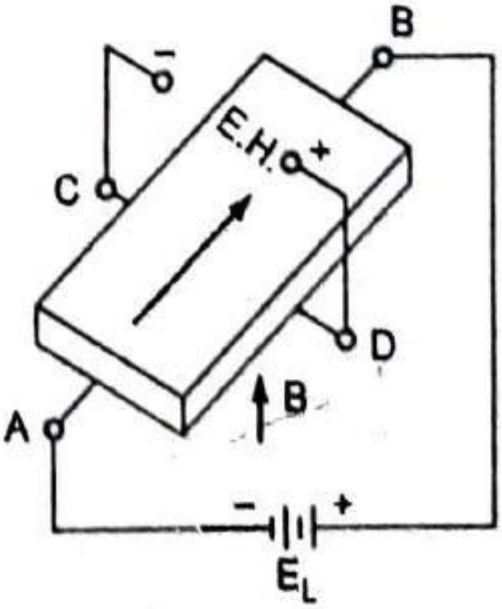


(a) NPN Transistor Structure



(b) PNP Transistor Structure

7. **Hall Effect Generators:** When a current flows through a semiconductor bar placed in a magnetic field, a voltage is developed at right angles to both the current and the magnetic field. This voltage is proportional to the current and the intensity of the magnetic field. This is called the *Hall Effect.*



Hall Effect Device

Consider the semiconductor bar which has contacts on all four sides. If a voltage E_L is applied across the two opposite contacts A and B a current will flow. If the bar is placed perpendicular to a magnetic field B, an electric potential E_H is generated between the other two contacts C and D. This voltage E_H is a direct measure of the magnetic field strength and can be detected with a simple voltmeter.

The Hall Effect generator may be used to measure magnetic fields. It is capable of measuring magnetic field strengths that have a strength 10^{-6} of that of the magnetic field of the earth.

8. **Strain Gauges:** Semiconductors besides being sensitive to heat, light, voltage and magnetic field are also sensitive to mechanical forces. If a long thin rod of silicon is pulled from end to end its resistance increases considerably because the mechanical force pulls each silicon atom slightly away from its adjacent atom. This increases the width of the forbidden energy gap, thus increasing the resistivity of the rod.

   Silicon and other semiconductor material make very sensitive strain which gauges which are devices used to measure small changes in the lengths of solid objects.

   Strain gauges are used extensively by civil engineers to test the tensile strength of materials and in determining the change in the length of structures.

   Its major drawback is its temperature sensitivity. This effect can usually be reduced to a minimum by using a thermister in the circuit so that the temperature effects cancel out.

9. **Solar Power:** Sun is a vast source of energy. The phenomenon of conversion of solar power into electrical power is called the photo voltaic effect.

   Solar cell is the most important photovoltaic device which directly converts the solar radiations (light energy) into electrical energy. Solar cell is basically a thin disc of P-N junction with a large surface area. A very thin layer of °P"-type material of the order of few microns is diffused on the upper surface of the disc to form a shallow p-n junction. This is then enclosed in a glass container with the top surface filled with silicon grease to prevent losses by reflection. When light rays fall on the surface of this arrangement electrons start flowing from N-plate to the P-plate by means of the photoemission process. This gives rise to a potential difference and constitutes flow of an electric current.

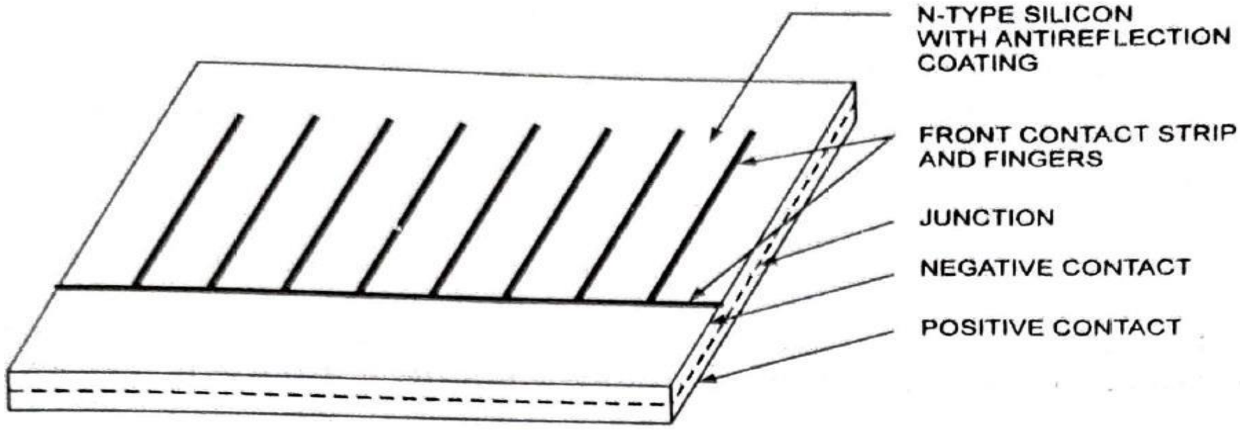


Fig: Top View of a Commonly Used Solar Cell

The N-P configuration is obtained by diffusing phosphorous into the boron doped crystal. Metal contacts are plated on the front and the back of the cell and the active surface is coated with silicon oxide or titanium oxide anti-reflective layer.

The output depends on the intensity of the sun rays. As the cell is turned away from the sun, the output decreases approximately as the cosine of the angle of incidence. The rise in temperature causes a sharp fall in conversion efficiency. The optimum temperature for getting a steady state conversion is about 600°C.

The presence of moisture or carbon dioxide in the atmosphere affects adversely to the performance of a solar cell. The overall efficiency of a solar cell is about 10 to 12 percent.

The total voltage or current required can be increased by series/parallel connections of solar cells thus developing solar batteries popularly known as solar tank.

Applications of solar cells are small power source such as in watches, calculators, telephones in rural areas, solar water heater, solar pump, space research work etc.

MERITS OF SEMICONDUCTOR MATERIALS FOR USE IN ELECTRICAL ENGINEERING:

(i) They are much smaller in size and light in weight.
(ii) When used as rectifiers and transistors they do not require a heater or filament as is required in electron tube rectifiers and valves.
(iii) They consume low power resulting in high efficiency.
(iv) They have long life and hardly show ageing effects.
(v) They are almost shock proof.
(vi) They operate on low voltage.

Chapter-3

Insulating Materials

Introduction:

Primarily any material that is able to insulate *i.e.* to prevent the flow of electricity through it when a difference of potential is applied across it is called insulator. Or

It is the materials through which electric current cannot pass easily are called insulators. Example: Glass, Mica, dry Air,Bakelite etc.

FACTORS AFFECTING SELECTION OF AN INSULATING MATERIAL:

1. Operating condition : Before selecting an insulating material for a particular application the selection should be made on the basis of operating temperature, pressure and magnitude of voltage and current.
2. Easy in shaping : Shape and size is also important affect.
3. Availability of material : The material is easily available.
4. Cost : Cost is also a important factor.

INSULATING MATERIALS, GENERAL PROPERTIES:

The different properties selected for our study are classified as :

1. Visual properties
2. Electrical properties
3. Mechanical properties
4. Chemical properties

1. ELECTRICAL PROPERTIES :

a) INSULATION RESISTANCE OR RESISTIVITY
b) DIELECTRIC STRENGTH(BREAKDOWN VOLTAGE)
c) DIELECTRIC CONSTANT
d) DIELECTRIC LOSS

a) INSULATION RESISTANCE:

The resistance offered to the flow of electric current through the insulating material is called insulation resistance.

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

Where; v= applied volatge
I= current through it

R=Insulation resistance

Insulation resistance is of two types :
(i) Volume Resistance; *(ii)* Surface
Resistance.

(i)VOLUME RESISTANCE:

The resistance offered to current Iv which flows through the material is called volume insulation resistance.As shown in the below fig. For a cube of unit dimensions this is called volume resistivity. As from A to C. It is expressed as:

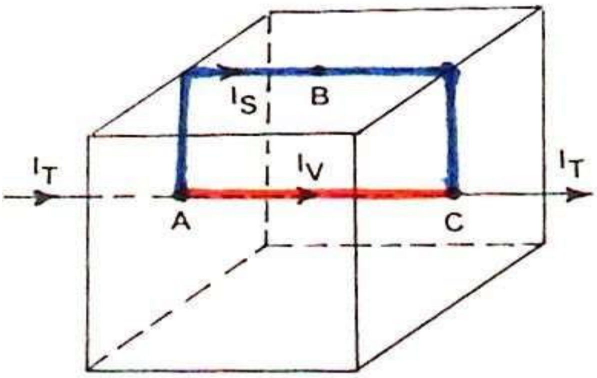
$$R_v = \rho_v \frac{d}{a},$$

Where;

ρv = Volume resistivity in ohm-m.

d = Length of the path current through the materal in meter.

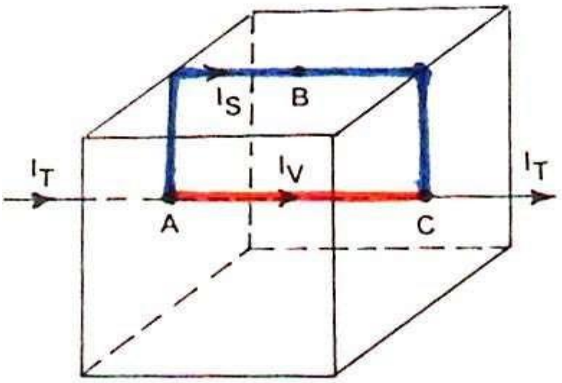
a = cross sectional area of current path in sq.m.



