DIELECTRIC PROPERTIES
Unit IV

PRESENTATION

BY

Dr.L.JOTHI

DEPARTMENT OF PHYSICS

N.K.R.GOVT. ARTS COLLEGE FOR WOMEN

NAMAKKAL

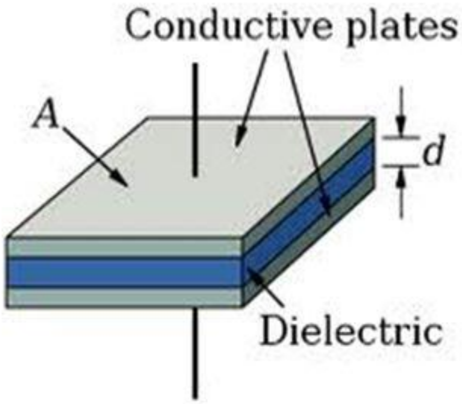
Overview of the presentation

- Dielectrics-Introduction
- Basic Definitions in dielectrics
- Types of Electric Polarization
- Dielectric Loss
- Clausius-Mosotti Relation
- Determination of Dielectric Constant
- Dielectric breakdown
- Properties of different types of Insulating Materials
- Uses of Dielectrics

Dielectrics

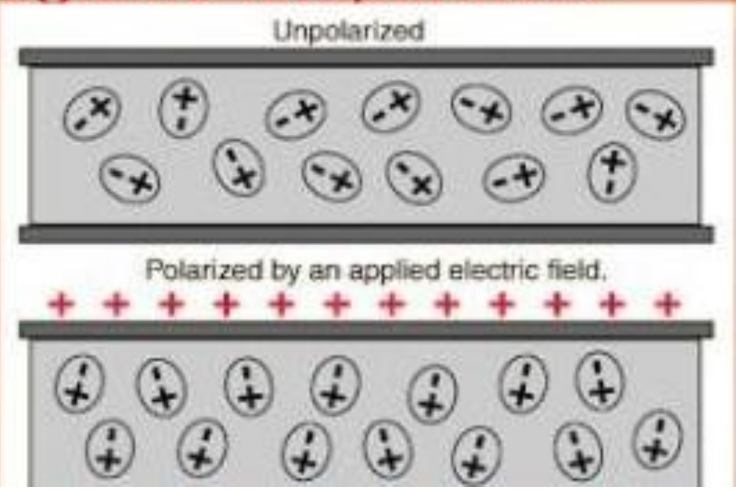
- Any insulating material placed between the plates of a capacitor is called a *dielectric*

- Ex: paper, Mylar, mica, oil, ceramic



Dielectric Materials

- Dielectric materials are also called as insulators.
- In dielectric materials, all the electrons are tightly bound to their parent molecules and there are no free charges
- Dielectrics are non-metallic materials of high specific resistance and negative temperature coefficient of resistance.
- They have permanent electric dipole moment



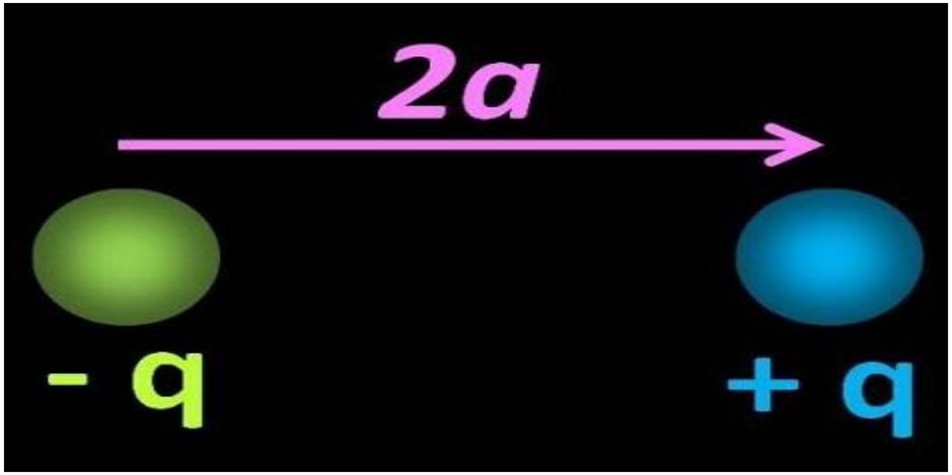
Properties of Dielectric Materials

- Dielectric materials: high electrical resistivities, but an efficient supporter of electrostatic fields.
- Can store energy/charge.
- Able to support an electrostatic field while dissipating minimal energy in the form of heat.
- The lower the *dielectric loss* (proportion of energy lost as heat), the more effective is a dielectric material.
- Another consideration is the *dielectric constant*, the extent to which a substance concentrates the electrostatic lines of flux.

