UNIT I

DIELECTRIC MATERIALS AND INSULATION

Matter polarization and relative permittivity: definition - Dipole moment and polarization vector Polarization mechanisms: electronic, ionic, orientation, interfacial and total polarization - Frequency dependence - Local field and Causius-Mossotti equation - Dielectric constant and dielectric loss - Gauss's law and boundary conditions - Dielectric strength, introduction to insulation breakdown in gases, liquids and solids - Capacitor materials - Typical capacitor constructions - Piezo and pyroelectric crystals (qualitative).

1.1. Introduction

Dielectric materials are electrically non-conducting materials such as glass, ebonite, mica, rubber, wood and paper. All the dielectric materials are insulating materials. The difference between a dielectric and an insulator lies in its applications

If the main function of non-conducting materials is to provide electrical insulation, then they are called insulators. Alternatively, if the main function of non-conducting materials is to store electrical charges, then they are called as dielectrics.

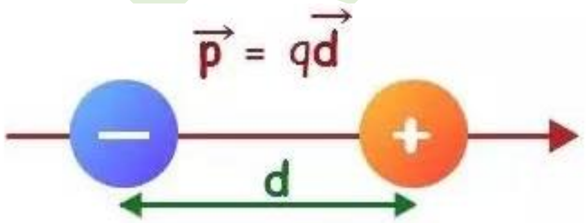
Properties

- ✓ Generally, the dielectrics are non-metallic materials of high resistivity
- ✓ All the electrons in the dielectrics are tightly bound to their parent nucleus.
- ✓ As there are no free electrons to carry the current, the electrical conductivity of dielectrics is very low
- ✓ They have negative temperature coefficient of resistance and high insulation resistance.
- ✓ They have a very large energy bandgap (> 3eV)

Basic definitions

Electric dipole

A system consisting of two equal and opposite charges separated by a distance *d* is called an electric dipole



Dipole moment (μ)

The product of magnitude of the charge (q) and distance between two charges is called dipole moment

Permittivity (ε)

The permittivity denotes the dielectric property of a medium. It indicates easily polarisable nature of the material. Unit: Farad metre^{-1}

The value of permittivity of free space is $\varepsilon_0 = 8.854 \times 10^{-12}$ F m^{-1}

Dielectric constant (ε_r)

It is the ratio between the absolute permittivity of the medium (ε) and the permittivity of the free space (ε_0) $\therefore \varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$

Polarization

The process of producing electrical dipoles inside the dielectric by an external electric filed is called polarization in dielectrics

Active & passive dielectrics

S.No	Active dielectrics	Passive electrics
1.	Dielectrics which can adapt itself to store the electrical energy in it is called active dielectrics	Dielectrics which restricts the flow of electrical energy in it are called passive dielectrics
2.	It is used in the production of ultrasonics	It is used in the production of sheets , pipes, etc.,
3.	Eg: Piezo, Ferro, Pyroelectrics	Eg: Glass, Mica, Plastic

Polarizability (α)

It is found that the average dipole moment of a system is proportional to the applied electric field (E). i.e., $\overline{\mu} \infty E$ (or) $\overline{\mu} = \alpha E$

Where α is the proportionality constant and it is known as the polarizability.$\alpha = \frac{\overline{\mu}}{E}$

It is defined as the ratio of average dipole moment to the electric field applied. Unit: Fm^2

Polarization vector ($\overline{P}$)

It is defined as the average dipole moment per unit volume of a dielectric. If *N* is the number of atoms per unit volume and $\overline{\mu}$ is the average dipole moment per atom, then

$\overline{P} = N\overline{\mu}$ coulomb / m^2.

Electric displacement vector ($\overline{D}$)

The electric displacement vector 'D' is a quantity which is very convenient function for analyzing the electrostatic fields in the dielectrics and is given by,

$$D = \varepsilon E = \varepsilon_0 E + P$$

Electric susceptibility (χ_e)

The polarization vector P is proportional to the total electric field intensity E and is in the same direction of E. therefore, the polarization vector can be written as,

$$P = \varepsilon_o \chi_e E$$

Where, the constant χ_e is referred as the electric susceptibility and is a characteristic of very dielectric.

$\therefore \chi_e = \frac{P}{\varepsilon_o E} = \varepsilon_r - 1$ or $\varepsilon_r = 1 + \chi_e$

The electric susceptibility 'χ_e' easily determines the polarizable nature of the materials.