(ii)SURFACE RESISTANCE:

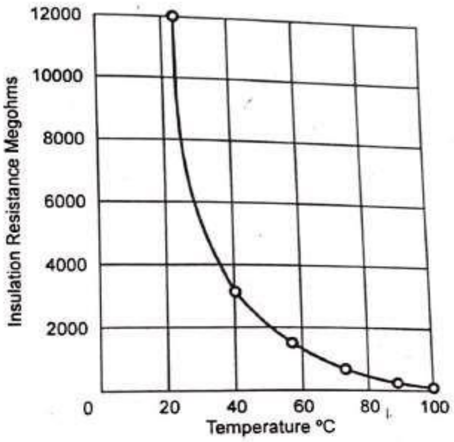
The resistance offered to current which flows over the surface of the insulating material is called surface insulation resistance. As from A to B and then B to C.

Surface resistance depends upon humidity.



b) FACTORS AFFECTING INSULATION RESISTANCE:

Temperature:As the temperature of the insulating material rises its insulation resistance keeps on falling.



Variation of Insulation Resistance with Temperature for Oil Impregnated Paper Insulation

- Moisture: Insulation resistance is reduced if the material absorbs moisture, so insulation material should be non hygroscopic.

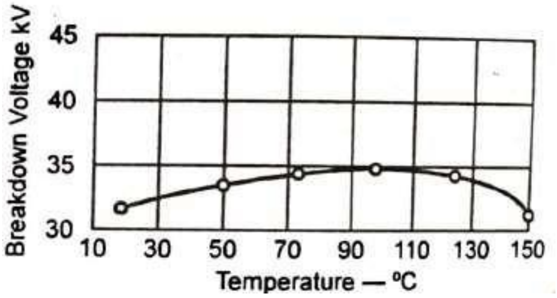
- Applied voltage: Applied voltage also affects insulation resistance.
- Ageing: Ageing reduces the insulation resistance. As age of insulation material is increased the insulation resistance decreases.

c) DIELECTRIC STRENGTH:

- Dielectric strength is the minimum voltage which when applied to an insulating material will result in the destruction of its insulating properties.
- Electrical appliances/apparatus is designed to operate within a defined range of voltage.
- If the operating voltage is increased gradually at some value of voltage, the breakdown of the insulating materials will occur.
- The property which attributes to such type of break down is called the dielectric strength.
- e.g. dielectric strength of mica is 80kV/mm. It means if the voltage applied across 1mm thick sheet of mica becomes 80kV mica will lose its insulating properties and current will start passing through mica sheet.
- In other words dielectric strength of an insulating material is the maximum potential gradient that the material can withstand without rupture.

FACTORS AFFECTING DIELECTRIC STRENGTH/ BREAKDOWN VOLTAGE

- Temperature: Dielectric strength is affected by temperature. It reduces as temperature of the insulating material is increased.



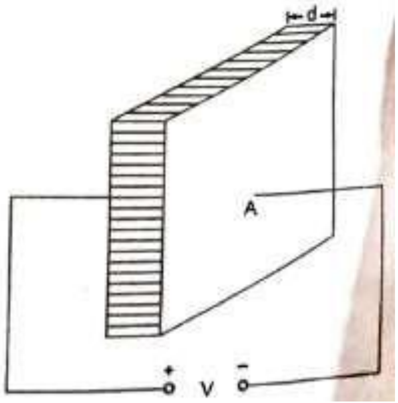
- Humidity: Absorption of the moisture by the insulating material or humidity reduces the dielectric strength of the insulators.

d) DIELECTRIC CONSTANT

- The ratio of capacity of storing the electric charge by an insulating material to that of air is called dielectric constant of the material.
- Every insulating material has got the basic property of storing charge (Q) when a voltage (V) is applied across it. The charge is proportional to the voltage applied *i.e.,* $Q \alpha v$,

$$Q=CV$$

Where c is the capacitance and v is applied voltage.



- The capacitance of the capacitor will change if the air between the plates of a capacitor is replaced by an insulating material acting as a dielectric.
- The property of insulating materials that causes the difference in the value of capacitance, physical dimensions remaining same, is called the dielectric constant or permittivity.

$$C \alpha \frac{A}{d}, \quad \text{or} \quad C = \epsilon \frac{A}{d},$$

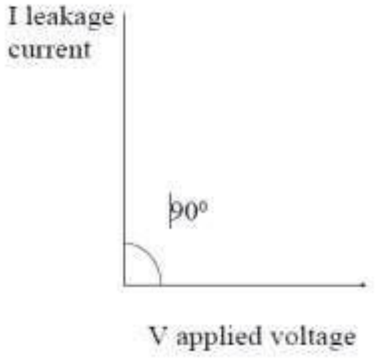
where : A is face area of insulator
d is distance between two faces
ε is permittivity.

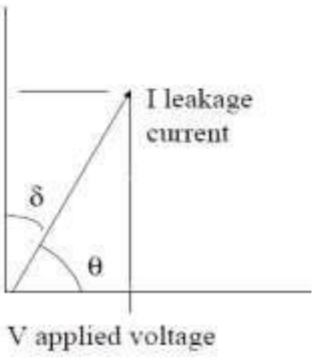
$$\epsilon = \epsilon_0 \epsilon_r$$

E,E0,Er are dielectric constant.(permitivity).
ε0 = 8.854 *x* 10-12 Farad per m.

c) DIELECTRIC LOSS:

- Electrical energy absorbed by the insulating material and dissipated in the form of heat when an alternating voltage is applied across it is called dielectric loss.
- When a perfect insulation is subjected to alternating voltage it is like applying like alternating voltage to a perfect capacitor. In such a case there is no consumption of power.
- Only vacuum and purified gases approach this perfection. In such a case the charging current would lead the applied voltage by 90 degree exactly.
- This would mean that there is no power loss in the insulation.
- In most of the insulating materials, that is not the case. There is a definite amount of dissipation of energy when an insulator is subjected to alternating voltage. This dissipation of energy is called dielectric loss .
- In practice, the leakage current does not lead applied voltage by exactly 90 degree. The phase angle is always less than 90 degree. The complementary angle d=90-q is called dielectric loss angle.





Factors Affecting Dielectric Loss :

(i) The loss increases proportionately with the frequency of applied voltage (ii) presence of humidity increases the loss.
(iii) Temperature rise normally increase the loss.
(iv) Voltage increase causes increased dielectric loss.

2.Visual properties:

a. Appearance
b. Colour
c. Crystallinity

3.Mechanical Properties:

a) MECHANICAL STRENGTH
b) VISCOSITY
c) POROSITY
d) SOLUBILITY
e) MACHANICALABILITY & MOULDABILITY

a. Mechanical Strength: The insulating material should have high mechanical strength to bear the mechanical stresses and strains during operation.

It depends upon following factors:

i. Temperature rise: Temperature rises as a result of dielectric losses in insulators. High temperature adversely affect the mechanical strength of the insulating materials.
ii. Climatic effect: Humidity can also adversely affect mechanical strength.

b. Viscosity: Viscosity in liquid dielectrics will affect manufacturing processes. For example, in paper insulated cable the temperature at which the oil will penetrate through paper will depend on its viscosity.

c. Porosity: High porosity insulating materials will increase the moisture holding capacity and consequently adversely affect electrical properties. Therefore normal it is desired to have a dielectric of high porosity.

d. Solubility: In certain application insulation can be applied only after it is dissolved in some solvents . In such cases the insulating material should be soluble in certain appropriate solvent. If the insulating material is soluble in water then moisture in the atmosphere will always be able to remove the applied insulation and cause break down.

e. MACHIABILITY & MOULDABILITY: This property of insulating material helps us to give the desired shapes to the insulating materials.

4.Thermal Properties:

It is one of the major functions of insulation is heat transfer.

a) Melting points, flash point,volatility: Melting point assumes importance in specific case like nondraining compound impregnated paper insulated cables. Flash point will imposes restriction in manufacturing processes to avoid possible hazards. A volatile material cannot be a good insulators.
b) Thermal conductivity: Heat generated due to I2R losses and dielectric losses will be dissipated through the insulator itself. How effectively this flow of heat takes place, depends on the thermal conductivity of the insulator. An insulator with better thermal conductivity will not allow temperature rise because of effective heat transfer through it to the atmosphere.

c) Thermal expansion: An insulator with high coefficient of expansion poses problems. Repeated load cycle causes corresponding expansion and contraction that will causes void. These void causes insulation breakdown.

d) Heat Resistance: This is general property of insulating material to withstand temperature variation within desirable limits, without damaging its other important properties. If an insulator has favorable properties at ambient temperature but, if it is not able to retain these, it is not a good insulator. The insulator which is capable of withstanding higher temperature without deterioration of its other properties can be used for operation for such higher temperature.

e) Classification of insulating materials on the basis of operating temperature: The classification of dielectrics in insulating materials made based on operating temperature.

f) Effect of temperature increase on life of insulators: There is always some recommended operating temperature for an insulator. The operating temperature has a bearing on thelife of the concerned apparatus. A thumb rule suggested by many experts is that life of insulator is halved for 8-10 degree centigrade rise above the recommended operating temperature for a given apparatus.

5.Chemical properties:

a) Chemical Resistance: Presence of gases, water, acids , alkalis and salts affects different insulators differently. Chemically a material is a better insulator if it resist chemical action.Certain plastic are found approaching this condition. Consequently their use is very much increase.