BASIC DEFINITIONS

Electric dipole

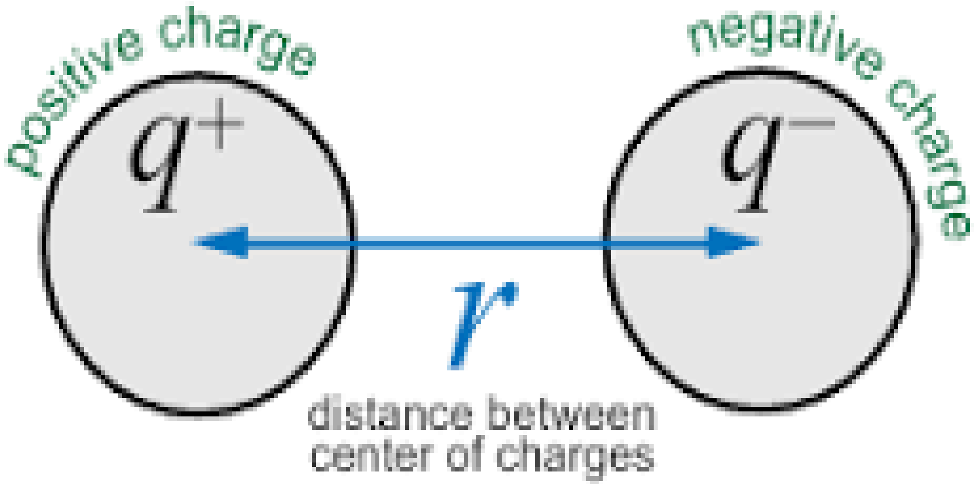
An electric dipole is a pair of equal and opposite point charges -q and q, separated by a distance 2a. The direction from q to -q is said to be the direction of the dipole.



Electric dipole moment

- The electric dipole moment is a measure of the separation of positive and negative electrical charges within a system, that is, a measure of the system's overall polarity.
- The SI units for electric dipole moment are coulomb-meter (C·m); however, a commonly used unit in atomic physics and chemistry is the debye (D).

Electric dipole moment



$$\mu = q \cdot r$$

dipole moment — separated charge — distance between

Permittivity

Permittivity, is a measure of the electric polarizability of a dielectric. A material with high permittivity polarizes more in response to an applied electric field than a material with low permittivity, thereby storing more energy in the material. In electrostatics, the permittivity plays an important role in determining the capacitance of a capacitor.

Permittivity of free space

The permittivity of free space, εo, is described as

$$\epsilon_0 = \frac{1}{\mu_0 c^2} \approx 8.8542 \times 10^{-12} \text{ F/m}$$

Relative Permittivity

- Relative permittivity: Relative permittivity is defined as the permittivity of a given material relative to that of the permittivity of a vacuum. It is normally symbolised by: ε_r.

- Dielectric constant: The dielectric constant is defined as the relative permittivity for a substance or material.

- The permittivity ε of a medium is given by

$$\varepsilon = D / E$$

Where:

ε = permittivity of the substance in Farad per metre

D = electric flux density

E = electric field strength

Dielectric Constant

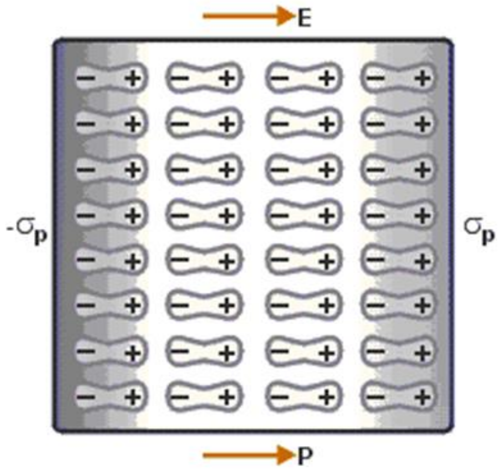
Dielectric Constant is the ratio between the permittivity of the medium to the permittivity of free space.