Polar molecules

In polar molecules, the centre of positive and negative charges do not coincide, because they do not have centre of symmetry. These molecules possess some dipole moments which are oriented randomly and net dipole moments which are oriented randomly and net dipole moment is very less.

When an electric field is applied to the polar molecules, the dipole moments are aligned themselves in a direction parallel to the direction of the field and net dipole moment is produced.

Examples: NH_3, $CHCl_3$, and HCl.

Non-polar molecules

In non-polar molecules, the centers of positive charges will coincide with each other due to presence of centre of symmetry. They do not possess any dipole moment in it and net dipole movement will be zero.

When an electric field is applied to these molecules, the positive and negative charges are separated by some distance from their equilibrium positions and dipoles are created. Now a net dipole moment is produced in non-polar molecules.

Examples: O_2, CH_4 and H_2.

Difference between Polar and Non-polar Molecules

S.No.	Polar molecules	Non-polar molecules
1	These molecules have permanent dipole moment even in the absence of an applied field.	These molecules do not have permanent dipole moment.
2	The polarization of polar molecules is highly temperature dependent.	These types of molecules are independent of temperature.
3	These molecules have absorption or emission in the infrared range .	These molecules do not have absorption or emission in infrared range.
4	These molecules do not have symmetrical structure and they do not have centre of symmetry.	These molecules have symmetrical structure and they have centre of symmetry.
5	*Examples:* HCl and H_2O	*Examples:* CCl_4 and CO_2

1.2. TYPE OF THE DIELECTRIC POLARIZATION:

There are four different types of mechanisms through which electric polarization can occur in a dielectric material when they are subjected to an external electric field.

There are:

(a) Electronic polarization.

(b) Ionic polarization.

(c) Orientation polarization.

(d) Space charge or interfacial polarization.

(a) Electric polarization

The electronic polarization occurs, due to the displacement of the positively charged nucleus and the negatively charged electric cloud in opposite direction within a dielectric material upon applying an external field E.

Thus, the separation created between the charged includes a dipole. This process occurs throughout the material and the material as a whole will be polarized. Electric polarization is more in liquid and solid dielectric than in gases.

Therefore, the include dipole moment $\mu = \alpha_e E$. Where α_e is electronic polarization

The electronic polarization for a rare gas atom is given by $\alpha_e = \frac{\varepsilon_0(\varepsilon_r - 1)}{N}$

Where N is the number of atoms per unit volume.

Expression for electronic polarization α_e

(i) **Without field**:

Let us consider one of the constituent atom of a dielectric material in the absence of a electric field E. let the radius of the atom be R and its atomic number be Z as shown in figure 1. Here, the nucleus of charge Ze is surrounded by an electronic cloud of charge –Ze. If the electron is spherically symmetric.

Therefore, the charge density for electron cloud is given by

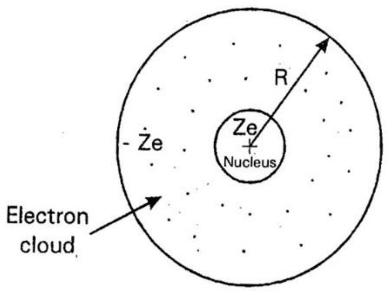


Fig. 1

$P = \frac{-Ze}{\left[\frac{4}{3}\pi R^3\right]} = \frac{-3}{4}\left[\frac{Ze}{\pi R^3}\right]$ ………………….. (1)

With Electric Field:

When an electric field is applied, the nucleus and the electron cloud experience a Lorentz force of magnitude ZeE in opposite directions. Hence, the nucleus and the electron cloud are pulled by a distance. Since, the nucleus is much heavier than the electron cloud it is assumed that only the electron cloud displaced upon applying an electric field. Let the electron cloud displacement be x with respect to the center of the nucleus.