CLASSIFICATION ON THE BASIS OF OPERATING TEMPERATURE
CLASS ‘Y’ INSULATION - 90 ºC e.g. paper, cardboard, cotton,poly vinyl chloride etc.
CLASS ‘A’ INSULATION - 105 ºC when impregnated fall in oil class A
CLASS ‘E’ INSULATION - 120 ºC Insulators used for enameling of wires e.g pvc.
CLASS ‘B’ INSULATION - 130 ºC e.g. impregnated mica, asbestos, fiber glass etc.
CLASS ‘F’ INSULATION - 155 ºC e.g.polyurethane, epoxides etc.
CLASS ‘H’ INSULATION - 180 ºC e.g. fiberglass, mica, asbestos, silicon rubber etc
CLASS ‘C’ INSULATION - >180 ºC e.g. glass,ceramics, poly tera fluoro ethylene,mica etc.

b) HYGROSCOPICITY: The property of insulating material by virtue of which it absorbs moisture. The insulating material should be non-hygroscopic. The absorption of moisture reduces the resistivity of the insulator.
Moisture due to high humidity atmosphere can affect insulators in two ways:
(i) It acts on the surface of insulation.
(ii) It may be absorbed by insulator.

c) Effect of contact with other materials: Insulation remains invariably in contact with different types of materials like air, gases, moisture, conducting materials and

structural materials. The conducting and structural material have little effect due to contact with insulations.
For eg. When rubber came into contact with the copper some chemical reaction takes place, so tin coating is applied to copper.

Ageing: Ageing is the long time effect of
(i)Heat
(ii)Chemical action
(iii)Voltage Applications

INSULATING MATERIALS- CLASSIFICATION,PROPERTIES,APPLICATIONS:

Classification of Insulating Materials on the basis of Physical and Chemical Structure :
Insulating materials, on the basis of their physical and .chemical structure may be classified in various categories as follows:

(i)Fibrous materials;
(ii) Impregnated fibrous materials:
(iii) Non resinous materials:
(iv) Insulating liquids;
(v) Ceramics;
(vi) Mica and mica products;
(vii) Asbestos and asbestos products;
(viii) Glass;
(ix) Natural and synthetic rubbers:
(x) Insulating resins and their products
(xi) Laminates, Adhesives, Enamels and Varnishes.

(i) Fibrous Materials :

Fibrous materials are either derived from animal origin or from cellulose which is the major solid constituent of vegetable plants The majority of materials are from cellulose. In certain materials the cellulose fibres are clearly visible as in cloth, tape yarn, thread etc. In certain other materials like paper, wood, card board, the fibre is the order of 25 mm length and 0.015 mm thickness. Follow.ng are the different fibrous materials:

(a) Wood :

- Wood was in the past frequently used for low voltage installations. ○ This is light in weight with relative density varying between 0.5 and 1.0 ○ Tensile strength varies, between 700 and 1300 kg/ cm2.
- The grain the tensile strength is low Temperature is obviously a limitation.
- Wood is very hygroscopic and after absorbing moisture tends to lose markedly its mechanical properties.

Uses:

- An insulating material it is impregnated in oil. In early days cheapness, ease of availability and fabrication were the reasons for its use as structural material for transmission and distribution poles.

(b) Paper and card board:

- The base material for manufacturing insulating paper is coniferous wood.
- The organic contamination like lignin and pentosan must be properly removed.
- Crushed wood is boiled after adding some alkaline reagents.
- The process is called sulphate process.
- Normal insulating paper still contains lignin and pentosans upto 7 %. The specified composition of typical paper used in capacitor is given below:

  Cellulose - 95-97% max.
  Pentosans - 4% max
  Lignin - 3% max.
  Iron - 0.01% max
  Copper -0.003% max

- Impregnated Paper are good mechanical strength, ability to withstand at high temperature ,low dielectric losses, ease of wrapping around the conductor ,wide availability and cheapness.

- The use of unimpregnated paper are limited.
  Because of ;

(i) Hygroscopicity,
(ii) (ii) Re-action with oxygen,
(iii) (iii) Thermal instability

- A few of the major applications of unimpregnated paper are in telephone cables and capacitors.

(c) Insulating Textiles :

- Textiles are woven from fibrous materials like cotton, jute and hemp. Sometimes silk from animal origin is also used for special purpose.
- This class of material are mechanically strong in tensile and tear strength. These strength do not get affected markedly even after getting wet.
- Use of synthetic material has been on the increase. This is because of improved property such as high mechanical strength, heat resistance, low hygroscopicity, stability in the presence of chemical agents etc.

(d) Cotton :

- It is made in the form of fibre or cloth and tapes for the purpose of promoting insulation.
- It is combustible and chars when heated even without the presence of sufficient air or oxygen. It is a porous material and absorbs water quickly. It gets moist by moisture or humid nir when it is damp, it is not a good insulator. It is used where flexibility is prime requirement and high temperature and humid atmophere is not envisaged.
- Cotton covered wire is widely used for winding of small and medium aized machines, chokes and small transformer coile etc.

- Cotton hygroscopic and has low dielectric strength. The cotton in use of insulators are impregnated with varnish or wax. The operating temperature of cotton is 100C and at higher temperature it gets carbonized.

(e) Silk:

- It is protein fibre consisting of long chain structure similar to that of cellulose. The silk yarn clothes are thin and strong. It has better factor than copper but it is quite expensive.
- Its electrical characteristics are better than cotton but is more hygroscopic.
- It is poor conductor of heat as compared to cotton.
- Natural silk is used in application where space is of prime importance i.e, in instrument meters and other measuring instruments. Artificial silk is less af affected by water and has coarse fibre and less elastic as compared to the natural silk.

(f) Jute :

- It is made from cellulose which is the major solid constituent of vegetable plants. Its fibres are thicker and is similar to cotton cloth but is cheaper in cost.

(ii) Impregnated Fibrous Materials:

Introduction of proper impregnating compounds into the fibrous materials discussed above has resulted in some very stable insulating materials. It is by proper impregnation that limitations like fibrous hygroscopicity and thermal and chemical degradation of unimpregnated materials are overcome.

(A) Impregnated paper dielectric :

- Amongst all fibrous materials used as insulators this class contributes the maximum. The technique of impregnation is complicated. Oils used for this purpose are selected carefully depending on requirements.
- Paper insulation is usually provided on the conductor without impregnation After the conductor with unimpregnated paper is placed in position in any appratus the semi-finished apparatus is then put through the impregnation process which involves the following steps:

(i) Extracting most of the air and moisture before allowing any contact with impregnating oil. This requires indirect heating of the apparatus in vacuum for complete removal of moisture.

(ii) Having thus made the apparatus ready, the oil which is already dehydrated separately is allowed to impregnate through the paper.

(iii) Cooling is then carried out before exposing the insulation to atmosphere so that oil does not flow out of the paper which may make it once again vulnerable to absorb moisture.

(iv) If the insulation is to be used for high voltage, a proper sealing of the apparatus after impregnation is very essential.

Main features of impregnated paper insulation are

(a) Good mechanical properties:
(b) Good chemical stability:
(c) Ability to withstand high temperatures:
(d) Dielectric constant varying between 2.25 and 6.35: (e) Comparatively less dielectric loss; (f) Non-inflammable.

Experience over the last 100 years of use has proved paper insulation to be of the highest quality and most reliable. However, suitable grades of paper im pregnating oils are not available in India, so paper insulation low voltage cable has been replaced by plastics.

Applications of impregnated paper : Major applications of impregnated paper are in :

(i) Cables : In all types of cables i.e. underground power cables, mining cables and submarine cables in the operating voltage range of 220 V to 400kV.

(ii) Transformers: Paper dielectric is frequently used in high voltage power transformers.

(iii) Capacitors.
(B)Varnished or impregnated textiles:
Cotton or silk textiles can be varnished by two types of varnish: (1) Oil varnishes and (ii) Oleo Bituminous varnishes. Commonly used thicknesses of varnished textiles vary between 0.08 mm to 0.25 mm. This material belongs to class A insulating materials.

Outstanding features of varnished textiles are:
(i)Good mechanical strength (ii)
Good dielectric strength;
(iii) Low hygroscopicity,
(iv) Low resistance to organic solvents (especially in the case of Oleo Bituminous varnished textiles):
(v)Limiting working temperature of 105°C (for normal varnished textiles) (vi)
Oleo Bituminous varnish textiles are not resistant to oil.

Applications of varnished or impregnated textiles :

This insulation widely used for windings in electric machines of low and medium rating. It also used in cables as wrappers and liners. In the form of adhesive tape the materials used by electrician ns on the spot insulation for job relating to electric installation.

(iii)Non Resinous Material:

Solid or semisolid insulations which are di rectly available in nature and are organic based fall under this class, Thee materiala are mineral waxon, nepal, bitumen, and chlorinated naphthalene.

Non Resinous materials are classified as follows:

(A) Bitumen: Bitumena are solid or semisolid material obtained by refining crude petroleum.

Special features of bitumen are:

(i) Highly soluble in mineral and synthetic oils:
(ii) Easily oxidized;
(iii) Resistant to moisture penetration:
(iv) Poor insulation property
(v) Softening point varies between 30°C to 140C depending on the variety
(vi) Acid and alkali resistant;
(vii) Specific gravity is about one

Applications of bitumen:

- Bitumen is normally used in electric engineering because of its outstanding property of being water resistant. It is very cheap Bitumen find wide applications in underground cable for the protection of lead and steel armour against corrosion.