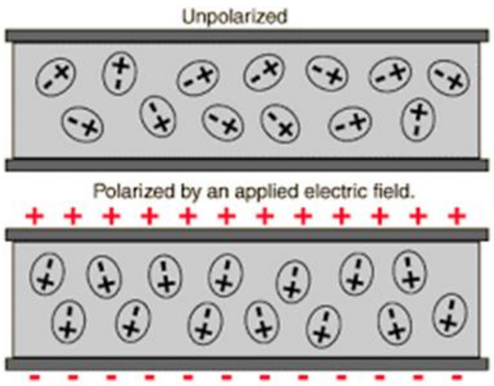
$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$

The characteristics of a dielectric material are determined by the dielectric constant and it has no units.

Polarization

- When a dielectric material is placed in external electrical field, it's molecule gain electric dipole moment and dielectric said to be polarised.
- The induced moment per unit volume of dielectric material is called the electric polarization of dielectric.





- In most neutral atoms or molecules, the center of positive charge coincides with the center of negative charge.
- In the presence of a charged object, these centers may separate slightly. This results in more positive charge on one side of the molecule than the other side.
- This realignment of charge on the surface of an insulator is known as polarization.

Polarizability

- Polarizability, which is represented by the Greek letter alpha, α, is experimentally measured as the ratio of induced dipole moment p to the electric field E that induces it.

$$\alpha = p/E$$

- Polarizability has the SI units of $C \cdot m^2 V^{-1}$.

Electric susceptibility

- Electric susceptibility, is a quantitative measure of the extent to which an electric field applied to a dielectric material causes polarization, the slight displacement of positive and negative charge within the material.
- For most linear dielectric materials, the polarization P is directly proportional to the average electric field strength E so that the ratio of the two, P/E, is a constant that expresses an intrinsic property of the material.
- The electric susceptibility, χ_e, in the centimetre-gram-second (cgs) system, is defined by this ratio; that is,

$$\chi_e = P/E.$$

- In the metre-kilogram-second (mks) system, electric susceptibility is defined slightly differently by including the constant permittivity of a vacuum, ε_0, in the expression; that is, $\chi_e = P/(\varepsilon_0 E)$.

Types of dielectric polarization

There are four types of dielectric polarization

1. Electronic polarization
2. Ionic polarization
3. Orientational polarization
4. Space charge polarization

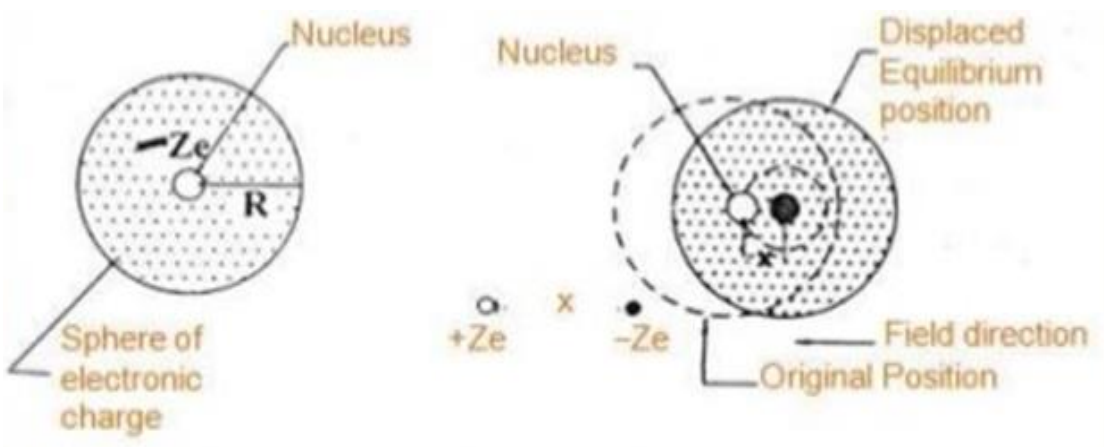
Electronic Polarization

When an EF is applied to an atom, +ve ly charged nucleus displaces in the direction of field and ẽ could in opposite direction. This kind of displacement will produce an electric dipole with in the atom.

i.e, dipole moment is proportional to the magnitude of field strength and is given by,

$$\mu_e = \alpha_e E$$

where 'α_e' is called electronic Polarizability constant.