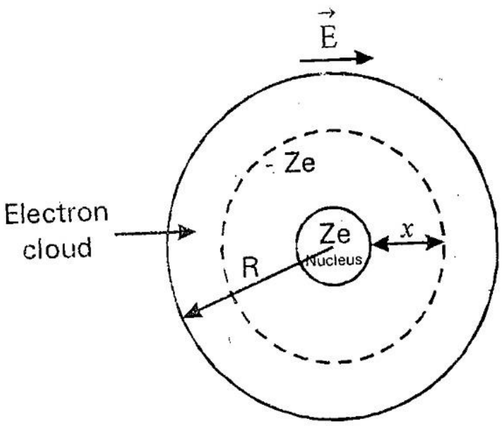


Fig. 2

Hence, the Lorentz force acting over the electron cloud is = -ZeE ……….…... (2)

But, according to gauss theorem a coulomb attractive force is said to act over the nucleus due to the electron cloud in sphere of radius x and this force tends to oppose the displacement.

Thus, the Coulomb force = Ze ×E ……………………………..… (3)

Based on coulomb's theorem

$$\boldsymbol{E} = \frac{\text{total charge enclosed in a sphere of radius x}(\boldsymbol{q})}{\boldsymbol{4\pi\varepsilon_0 x^2}}$$

Note: *coulomb's theorem statement: The electric field at any point in a charge conductor is 1/ ε0 times the surface charge density, i.e., charge per unit area.*

But the total charge enclosed in a sphere of radius *x* is $q = P \times \frac{4}{3}\pi x^3$ ….. (5) Where P is negative charge density and $\frac{4}{3}\pi x^3$is volume of the sphere of radius *x*

Substituting for p from equation (1) we get, $Q = \frac{-3}{4}\frac{Ze}{\pi R^3} \times \frac{4}{3}\pi x^3$

(or) $\therefore Q = \frac{-Zex^3}{R^3}$ ………………….. (6)

Substituting for P from equation (4) we get, $E = \frac{Ze}{4\pi\varepsilon_0 x^2} \times \left[\frac{-Zex^3}{R^3}\right]$

Or $E = \frac{-Z^2e^2x}{4\pi\varepsilon_0 R^3}$ …………………….. (7)

These two forces i.e., the Lorentz force and the coulomb force are equal in magnitude but opposite in direction as a result, a equilibrium is reached. Hence, at equilibrium

Lorentz force = Coulomb force

$$-ZeE = \frac{-Z^2e^2x}{4\pi\varepsilon_0 R^3} \quad \text{.......................... (8)}$$

$$\text{(or) } E = \frac{Zex}{4\pi\varepsilon_0 R^3}$$

$$\text{(or) } x = \frac{4\pi\varepsilon_0 R^3 E}{Ze} \quad \text{... (9)}$$

Thus, the displacement of the electron cloud is proportional to the applied field E. due to the displacement the atoms acts as a dipole.

The induced displacement (μ) = Magnitude of Charge (Ze) × Displacement (*x*)

$$\mu = \frac{Ze4\pi\varepsilon_0 R^3 E}{Ze}$$ (Substituting for x from equation (9))

Or $$\mu = 4\pi\varepsilon_0 R^3 E \quad \text{..............................(10)}$$

But, $\mu = \alpha_e E$ ....(11)

Comparing equation (10) and (11), we have

$\alpha_e = 4\pi\varepsilon_0 R^3$ ....(12)

Thus, the electronic polarization is proportional to the volume of the atom and is independent of temperature.

The polarization vector $p = N\mu$

$p = N \alpha_e E$ .... (13)

But, we know that

$p = \varepsilon_0 E (\varepsilon_r - 1)$ .... (14)

Equating equations (15) and (16), we get

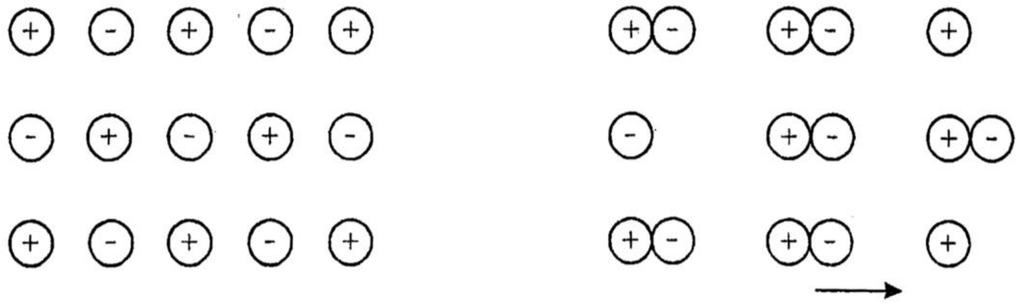
$N \alpha_e E = \varepsilon_0 E (\varepsilon_r - 1)$

or $$\alpha_e = \frac{\varepsilon_0(\varepsilon_r - 1)}{N} \quad \text{.......... (15)}$$

Ionic polarization

Ionic polarization occurs only in ionic solid such as NaCl which possess ionic bonds. It does not occur in covalent crystal such as diamond, silicon and germanium.