- Bitumen compounded paper, hosain and cotton tape are widely used in the manufacture of underground cable to provide bedding and serving for steel ar mour

(B) Waxes
(a) Paraffin and Microcrystalline Waxes: These waxes are obtained by the process of distillation of mineral petroleum oils. These waxes are hydrocarbons in composition

Special features of these waxes are :

(i)Easily soluble in mineral and synthetic insulating oil;

(ii) Marked change in volume when waxes changes state i.e. from liquid to percent in certain cases. This abnormal shrinkage solid or vice versa. The maximum amount of shrinkage is as much as 15 percent in certain cases.The abnormal shrinkage results in tht information of gaps and cracks.
(iii)Mechanical weak
(iv) Poor electrical properties which become poorer when heated.
(v)Paraffin waxes get oxidised when they are heated beyond melting point.

Application of paraffin and microcrystalline waxes : The excellent sealing property of waxes makes them fit for use an sealing material. Microcrystalline axes having high melting points are used as a constituent material to make non-draining impregnated compound which is extensively used for MIND (Masa Impregnated Non Draining) paper cables.

These cables are extensively used in India for transmission in urban areas.

(b) Natural waxes : As the name implies these waxes are available in nature. Natural wax is often used, after processing, in the form of chlorinated wax. Natural wax also suffers from shrinkage or expansion when undergoing change of state. This limits the use of these waves to low voltage systems only.

Application of natural waxes : These waxes are mixed with insulating oils to improve the viscosity and pour point of the latter to form non draining cable compound. These waxes also are used as a constituent of sealing compound.

(iv)Insulating Liquids :

Insulating liquids apart from working as insulation, fulfil other important requirements like (a) they are able to improve insulating properties of other solid materials (fibrous especially) by eliminating air and other gases, (b) they offer good heat dissipation media, (c) they are sometimes required for extinguishing arcs in certain applications like circuit breakers. The reason for use this are : (a) cheapness, (b) easy availability (being a product of crude petroleum(c)good electrical properties.

Application of insulating liquids:

These liquids are used in application like capacitors and transformers. These applications are high frequency capacitors where fluorinated liquids are used at high temperature.
Mineral oils, askarels and vegetable oils, are liquids used in the normal operating temperature range of-50°C to 130°C. Flourinated and silicon liquids are utilized in higher temperature range -50°C to 200°C.

Main features of insulating liquids :

Before proceeding to make a specific study of these different classes of insulating liquids it is worthwhile to consider the effect of some important influencing factors on these oils. These factors are given below :

(i) Oxidation: Most of these liquids are susceptible to oxidation whose effect is further increased in most such liquids with increase in temperature. Oxidation impairs electrical properties, especially the dielectric loss.
To overcome the ill effects of oxidation we must either prevent oxidation or remove the oxidized part periodically.
(a) not letting air in contact with oil for more time than is absolutely necessary,
(b) use of conservators,
(c) use of inhibitors (oxidation retarders).

(ii) Moisture : Moisture is soluble in most insulating liquids that decreases the dielectric strength and increases dielectric losses. The moisture in oils should be avoided because of the fact that it increases oxidation which enhances the deterioration of oil. In commercial applications moisture is always removed from oil before it is used. Removal of moisture from insulating oil is mainly done by dehydration process. In this process the oil is atomized by means of a special apparatus. This atomized oil is exposed to high vacuum and temperature (l00°C-120°C) which Different Temperatures extracts the moisture completely. Moisture is also extracted by special machines called centrifuge machines.

(iii) Temperature : Temperature rise as mentioned earlier_increases the oxidation of liquids. Temperature rise also increases the gas ·solubility of liquids which adversely affects their insulating properties. Temperature affects insulating properties of liquids very markedly.

(a) Mineral Insulating oils:

These oils are derived from crude petroleum. Distillation of crude petroleum gives many industrial byproducts like alcohols, kerosene, lubricating oils, asphalts, waxes and insulating oils. These oil fInd frequent use in transformer cables and capacitors.

(b) *Synthetic liquids* :

It has been mentioned earlier that mineral insulating oils are the most widely used insulating liquids. However, easy oxidation,comparatively quick degradation of insulation and chemical properties and the possibility of catching fire have been the limitations of such oils.In actual applications the high dielectric constant (between 5 and 6) of these liquids compared to about 2.8 for mineral insulating liquids is of major importance.This property contributes towards the great reduction in the thickness of solid insulations which use synthetic liquids as impregnants resulting in economy in material which in the case of capacitors is as high as 40% compared to mineral oil impregnated capacitors. Synthetic oils are very resistant to oxidation and to fire hazards. The use of these liquids in transformers is increasing because of these reasons. However, synthetic oils react adversely with a large number of materials with which they come in contact.

(c) *Miscellaneous Insulating liquids* :

(i) *Vegetable oils :* These are the earliest used liquids. These oils are obtained from seeds of pulp. Linseed, cotton-seed, sunflower, soyabean, castor, palm, olive peanut oil etc. were the liquids used in the past. The main reason of their being used was their easy availability. These liquids are rarely used in the present day.

(ii) *Flourinated liquids :* These liquids are similar to synthetic liquids. This class shows a greater volatility at a prescribed temperature but chemical instability is less than that of synthetic oils. High teniperature operation and excellent cooling properties are assets of these liquids. Flourinated liquids are sometimes used in transformer.

(iii) *Silicon liquids :* These liquids are found to possess some exceptional properties. These properties are stability at high temperatures and very wide range of viscosity from as low as one to as high as 1000 000 centi&tocks. The dielectric constant of these liquids is same as that of mineral oils (2. 7 to 2.8).Power factor is very low. These .liquids are sometimes used in transformer.

Ceramics: Ceramics are materials made by high temperature firing treatment of natural clay and certain inorganic matters. Structurally ceramics are crystals bonded together. Other materials used with clay in different type of ceramics are Alumina, Quartz, Talc, Magnesite, Feldspar etc.

Main features of ceramics :

The main features of ceramics are :

(i) . Ceramics are hard, strong and dense;
(ii) Not affected by chemical action except by strong acids and alkalies;
(iii) Stronger in compression than in tension-;
(iv) Stability at high temperatures likely to occur in electrical engineering applications;
(v) Excellent dielectric properties;
(vi) Weak in impact strength. They cannot be used as self supporting thin films like paper, cotton etc.

The effects of various fac tors on ceramics are as follows:

(a)Effect of temperature: Electrical resistance of ceramics decreases with increase in temperature.
(b)Effect of Moisture : The effect of humid atmospheres on the surface resistivity of ceramic materials is not very pronounced.
Ceramic insulators are often exposed to huni1d atmosph~re, rain etc, *in* order to reduce and as far as possible eliminate the penetration of moisture. Ceramic insulators are glazed. Glazing also prevents dirt and dust from accumulating on the surfaced of insulators.

Applications of ceramics : The capacity to withstand high temperature, immunity to moisture, good electrical properties, excellent compressive strength, mouldability are the properties which make ceramics valuable for many electrical applications. MaJor applications are as follows : ·

(a) ***Porcelain Insulators*** **:**

Porcelain materials are used to make many different types of insulators, like transformer bushing pins, suspension insulators for transmission and distribution lines, disconnecting switches, porcelain parts used for switches, plugs and sockets, fuse holders, telephone insulators etc. In order to carry out the requirements of given application, procelain is required in different dimensions and shapes. Thick solid insulators should be avoided. Where large insulators are necessary thin insulators bonded together by glazing should be used.

(b) ***Line Insulators*** **:**

Porcelain finds one of the largest applications as line insulators. Rain and dirt affect surface resistivity.

(c) ***Other Ceramic Material*** **:**

Apart from porcelain there are some other ceramics.

(i) *Steatite:*Mixture of clay and talc. Excellent compressive strength, less moisture absorption and good electrical properties of steatite. Steatite is used in· making equipment for high frequency system. Also when thermal shock resistance desired , steabte, is used.

(ii) *Alumina :* This is primarily made up of aluminium oxides. Alumina is characterized by high limiting temperature less water absorption , high compressive strength.

(iii) *Titanate Ceramics :*

- Inclusion of certain titanates like barium titanate,lead titanate etc. during manufacture takes titanate ceramics. Titanate ceramics have an astoundingly high dielectri constant.
- Barium titanate ceramic can possess a dielectric constant of up to 1000.
- Used in capacitor design.

(iv) *Oxide Free Ceramics :*

- There is another class which has been developed in which there are no oxides. Instead of oxides, they consist of nitrides,sulphides, carbides etc. These ceramics excel in their extreme heat resistance property.
- Boron nitride is used in manufacturing synthetic mica and metal crystals for making transistors.

Piezo Electric Ceramic Transducer Elements : Piezo electric ceramic transducers are based on lead zirconate lead titanate compositions. They have good efficiency for electrical to mechanical energy conversion and vice-versa.

The following three types are available commercially. ·

Type 1 : *Low power ceramic materials*

These have high dielectric constant, high voltage sensitivity, volume resistivity and stability over a wide temperat4~e range. Their applications are in low power transducers, accoustic sensing elemeb ts, flaw detection probes and gramophone pickups.

Type 2 : *High power ceramic materials*

These have high electro-mechanical coupling coefficient, low dielectric losses,and high coercive field Their applications are in high power electro acoustic devices, ultrasound cleaners, high voltage generators.

Type 8 : *The third grade is stabilised grade*

They are based on Lead zirconate titanate. Mechanical *Q* is 500, stability for resonant and anti resonant frequencies is 0.2%.

CHAPTER-4

Dielectric Materials

INTRODUCTION:

- The materials which are used for storing of electrical energy are classified as dielectric materials.
- Dielectric materials are essentially insulators, which means that no current will flow through the material when a voltage is applied.
- When a voltage is applied across a dielectric material, it becomes polarized. Since atoms are made of a positively charged nucleus and negatively charged electrons, polarization is an effect which slightly shifts electrons towards the positive voltage. They do not travel far enough to create a current flow through the material.
- Once the voltage source is removed from the material, it either returns to its original non-polarized state, or stays polarized if the molecular bonds in the material are weak.
- All dielectric materials are insulators, but a good dielectric is one which is easily polarized.The amount of polarization which occurs when a certain voltage is applied to an object influences the amount of electrical energy that is stored in the electric field.