Ionic polarization

Ionic polarization arises due to the displacement of -ve ions and + ve ions in opposite directions and it occurs in ionic solids, in the presence of electric field. The displacement is independent of temperature. Example : NaCl crystal

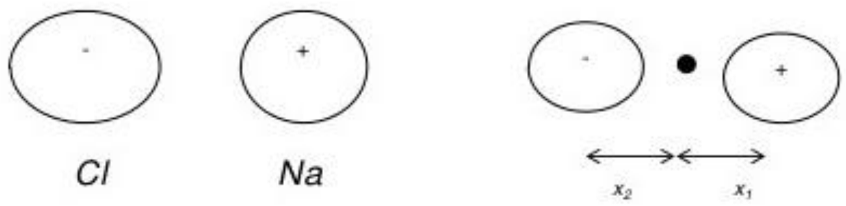


Fig. (a) Without field (b) With field

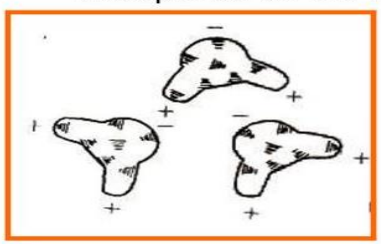
- The induced dipole moment due to ionic polarization is proportional to the applied electric field, i.e.
- For the most of the materials, the ionic polarizability is very less than the electronic polarizability,

$$\mu_i \propto E$$

$$\mu_i = \alpha_i E$$

Orientational polarization

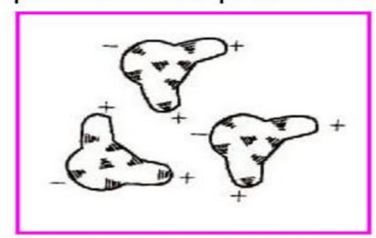
- It is due to the presence of polar molecules in the dielectric material which have permanent dipole moment.
- When electric field is applied on the dielectric material, it tries to align the dipole in its direction that results in the existence of dipole moment in the material.
- It occurs in asymmetric molecules.
- Its depends on the temperature.



No Field

$$P_o = \frac{\mu^2}{3KT}$$

μ is permanent dipole moment

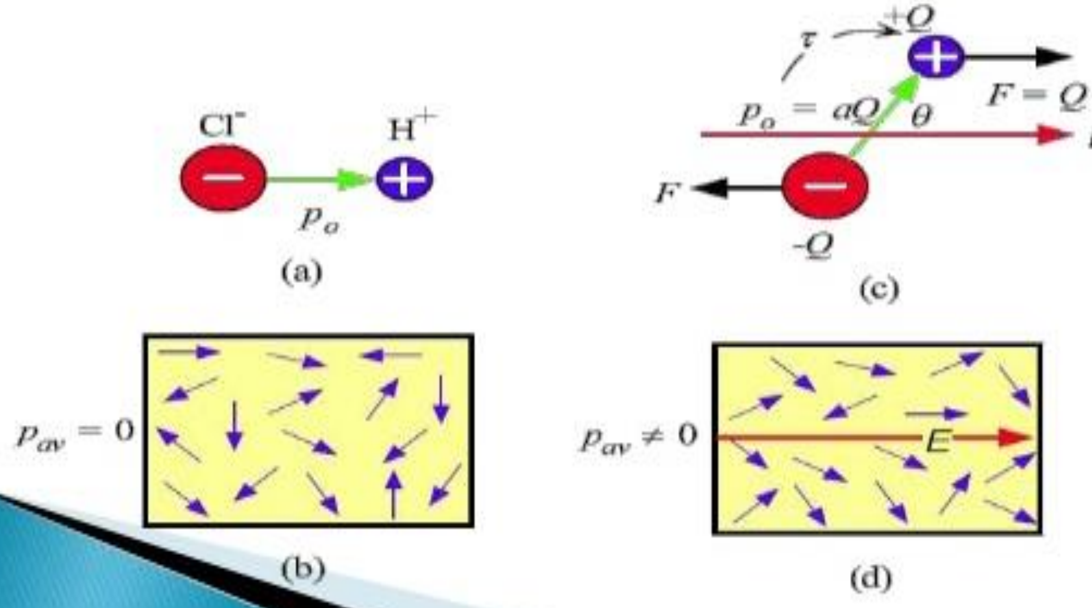


Electric Field

Orientational Polarizability, α_O is determined from

$$\mu_O = \alpha_O E$$

- Some molecules like H_2O, HCl having permanent dipole moment p_0.
- In the absence of a field, individual dipoles are arranged in random way, so net average dipole moment in a unit volume is zero as shown in fig. (b).
- A dipole such as HCl placed in a field experiences a torque that tries to rotate it to align p_0 with the field E.