When ionic solid are subject to an external electric field, the adjacent ionic of opposite sign undergo displacement. The displacement may cause either an increase or decrease in the distance of separation between the atoms depending upon the location of the ion pair in the lattice.



$E = 0$ Position of ions in the absence of field

$E \neq 0$ Ion displacement due to the applied field

Expression for ionic polarizability

Let an electric field E is applied to an ionic solid consisting of one cation and one anion per unit cell .This applied field causes the positive ions and negative ions to get displaced through a distance x_1 and x_2 respectively from their equilibrium position there by inducing a dipole moment per unit cell is

$\mu = (x_1 + x_2)$ ……………….(1)

Due to the application of electric field a restoring force is said to act over the cation and anion.

Thus, restoring forces $F = \beta_1 x_1; F = \beta_2 x_2$ ………. (2)

Hence $x_1 = \frac{F}{\beta_1} \& x_2 = \frac{F}{\beta_2}$ …………………. (3)

Where β1 and β_2 are restoring force constants of cation and anion. These restoring force constants depends upon the mass of the ion and angular frequency of the molecule in which the ions are present.

Thus $x_1 = \frac{eE}{m\omega_0^2} \& x_2 = \frac{eE}{M\omega_0^2}$ ……………..(4)

Where m is the mass of cation and M the mass of anion.

Substituting equation (4) in (1), we get

$\mu = e\left[\frac{eE}{m\omega_0^2} + \frac{eE}{M\omega_0^2}\right]$ …………………… (5)

(or) $\mu = \frac{e^2E}{\omega_0^2}\left[\frac{1}{m} + \frac{1}{M}\right]$ …………………… (6)

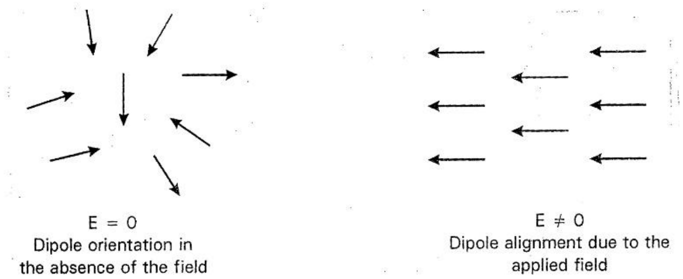
(or) $\mu = \alpha_i E$ ………………….. (7)

Where $\alpha_i = \frac{e^2}{\omega_0^2}\left[\frac{1}{m} + \frac{1}{M}\right]$

Thus, ionic polarizability is inversely proportional to the square of the nature frequency of the ionic molecule and directly proportional to its reduced mass. The ionic Polaris ability is also independent of temperature.

Orientation polarization (Dipolar polarization)

Orientation polarization occurs in dielectric materials which possess molecules with permanent dipole moment (i. e., in polar molecules). In the absence of an external electric field. Because of random orientation of the dipoles due to thermal agitation the material has net zero dipole moment. But under the influence of an external applied electric field, each of the dipoles undergoes rotation so as to reorient along the dielectric of the field. Thus, the material itself develops electrical polarization.



This polarization occurs in ferroelectric material such as Ba Ti O_3 and pbTiO_3 and produces a very high dielectric constant in these materials.