DIELECTRIC STRENGTH:

Dielectric strength (or electric strength or breakdown voltage) is, therefore, the minimum voltage which when applied to an insulating material will result in the destruction of its insulating properties. In other words, dielectric strength of an insulating material is the maximum potential gradient that the material can withstand without rupture. This value is expressed in volts or kilo-volts per unit thickness of the insulating material.

Factors Affecting Dielectric Strength

i. Dielectric strength decreases with rise of temperature in case of air. In case of liquid insulators the effect varies with the type of oil and its viscosity.
ii. Humidity generally decreases the value of dielectric strength.

DIELECTRIC CONSTANT OR PERMITTIVITY (ε):

The dielectric constant of a material, also called the permittivity of a material, represents the ability of a material to store electrical energy in the presence of anelectric field.

The ratio of the capacitance using a material as the dielectric to the capacitance when air is substituted for the material is called the permittivity or dielectric constant of that material.

Every insulating materials store charge (Q) when a voltage (V) is applied across it. The charge is proportional to the voltage applied i.e, $Q \propto V$

$$\text{Or } Q = C\,V$$

Where C is called the Capacity or Capacitance of the material across which the voltage is applied.

Capacitance is different for different insulating material. The property of insulating materials that causes the difference in the value of capacitance is called the dielectric constant or permittivity (ε).
Capacitance can be expressed as

$$C \propto \frac{A}{d} \quad \text{or} \quad C = \varepsilon\frac{A}{d}$$

where A is face area of insulation, d is distance between two faces, ε is dielectric constant (or permittivity).

Also $\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon_0 \varepsilon_r}$

where, $\boldsymbol{\varepsilon_r}$ is dielectric constant of the material and, $\boldsymbol{\varepsilon_0}$ is dielectric constant or permittivity of vacuum.

The value of $\boldsymbol{\varepsilon_0} = \mathbf{8.854} \times \mathbf{10^{-12}}$ Farad per meter

The dielectric constant of air is practically taken as 1. Permittivities of dielectrics other than air are more than 1.

Permittivity of most gaseous dielectrics is nearly equal to that of air but the permittivity of liquid and solid dielectrics varies from about 2 to 9 except in the case of distilled water in which case this value varies from 40 to 90 depending upon temperature.

Permittivity and dielectric strength of some commonly used dielectric materials

Material	Permittivity	Dielectric Strength (kV/mm.)
Air	1	3
Bakelite	5-6	20-25
Empire cloth	2	1-20
Glass	3.3	5-12
Mica	3-8	40-150
Paper	2-2.5	4
Paraffin Wax	2	8
Porcelain	4-7	9-20
Rubber	2-3.5	10-25
Transformer oil	2	25-30

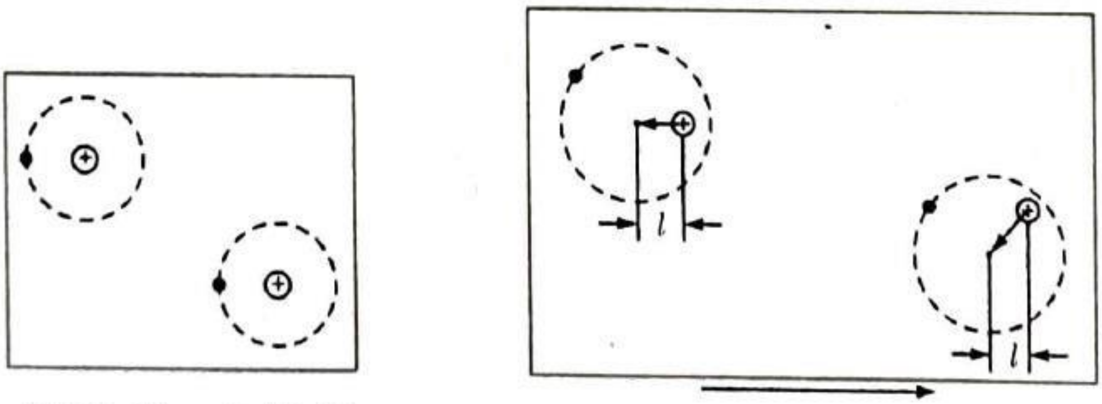
POLARISATION:

Polarisation is defined as the definite orientation of electrostatic dipoles in a material due to an applied electric field. Polarisation is defined as the electric dipole moment per unit volume. The SI unit of Polarisation P is coulomb metre per cubic metre or coulomb per square metre (C/m^2).

If a slab of dielectric is placed in an electrostatic field it will undergo polarisation. Consider the two conducting plates of a capacitor. When the capacitor is charged a definite potential will exist between the two capacitor plates. Electric field existing between the two charged capacitor plates is shown in Fig. 5.1. When a dielectric is introduced in between the two plates it has been observed that the intensity of the electric field and hence the potential difference which was existing between the two charged plates is reduced. This is due to the polarisation of the dielectric material under the influence of an electric field.

The molecules of a dielectric may be classified as either polar or non-polar.

A non-polar molecule is one in which the “centre of gravity" of the positive nuclei and the electrons normally coincide. When placed within an electric field, the electrons are attracted by the positive charges of one electrode and are repelled by the negative charges of the second electrode. As a result the electrons undergo some displacement towards the direction of the positively charged electrode. This displacement of the electrons within atoms is called electronic polarisation. Electronic polarisation makes each atom a dipole because the centres of electron orbits and the positively charged nucleus are displaced with respect to each other by some distance, say l.Due to this dipoles are induced (a pair of opposite charges separated by a small distance form a dipole).



(a) No Electric Field

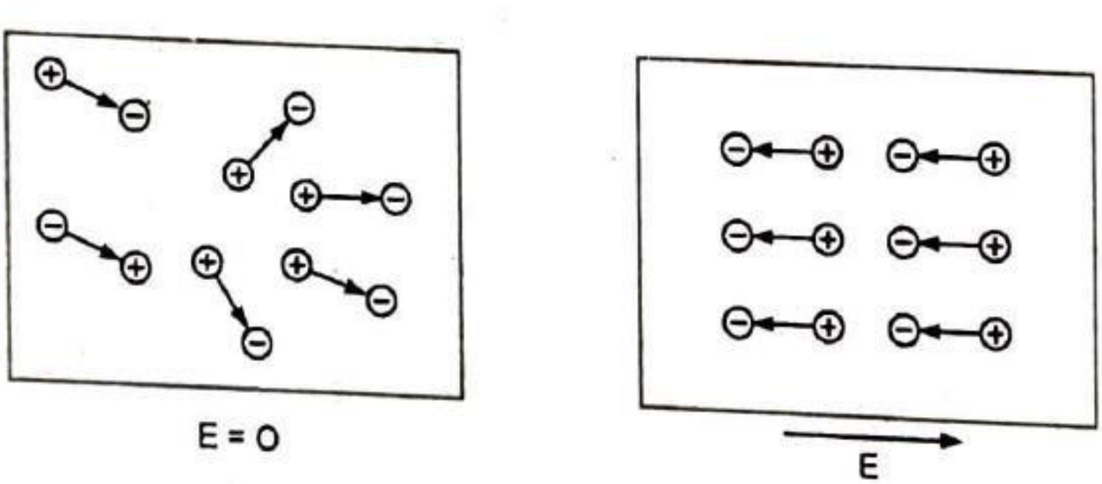
(b) Electric Field

The Behaviour of non-polar Molecule in The Absence and in
The Presence of an Electric Field

A polarized particle will possess an electric dipole moment that can be expressed mathematically as: M =q. I where q is the elementary charge of the particle.

The sum of the dipole moments per unit volume of the material of the dielectric is equal to the polarisation of the dielectric. The degree of polarisation case of electronic polarisation largely depends upon the density of the material.

In polar molecule, the centres of their positive and negative charges displaced with respect to each other and therefore form a dipole. These dipoles are oriented in a random fashion when no electric field is present. Under the influence of an electric filed these dipoles orient themselves in lines in direction of the applied electric field. The stronger the field, the greater will be the number of dipoles pointing in the direction of the field.



The Behavior of Polar Molecules in The Absence and
in The Presence of an Electric Field

Whether the molecules of an dielectric are non-polar or polar, the net effect of an external field on the dielectric is the same. As a result of polarisation in the presence of an electric field the dipoles line up in the direction of the applied field. Due to this negative charges will appear on the surface of the dielectric facing the positive plate and positive charge will appear on the surface of the dielectric facing the negative plate of the capacitor. Thus the electric field which will be induced within the dielectric due to polarisation will be in the opposite direction to the applied field. The strength of the field induced in the dielectric will, depend upon the dielectric. This field is opposite to the main field due to the voltage applied across the two plates. Due to this the resultant field is weakened. As the field is weakened, the potential difference appearing across the plates will be reduced. Thus when the plates are connected across a battery, more charge will be stored in the capacitor.