Space charge polarization

Space-charge polarization occurs due to the accumulation of charges at the electrodes or at the interfaces in a multiphase material. The ions diffuse over appreciable distances in response to the applied field, giving rise to redistribution of charges in the dielectric medium.

- The tendency of redistribution of charges in the dielectric medium in the presence of external electric field is known as space charge polarization.

No Field
E=0

Field E

Total Polarization

The total amount of dielectric polarization in a material is the sum of the electronic, ionic and orientational polarizabilities.

$$\alpha = \alpha_e + \alpha_i + \alpha_0$$

Since the space charge polarization is very small and it is negligible.

Dielectric Loss

- Loss of energy that goes into heating a dielectric material in a varying electric field.
- Capacitor incorporated in an alternating-current circuit is alternately charged and discharged each half cycle.
- During the alternation of polarity of the plates, the charges must be displaced through the dielectric first in one direction and then in the other, and overcoming the opposition that they encounter leads to a production of heat through dielectric loss.

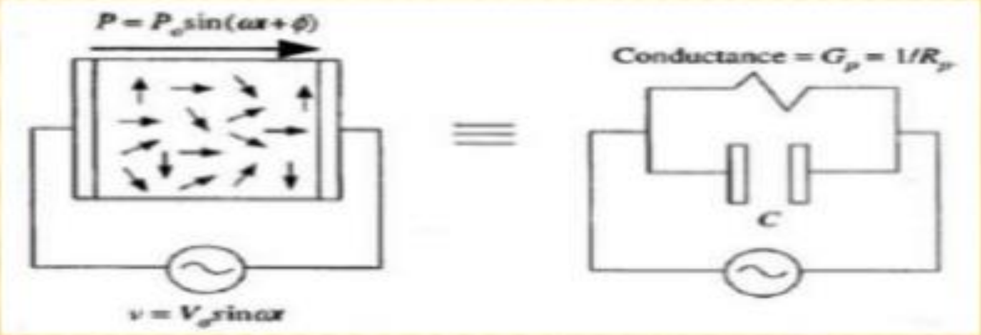


Fig. Dielectric loss in dielectric

- Dielectric losses depends on frequency and the dielectric material.

Dielectric Loss

- ε'' is also known as the loss factor.
- The small difference in phase from ideal behaviour is defined by an angle δ, defined through the equation

$$\frac{\varepsilon''}{\varepsilon'} = \tan\delta$$

- $\tan\delta$ is known as the loss tangent or dissipation factor.
- A quality factor, Q, for the dielectric is given by the reciprocal of $\tan\delta$.

Clausius Mosotti Equation

The relation is in between the microscopic property called molecular Polaris ability and macroscopic property called dielectric constant.

The dipole moment $\bar{P}_m$ or $\bar{P}_i$ induced in the molecule to the local field or polarizing field E_L or E_m that is

$$\alpha = \frac{Pi}{E_L} \text{ or } \frac{P_m}{E_m}$$

$$P_i = \alpha E_L \qquad \text{or} \qquad P_m = \alpha E_m$$

If there are N number molecules per and volume of the dielectric then the polarization $\bar{p}$ is given by

$$\bar{p} = N\bar{P}_i = N\alpha\bar{E}_L \qquad \ldots(1)$$

According to lorentz equation the polarizing field acting on a single atom or molecule of a non-polar dielectric in macroscopic field $\bar{E}$ is

$$\bar{E}_L = \bar{E} + \frac{\bar{P}}{3\epsilon_0}$$

Therefore

$$\bar{p} = N\,\alpha \quad \bar{E} + \frac{P}{3\epsilon_0}$$

But $P = (K - 1) \in_0 \vec{E}$ By electrical suscepribility

$$(k - 1) \in_0 \vec{E} = N \alpha \quad \vec{E} + \frac{P}{3\in_0}$$

$$= N \alpha \quad 1 + \frac{(k-1)\in_0}{3\in_0} \; \vec{E}$$

$$(k - 1)\in_0 = N \alpha \quad \frac{K \quad 2}{3}$$

$$\alpha = \frac{3\in_0}{N} \; \frac{K \quad 1}{K+2}$$

OR $K = \in r$

$$\alpha = \frac{3\in_0}{N} \; \frac{r \quad 1}{\in r + 2}$$

This is known as clausias Mosstti equation. This equation is valid for Non – polar solid having cubic crystal structure.