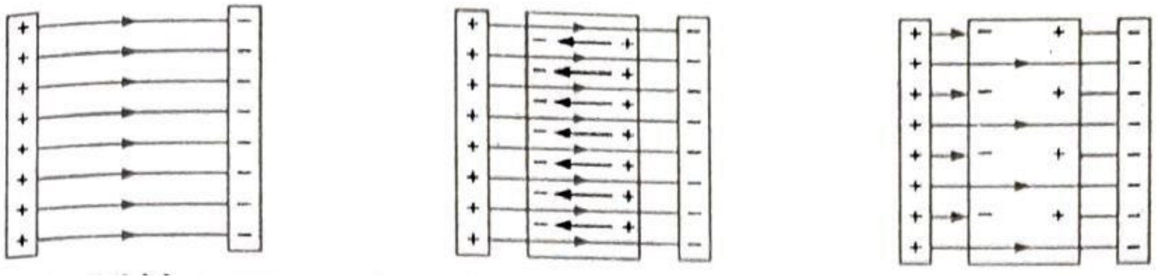


Fig:(**a) electric field between two charged plates; (b) induced surface charges and their field due to the polarisation ofa dielectric now introduced between the two plates; (c) result. ant field when a dielectric is placed between the charged plate**

Dielectric Loss:

When a perfect insulation is subjected to alternating voltage it is like applying alternating voltage to a perfect capacitor then there is no consumption of power. In such cases the charging current would lead the applied voltage by exactly 90 degrees as in Fig.(a). This would mean that there is no power loss in the insulation.

But in practical case there is a definite amount of dissipation of energy when an insulator is subjected to alternating voltage. This dissipation of energy that is called dielectric loss. The leakage current does not lead applied voltage by exactly 90° in Fig:(b). The phase angle is always less than 90°. The complementary angle δ =$90° - \theta$ is called dielectric loss angle.

For an insulator having a capacitance C and having a voltage V applied to it at a freqeney f Hz the dielectric power loss can be calculated as:

$$P = VI\cos\theta$$

$$= V \times \frac{V}{X}\cos\theta \text{(where X is the capacitive reactance)}$$

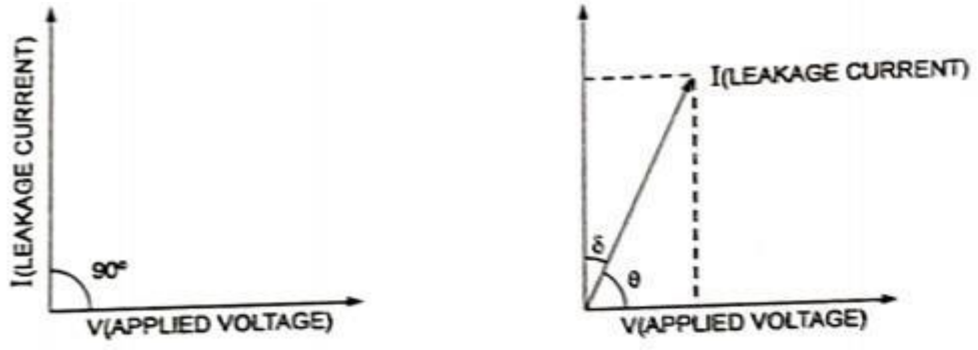
$$= V^2 \times 2\pi f C \times \sin\delta \qquad \text{since}(\cos\theta = \sin\delta)$$

In most insulators the angle δ is negligibly small.

$$P = V^2 \times 2\pi f C \times \tan\delta$$

$\tan\delta$ is called the power factor of the insulator.

From the above equation it is seen that power loss is dependent on $\tan\delta$ so long as the other factors like voltage, frequency and capacitance are constant.



(a) (b)

Factors Affecting Dielectric Loss

i. The loss increases proportionately with the frequency of applied voltage.

ii. Presence of humidity increases the loss.

iii. Temperature rise normally increase the loss.

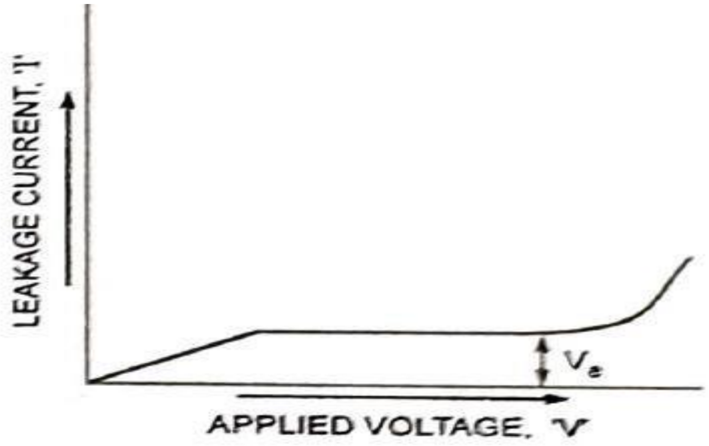
iv. Voltage increase causes increased dielectric loss.

Electrical Conductivity of Dielectrics and their Break down:

Gaseous Dielectrics:

- The electrical conductivity of all gaseous dielectrics is identical. Air is the most commonly used gaseous dielectric. The primary constituents of air are nitrogen and oxygen.
- Under the influence of various natural ionizing factors e.g. cosmic rays and ultra violet rays some ionization takes place in air. This natural ionization gives rise to equal number of free electrons and positive charge appearing at the same time.
- The natural ionizing factors are unable to ionize all the air molecules because ionization of new molecules is counterbalanced by recombination of previously formed ions with the free electrons. Recombination takes place whenever the continuous random thermal motion of the gas particles brings an ion close enough to a free electron.
- When there is no electric field there will be no directed motion of these free Charges and hence there will be no flow of current through the gaseous dielectric.

- Under the influence of an electric field, however, the free charges get a directed motion and give rise to an electric current which is known as the leakage current. Free electrons will move towards the positive plate whereas the positive ions will be attracted towards the negative plate. Thus the conductivity of a gaseous dielectric may be considered to be as both electronic and ionic.
- If the applied electric field is weak i.e. on weak electric field, the leakage current will be negligible. If the electric field is further increased all the free charges will be directed towards the two plates before they can be recombined. All charges produced will reach the electrode and the leakage current at this stage will be independent for the electric field strength i.e. the applied voltage.
- If the voltage applied is increased further the free charges will acquire sufficient energy to knock out electrons from other neutral atoms by collision. Each newly freed electron gets accelerated to a very high speed due to the applied electric field and this in turn knocks out an electron from other gas atoms and ionizes them. This process is known as ionization by collision.
- Due to ionization by collision the number of the free charges increases in geometric progression and the strength of the leakage current increases rapidly. The voltage at which a sudden increase in leakage current takes place in a gaseous dielectric is called the breakdown voltage (Ve).



Leakage Current through a Gaseous Dielectric as a Function of applied Voltage

Liquid Dielectrics:

- All liquid dielectrics easily get contaminated with some impurities in the form of solid particles which become suspended in such dielectrics. Another contaminant in hygroscopic liquid dielectrics is water. All these contaminants give rise to conductivity called impurity conductivity.
- In liquid dielectrics the impurity conductivity plays a very significant role. The basic molecules of a liquid dielectric get dissociated under the influence of an electric field. Dissociation of molecules causes conductivity. The degree of dissociation of the molecules of a liquid dielectric depends upon the molecular structure.
- Neutral molecules are less capable of dissociation than polar molecules. So dielectrics having low values of permittivity have low conductivity and Dielectrics having high values of permittivity show considerable conductivity.
- Contaminants in liquid dielectrics can increase the conductivity under the action of an applied electric field. When the dielectric is placed in an electric field, the

contaminants become electrically charged and may act as current carriers. The effect produced by the contaminants depends upon their concentration in the liquid.

- A breakdown in a contaminated liquid dielectric may occur due to the formation of conductive bridges between the electrodes by the contaminants drawn into the interelectrode space by the applied electric field.
- This is predominant if some fibrous particles are present as contaminant in a dielectric like oil. The fibrous particles will absorb moisture and are liable to arrange themselves into a continuous chain extending from one electrode to the other. There may be breakdown of the dielectric through the bridges thus formed.
- At the place where breakdown occurs, considerable amount of heat will be produced which will result in convection flow of the liquid dielectric. This will break up any bridge formed and the dielectric strength will be restored. But after some time another conducting bridge will be formed causing breakdown again.
- In an uncontaminated liquid such conducting bridges cannot be formed. Breakdown of uncontaminated liquid dielectrics is caused due to the ionization of the gases of present in the liquid.
- The applied electric field ionizes the gas present in the dielectric and the places in a dielectric where the gas exists, the electric field intensity rises. This causes further ionization resulting in ultimate breakdown of the dielectric.

Solid Dielectrics:

- Electrical conductivity of solid dielectrics may be ionic, electronic or combined (ionic plus electronic) in nature.
- The electrical conductivity of solid dielectrics also depends upon the presence of various contaminants or impurities. In most dielectrics these impurities dissociate more readily to form ions and free electrons than the dielectric containing them.
- At low temperatures the volume of electrical conductivity of solid dielectrics may be wholly due to the impurities but at increased temperatures the magnitude of the leakage current may depend upon the contribution of free ions of the basic dielectric to electric conduction.
- Breakdown in solid dielectrics may commonly be either electro thermal or electrical depending upon the prevailing conditions. Electro thermal breakdown

  is caused by the destruction of the dielectric due to heating produced by dielectric losses.
- Solid dielectrics are poor conductors of heat. Dielectric loss in these dielectrics increases very sharply with increase in temperature. If the heat generated is not conducted away rapidly through the dielectric then there will be thermal breakdown of the dielectric.
- If at a particular applied voltage, the dielectric is not able to radiate away the heat generated due to dielectric loss in it, and if the applied voltage is kept for a long period, the material will be charred or melted thus short circuiting the electrodes.
- The most probable mechanism of electric breakdown in many solids particularly crystals, is collision ionization by electrons. When the applied electric field accelerates the free electrons in the dielectric the electrons lose part of their kinetic

energy through collision with the particles in the dielectric which are torn away from the place of their fixing.

Properties of Dielectrics:

Material	Dielectric constant	Dielectric strength (kV/mm)	Tanδ	Max.working temperature (at 0°C)	Thermal conductivity (milli watt per Metre kelvin)	Relative density
Air	1	3	___	___	0.025	0.0013
Alcohol	26	___	___	___	180	0.79
Asbestos	2	2	___	400	80	3.0
Cellulose film	5.8	28	___	___	___	0.08
Cotton fabric: Dry	___	0.5	___	95	80	___
impregnated	___	2.0	___	95	250	___
Ebonite	2.8	50	0.005	80	150	14
Glass: Flint	6.6	6	___	___	1100	4.5
crown	4.8	6	0.02	___	600	2.2
Mica	6	40	0.02	750	600	2.8
Paper: Dry	2.2	5	0.007	90	130	0.82
impregnated	3.2	15	0.06	90	140	1.1
Porcelain:	5.7	15	0.008	1000	1000	2.4
Quartz fused	3.5	13	0.002	1000	1200	1.2
Rubber vulcanized	4	10	0.01	70	250	1.5
Resin	3	___	___	___	___	1.1
Silica fused	3.6	14	___	___	___	___
Silk	___	___	___	95	60	1.2
Sulphur	4	___	0.0003	100	220	2.0
Water	70	___	___	___	570	1.0
Paraffin wax	2.2	12	0.0003	35	270	0.88

Applications of Dielectrics:

The function of a dielectric is to store energy. The most common example of the use of dielectrics for the purpose of storing energy is in capacitors. There are various types of capacitors available in the market.
Capacitors are generally classified according to the kind of dielectric used in them.

Capacitors may be grouped in to:

i. Capacitors that use vacuum, air or other gases as dielectric,
ii. Capacitors in which the dielectric is a mineral oil,
iii. Capacitors in which combination of solid and liquid dielectrics such as paper, films of synthetic materials, glass, mica etc. and mineral oil, silicon etc. are used.
iv. Capacitors with only a solid dielectric such as glass, mica, titanium oxide etc.

- The first type of capacitors is used in applications where the energy loss in the capacitors must be small and where the value of capacitance needed is not very large. The dielectric losses in vacuum, air and other gaseous dielectrics are very small: such capacitors are used in radio frequency circuit and in low frequency measuring circuits where precision is highly desirable.
- Capacitors using oil as a dielectric are used in applications where a large value of capacitance is required and where a small amount of dielectric loss can be tolerated.
- Oil impregnated paper dielectric is used for making capacitors of large values of small size. Such capacitors are required in applications where precision is not so important but a high value capacitance is the need e.g. for power factor correction in electric power distribution systems.
- Mica, a solid dielectric, is used in making standard capacitors for laboratories because its dielectric constant does not change much with temperature variation and with time. Mica has high value of dielectric constant and high insulation resistance (dielectric strength). Dielectric loss of mica is very small.

Electrolytic Capacitors: Electrolytic capacitors make use of electrolytic materials as polarizing agent. Electrolytic capacitors are fixed value capacitors. They are polarized devices with high capacitance ratings normally used for bypass, coupling and motor starting applications.

Certain metals such as tantalum, aluminium, magnesium, titanium, niobium, zirconium, zinc etc. can be coated with an oxide film by electrochemical process and if these metals are made anodes in suitable electrolytes, then the oxides of these metals exhibit different characteristics useful for forming a capacitor. Out of these the oxides of tantalum and aluminium are found to be highly suitable.

Tantalum oxide is more suitable in electrolytic capacitors than aluminium oxide but is costlier. Boric acid is also used in electrolytic capacitors.

These capacitors are of high capacitance type and have high value of dielectric constant. The capacitors with aluminium electrolytic have capacitance approximately 30,000 Micro Farad. The value of dielectric constant for aluminium oxide is 7 and tantalum oxide is 11.

CHAPTER-5

MAGNETIC MATERIALS

INTRODUCTION:

Materials in which a state of magnetization can be induced are called magnetic materials when magnetized such materials create a magnetic field in the surrounding space.
The property of a material by virtue of which it allows itself to be magnetized is called permeability.
The permeability of free space is denoted by μo. Its value μo = 4π x 10-7.
The material permeability μ= μo x μr
When μr = Relative permeability

Classification of Magnetic materials :

Magnetic materials classified as : a.
Diamagnetic material
b. Para-magnetic material
c. Ferro-magnetic material

DIAMAGNETIC MATERIAL :

The materials which are repelled by a magnet are known as diamagnetic materials. Eg. Zinc, Mercury, lead, Sulphur, Copper, Silver. Their permeability is slightly less than one. They are slightly magnetized when placed in a strong magnetic field and act in the direction opposite to that of applied magnetic field.

PARAMAGNETIC MATERIALS :

The materials which are not strongly attracted by a magnet are known as paramagnetic materials. Eg. Aluminium, Tin, Platinum, Magnesium, Manganese, etc. Their relative permeability‟s is small but positive. Such materials are slightly magnetized when placed in a strong magnetic field and act in the direction of the magnetic field.

In paramagnetic materials the individual atomic dipoles are oriented in a random fashion. So the resultant magnetic field is negligible. When an external magnetic field is applied. The permanent magnetic dipoles orient themselves parallel to the applied magnetic field and give rise to a positive magnetization.

FERRO-MAGNETIC MATERIALS

The materials which are strongly attracted by a magnet are known as ferro-magnetic materials. Their permeability is very high. Eg. Iron, Nikel, Cobalt, etc. The opposing magnetic effects of electron orbital motion and electron spin do not eliminate each other in an atom of such a material.

MAGNETISIATION CURVE :

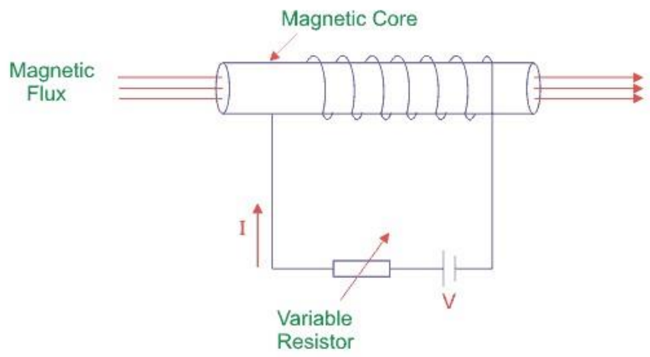
The curve drawn giving relationship between induction density „B‟ and magnetizing force „H‟ is known as magnetization curve or B ~ H curve.

This figure shows the general shape of B ~ H curve of magnetic material. In general it has four distinct regions oa, ab, bc and the regions beyond c. During the region oa the increase in flux density is very small, in region ab the flux density B increases almost linearly with the magnetizing force H, in region bc the increase in flux density is again small and in region beyond point c, the flux density „B‟ is almost constant. The flat part of the magnetization curve corresponds to magnetic saturation of the material.

Hysteresis loop is a four quadrant B-H graph from where the hysteresis loss, coercive force and retentively of s magnetic material are obtained.
To understand hysteresis loop, we suppose to take a magnetic material to use as a core around which insulated wire is wound. The coils is connected to the supply (DC) through variable resistor to vary the current I. We know that current I is directly proportional to the value of magnetizing force (H) as

$$H = \frac{NI}{l}$$

Where, N = no. of turn of coil and l is the effective length of the coil. The magnetic flux density of this core is B which is directly proportional to magnetizing force H.



Definition of Hysteresis

Hysteresis of a magnetic material is a property by virtue of which the flux density (B) of this material lags behind the magnetizing force (H).

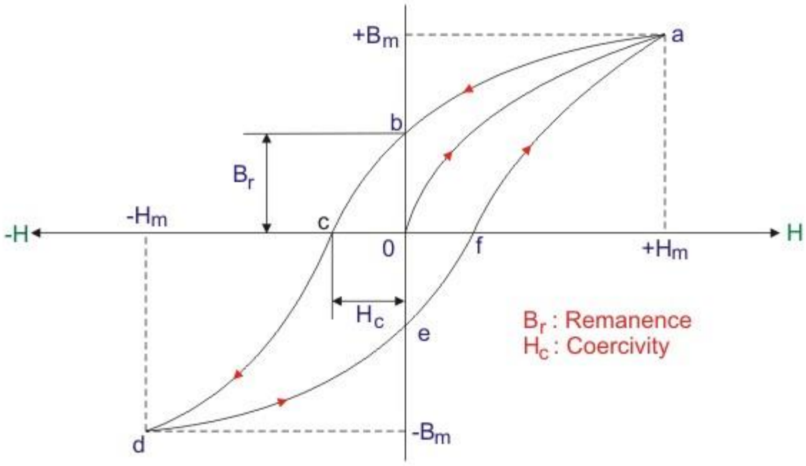
Definition of Coercive Force

Coercive force is defined as the negative value of magnetizing force (-H) that reduces residual flux density of a material to zero.

Residual Flux Density

Residual flux density is the certain value of magnetic flux per unit area that remains in the magnetic material without presence of magnetizing force (i.e. H = 0). **Definition of Retentivity**

It is defined as the degree to which a magnetic material gains its magnetism after magnetizing force (H) is reduced to zero.
Now, let us proceed step by step to make a clear idea about **hysteresis loop**.