Limitation of the Clausius Mossotti Equation

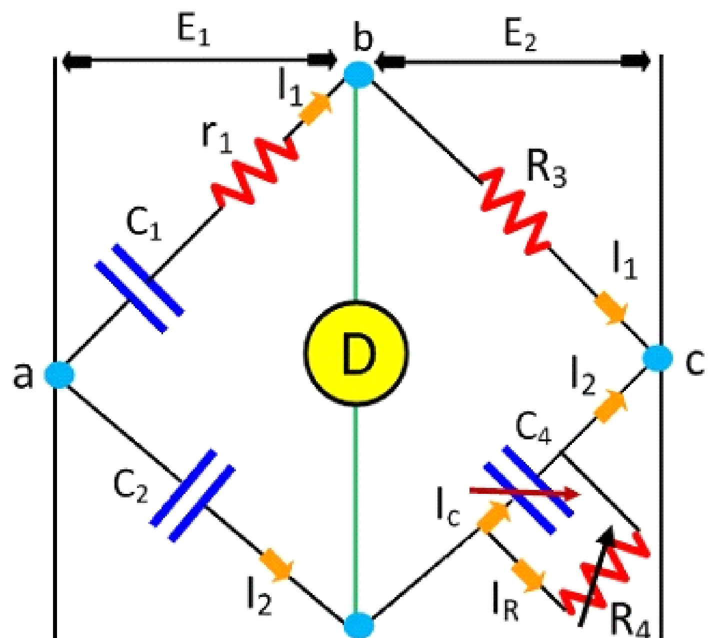
Clausius – Mossotti equation is derived based as the following assumptions.

i. Polarization is considered as proportional to the field.
ii. The polarizable molecules are isotropic.
iii. Absence of short – range interaction.

Determination of Dielectric Constant Schering Bridge

Schering Bridge

The Schering bridge use for measuring the capacitance of the capacitor, dissipation factor, properties of an insulator, capacitor bushing, insulating oil and other insulating materials. It is one of the most commonly used AC bridge. The Schering bridge works on the principle of balancing the load on its arm.



Breakdown in dielectric Materials

INTRODUCTION

- Solid dielectric materials are used in all kinds of electrical circuits and devices to insulate one current carrying part from another when they operate at different voltages.
- A good dielectric should have low dielectric loss, high mechanical strength, should be free from gaseous inclusion, and moisture, and be resistant to thermal and chemical deterioration.
- When breakdown occurs, solids get permanently damaged while gases fully and liquids partly recover their dielectric strength after the applied electric field removed.
- The mechanism of breakdown is a complex phenomenon in the case of solids, and varies depending on the time of application of voltage .

Classification of Breakdown

Breakdown in solid dielectric occurs, if solid dielectric strength less than electric stress. Breakdown Mechanism in solid dielectric depend on the time of application of voltage, and can be classified as follows:

i. Intrinsic breakdown
ii. Thermal Breakdown
iii. Electrochemical Breakdown
iv. Discharge Breakdown
v. Defect Breakdown

Intrinsic Breakdown

- In a pure and homogeneous dielectric under controlled temperature and environmental conditions we get a very high dielectric (breakdown) strength. This is known as the intrinsic.
- Dielectric strength which depends mainly on the characteristics and structure of the material. The dielectric strength obtained under such conditions is around MV/cm which is generally not obtained in practical conditions.

Thermal Breakdown

- When an electric field is applied to a dielectric, conduction current flows through the material.
- Current heats up the specimen and the temperature rises.
- Heat generated is transferred to the surrounding medium by conduction and radiation.
- Equilibrium is reached when the heat generated (W_{dc} or W_{ac}) is equal to heat dissipated (WT). Breakdown occurs when W_{dc} or W_{ac} exceeds WT.
- where, $W_{dc} = E^2\sigma$ W/cm^2

$$W_{ac} = \frac{E^2 f \varepsilon_r \tan\delta}{1.8\times10^{12}} \; W/cm^3$$

- f : frequency in Hz.
- δ : loss angle of the dielectric material
- E : rms value

$$W_T = C_V \frac{dT}{dt} + div(K \, grad \, T)$$

- CV : specific heat of the specimen
- T : temperature of the specimen
- K : thermal conductivity of the specimen
- t : time over which the heat is dissipated

- When electric field is applied to a solid specimen heat is produced due to dielectric losses in the specimen.