- Step 1:
  When supply current I = 0, so no existence of flux density (B) and magnetizing force (H). The corresponding point is ‘O’ in the graph above.
- Step 2:
  When current is increased from zero value to a certain value, magnetizing force (H) and flux density (B) both are set up and increased following the path o – a.
- Step 3:
  For a certain value of current, flux density (B) becomes maximum (B_{max}). The point indicates the magnetic saturation or maximum flux density of this core material. All element of core material get aligned perfectly. Hence H_{max} is marked on H axis. So no change of value of B with further increment of H occurs beyond point ‘a’.
- Step 4:
  When the value of current is decreased from its value of magnetic flux saturation, H is decreased along with decrement of B not following the previous path rather following the curve a – b.
- Step 5:
  The point ‘b’ indicates H = 0 for I = 0 with a certain value of B. This lagging of B behind H is called hysteresis. The point ‘b’ explains that after removing of magnetizing force (H), magnetism property with little value remains in this magnetic material and it is known as residual magnetism (B_r). Here o – b is the value of residual flux density due to retentivity of the material.
- Step 6:
  If the direction of the current I is reversed, the direction of H also gets reversed. The increment of H in reverse direction following path b – c decreases the value of residual magnetism (B_r) that gets zero at point ‘c’ with certain negative value of H. This negative value of H is called coercive force (H_c)
- Step 7:
  H is increased more in negative direction further; B gets reverses following path c – d. At point‘d’, again magnetic saturation takes place but in opposite direction with respect to previous case. At point‘d’, B and H get maximum values in reverse direction, i.e. ($-B_m$ and H_m).
- Step 8:
  If we decrease the value of H in this direction, again B decreases following the path de. At point ‘e’, H gets zero valued but B is with finite value. The point ‘e’ stands for residual

magnetism ($-B_r$) of the magnetic core material in opposite direction with respect to previous case.

- Step 9:
  If the direction of H again reversed by reversing the current I, then residual magnetism or residual flux density ($-B_r$) again decreases and gets zero at point ‘f’ following the path e – f. Again further increment of H, the value of B increases from zero to its maximum value or saturation level at point a following path f – a.

The path a – b – c – d – e – f – a forms hysteresis loop.

Importance of Hysteresis Loop

The main advantages of **hysteresis loop** are given below.

1. Smaller hysteresis loop area symbolizes less hysteresis loss.
2. Hysteresis loop provides the value of retentivity and coercivity of a material. Thus the way to choose perfect material to make permanent magnet, core of machines becomes easier.
3. From B-H graph, residual magnetism can be determined and thus choosing of material for electromagnets is easy.

CHAPTER-6 MATERIALS FOR SPECIAL PURPOSES

INTRODUCTION:

- Some materials used for special purposes such as fuses, solder, bimetal, storage battery plates. Those materials used for special purposes are in structural materials or protective materials.
- Structural materials like poles and towers for distribution and transmission of electric power, frames of rotating machines, frames of electrical heaters etc; protective materials like lead sheathing and steel armouring on cables, bitumen in cable joint boxes and function of underground the cables etc. These materials They do not perform the primary function of the concerned equipment.
- An electrical installation in conduit wiring the materials like the clamps, nails etc. only perform secondary function.

STRUCTURAL MATERIALS:

- Cast iron, steel, timber, reinforced concrete are the common materials used for this purpose.
- Cast iron is used as material for the frames of small and medium sized electrical machines.
- Steel finds its use in fabricated frames for large electrical machines, tanks for transformers, fabrication of transmission towers and a large number of other applications.
- Timber and reinforced concrete are commonly used poles for overhead lines.

PROTECTIVE MATERIALS:

Lead:

- Lead is soft, heavy and bluish-grey metal. It is highly resistant to many chemical actions but can corrode by nitric acid, acetic acid, lime and rotten organic substances.
- The electrical conductivity of lead is only 7.8 % of that of copper.
- Lead and its compounds are toxic. As lead is mechanically weak, it cannot withstand vibrations at high temperatures.
- In the field of electrical engineering lead is used in storage batteries and as sheathing of cables. Pure lead cable sheaths are liable to fail in service due to formation of cracks formed because of vibration.
- This difficulty can be eliminated by using lead alloyed with antimony, tin, cadmium and copper.
- Lead alloys easily with tin and zinc, and forms many commercial alloys, including solders and bearing metals.

Steel tapes, wires and strips: Steel tapes, wires and strips are commonly used as protective material for mining cables, underground cables, weather proof cables etc.

Bitumens: Bitumens are used for protection against corrosion.

OTHER MATERIALS:

Thermocouple materials:

- When two wires of different metals are joined together an e.m.f. exists across the junction which is dependent on the types of metals or alloys used and also directly proportional to the temperature of the junction.
- When one tries to measure this e.m.f. more junctions are to be made, which also will give rise to e.m.fs. When all the junctions are at the same temperature, the resultant e.mf. will not be zero.
- This resultant e.m.f. is proportional to the temperature difference of the junctions and is called thermoelectric e.m.f.
- The e.m.f. produced by a thermocouple is very small but it can be measured with reasonable accuracy by a sensitive moving coil millivoltmeter, which can be calibrated in terms of temperature.
- Thermocouples are made of different materials. The materials to be used will depend upon the range of temperature to be measured.
- Thermocouples can be used for the measurement of temperature.
- ***Principle of the thermocouple pyrometer**:* If one junction, called the cold junction, is held at a known constant temperature, the e.m.f. produced becomes measure of the temperature of the other junction.

Materials used for thermocouples (cold junction is at 10℃)

Materials	Temperature Range (℃)	e.m.f at 500℃ mV
Copper/Constantan	$-200\ to\ 400$	27.6
Iron/Constantan	0 to 900	26.7
Nickel/Nickelchromium	0 to 1100	10.0
Platinum/Platinumrhodium	500 to 1400	4.5

Bimetals:

- A bimetal is made of two metallic strips of unlike metal alloys with different coefficient of thermal expansion.
- At a certain temperature the strip will bend and actuate a switch or a lever of a switch. The bimetal can be heated directly or indirectly.
- When heated the element bends so that the metal with the greater coefficient of expansion is on the outside the arc formed while that with smaller coefficient is on the inside. When cooled the element bends in the other direction.

- Alloys of iron and nickel with low coefficients of expansion are used as one thermal element of the bimetallic strip. The other element consists of materials having high value of coefficient of thermal expansion e.g. iron, nickel, constantan, brass etc.
- Bimetallic strips are used in electrical apparatus and in devices such as relays and regulators.

Soldering Materials:

- An alloy of two or more metals of low melting point used for base metals is known as soldering. The alloy used for joining the metals is known as solder.
- The solder is composed of 50% lead and 50% tin. Its melting point is 185℃ tensile strength is 385 kg/cm^2 and electrical conductivity is 10% of copper.
- Good quality solders for electrical joints should have at least 40 percent tin, as the electrical conductivity of lead is only about half that of tin.
- For proper soldering, flux is to be used. In soldering process, the application of flux serves to remove oxides from the surface to be soldered. For ordinary soldering, zinc chloride is a common flux. Tallow, rosin or olive oil may also be used for soldering.
- Solders are two types such as soft solders and hard solders. Soft solders are composed of lead and tin in various proportions. Hard solders may be any solder with a melting point above that of lead tin solders.
- Hard solders are silver solders, aluminium solders, copper-zinc solders etc. Hard solder have high melting point and therefore are to be used for metals which can withstand high temperatures.
- The application of soft solders is in electronic devices and hard solder in power apparatus for making permanent connection.

EYRE No.7 Flux:

- It is an improved variety of organic flux which is used with Alca P for aluminium cable jointing.
- This on decomposition at a temperature a little below the jointing temp approx 316℃ (600°F) removes the refractory oxide from the strands of the core and makes the surface receptable to solder.

Fuse and Fuse material:

- A fuse is a protective device, which consists of a thin wire or strip. This wire is placed with the circuit which have to protect, so that the circuit current flows through it. When this current is too high, the temperature of the wire or strip will increase till the wire or strip melts. So braking the circuit and interrupting the power supply.
- The current is cut off by the fuse as follows: Upon melting of the wire, the metal-ions form an arc and constitute a conducting path through which the current continues to flow. In order to quench the arc, the resistance in the path must arc rise to such an extent that the available voltage is no longer able to sustain the arc.

A fuse material have following properties:

a) **Low resistivity:** This means, thin wires can be used, which will give less metal vapour after melting of the wire. Less metal vapour in the arc gives lower conductivity and thus makes quenching of the arc easier.
b) **Low conductivity** of the metal vapour itself.
c) **Low melting point:** This means that the temperature of the fuse material for normal currents stays at a low value.

Lead is used as fuse material because of its low melting point. But the resistivity of lead is high, thick wires are used. For rewirable fuses alloys of tin and lead are used.

Fusing current: Fusing current is the minimum current to fuse the wire in such a time interval as shall be necessary for the wire to have attained its steady temperature.

The important characteristic of a fuse material is its current-time relationship. For wire in which the heat is dissipated largely by radiation (rather than by conduction at the ends), the fusing current can be calculated using the relation,

$$I = a\, d^{n}$$

where I is the fusing current in amperes, d is wire diameter in cm and 'a' is a constant whose value varies from material to material. The approximate value of n is 1.5

The value of constant 'a' for some materials are:

Copper = 2530; Aluminium = 1870; Iron = 777; Tin = 405.5; Lead = 304.6;

Dehydrating Material: Silicagel:

- It is an in organic chemical, a colloidal highly absorbent silica used as a de-humidifying and dehydrating agent as a catalyst carrier.
- Calcium chloride and silica gel are used in dehydrating breathers to remove moisture from the air entering a transformer as it breathes.
- Now silica gel is used for breather of a transformer. Its main advantage is that when it becomes saturated with moisture it does not restrict breathing.
- Silica gel when dry is blue in colour and the colour changes to pale pink as it becomes saturated with moisture.
- It can be dried by heating it in an open container at a temperature of between 150°C and 200°C for two hours.