- The losses are due to :
  - Ohmic losses
  - Dipole oscillations
  - Partial discharges due to voids

- Due to losses, heat is generated

Electrochemical Breakdown

- In presence of air and other gases, dielectric materials undergo chemical changes when subjected to continuous electrical stresses. Chemical reactions that occur are:
- *Oxidation: In the presence of air or oxygen, materials such as rubber and polyethylene undergo oxidation giving rise to surface cracks.*
- *Hydrolysis: When moisture or water vapour is present on the surface of the solid dielectric, hydrolysis occurs and the materials lose their electrical and mechanical properties. Materials like paper, cotton tape and other cellulose materials deteriorate very rapidly due to hydrolysis.*

- Chemical Action: Progressive chemical degradation can occur due to a variety of processes such as chemical instability at high temperature, oxidation, cracking and hydrolysis.
- Chemical and electrochemical deterioration increases very rapidly with temperature.

Discharge breakdown

- Discharge breakdown is classified as external or internal.
- The external breakdown is caused by a corona discharge. Such discharge is observed at sharp edges of electrodes. Deterioration accompanied by the formation of carbon. Damaged areas become conducting leading to power arc and complete failure to the dielectric.
- Internal breakdown occurs when the insulator contains occluded gas bubbles. When large bubbles are present, this occurs even at low voltages

Corona Discharge

- The field is non-uniform, an increase in voltage will first cause a discharge in the gas to appear at points with highest electric field intensity, namely at sharp points or where the electrodes are curved or on transmission lines. This form of discharge is called a corona discharge and can be observed as a bluish luminescence.

Defect breakdown

- If the surface of the material has defects such as crackles and porosity then impurities such as dust at these discontinuities leading to a breakdown. Also if the defect in the form of strain, that region will also break on the application of fields.

Insulating Materials

- Insulating materials are non metallic materials that does not allow electric current to pass through it at normal temperatures.
- There are number of insulating materials used in Electrical apparatus and machinery. They may be organic or inorganic, uniform or heterogeneous in composition, natural or synthetic.
- There are many properties such as resistivity, breakdown voltage, thermal stability etc., that determine the suitability of a material to be used as insulating material.

Properties of insulating materials

An ideal insulating material must should have the following properties.

- High dielectric strength at the specified temperature
- High resistivity
- Low dielectric hysteresis
- Good thermal conductivity
- Good moisture withstanding capacity
- It should be chemically inert
- It should be able to withstand vibration, abrasion and bending

Classification of Insulating materials

Insulating materials are classified in to three categories:

1. Solid Insulating Materials
2. Liquid Insulating Materials
3. Gaseous Insulating Materials

Insulating Materials and Examples

State	Materials	Examples
Solid Insulating Materials	Fibrous materials	wood, paper and card board, insulating textiles Materials
	Impregnated fibrous materials	impregnated paper, varnished or impregnated textiles
	Non resinous materials	asphalts and bitumens, waxes
	Ceramics	porcelain, steatite, alumina, titanate, etc.
	Glass	fused quartz or silica glass, Pyrex, fiber glass
	Natural and synthetic rubbers	natural rubber, hard rubber, butyl rubber, neoprene, hypalon, silicon rubber
		Mica and its products; Asbestos and its products
Liquid Insulating Materials	Oils	Refined hydrocarbon minerals oils, Linseed oil, silicon liquids, vegetable oils etc.
	Varnishes	synthetic varnishes and spirit
Gaseous Insulating Materials		Carbon dioxide (CO_2), Dry air, argon, nitrogen, etc.

Uses of Dielectrics

We have seen that dielectric materials are electrically insulative, yet susceptible to polarization in the presence of an electric field. This polarization phenomenon accounts for the ability of the dielectrics to increase the charge storing capability of capacitors.

Now, we can summarize the main uses of dielectrics as follows:

(i) Piezoelectric and electro-optic devices
(ii) In capacitors, resistors and strain gauges
(iii) Thermionic valves, radiation detectors, electric devices, dielectric amplifier
(iv) Dielectrics are usually used as ordinary insulators in power cables, signal cables, electric motors, etc.
(v) Dielectrics are used in transformers and various form of switchgear and generators where the dissipation problem of heat is active, and a common way of getting rid of it is to insulate with a transformer oil, i.e. mineral oil.

Thank you...