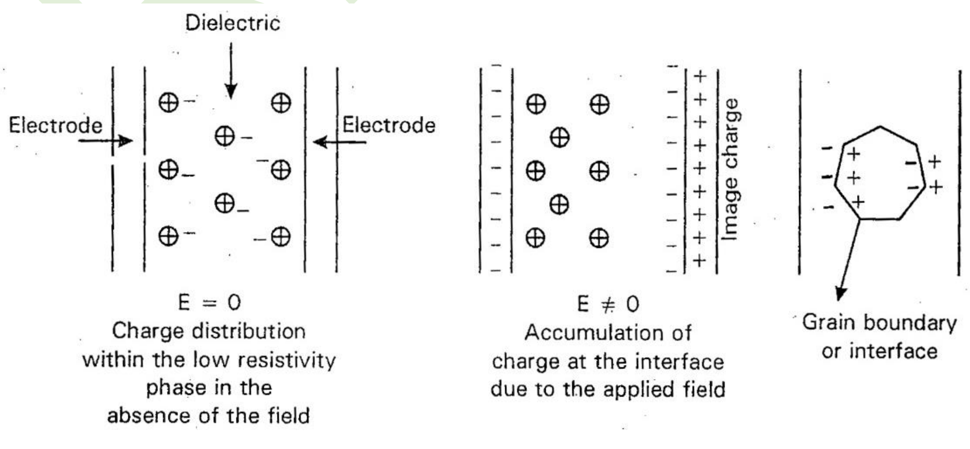
In the case of polar dielectrics, the orientation polarizability α_o is given by $\alpha_0 = \frac{\mu^2}{3K_BT}$

Where k_B is the Boltzmann constant, T is the temperature and is the permanent dipole moment. Thus, the orientation polarizability is inversely proportional to absolute temperature.

Space charge (interfacial polarization)

The space charge polarization occurs in multiphase dielectric materials. When such material are subjected to an external field, especially at high temperature the charge get accumulated at the interface or at the electrodes because of sudden change in conductivity.

Since, the accumulation of charge with opposite polarity occurs at opposite parts in the low resistivity phases, it leads to the development of dipole moment within the low resistivity. Grain boundaries often lead to interfacial polarization as they can trap charges migrating under the influence of an applied field. This type of polarization occurs in some materials like and certain glasses containing. This polarization is not an important factor in most common dielectric used in capacitor and other applications.



Total polarizability

The total polarizability of a material is thus given by the sum of the electric, ionic and orientational Polarizabilities (space charge is negligible).

$\alpha_T = \alpha_o + \alpha_i + \alpha_o$

Since, the space charge polarizability α_i very small when compared to other types of Polarizabilities.

Thus, the Total polarizability of a material is given by

$\alpha_T = \frac{\mu^2}{3K_BT} + \frac{e^2}{\omega_0^2}\left[\frac{1}{m} + \frac{1}{M}\right] + 4\pi\varepsilon_0 R^3$ [Substituting for α_o, α_i and α_o]

Hence the total polarization P is given by

$$P = N\,\alpha_T\,E$$

(or) $P = NE\left[\frac{\mu^2}{3K_BT} + \frac{e^2}{\omega_0^2}\left[\frac{1}{m} + \frac{1}{M}\right] + 4\pi\varepsilon_0 R^3\right]$

The above equation is known as Langevin – Debye equation.

1.3. Frequency dependence of polarization

On application of an alternating electric field, a polarization process occurs as a function of time. The polarization P (t) as a function of time t is given by

$$P(t) = P\left[1 - e^{\left[\frac{t}{t_r}\right]}\right]$$

Where p is the maximum polarization attained on prolonged application of a static field and t_r is the relaxation time for scale of a polarization process. The relaxation time t_r z is a measure of the time scale of a polarization process. It is the time taken for a polarization process to reach 0.63 of the maximum value. This varies widely for different polarization processes.

Electric polarization is an extremely rapid. Even when the frequency of the applied field voltage is very high in the optical range (~ 10^{15} H z) electric polarization occurs during every cycle of the applied voltage.

Ionic polarization is due to displacement of ions over a small distance due to the applied field. Since ions are heavier than electric cloud, the time taken for displacement is larger. The frequency with which ions are displaced is of the same order as the lattice vibration frequency (~ 10^{13} H z). this means that for optical frequency the ions do not respond, as the time required for lattice vibrations is nearly 100 times larger than the period of applied voltage at optical frequency. Hence, at optical frequencies, there is no ionic polarization. If the frequency of the applied voltage is less than 10^{13} the ions respond. Hence at 10^{13} H z, we have both electric polarization and ionic polarization responding.

Orientation polarization is even slower than ionic polarization. The relaxation time for orientation polarization in a liquid is less than that in a solid. For example, the relaxation time for orientation polarization is 10^{-10} s in liquid propyl alcohol while it is 3 ×10^{-6} in solid ice. Orientation polarization occurs, when the frequency of he applied voltage is in the audio range.

Space charged polarization is the slowest process, as it involves the diffusion of ions over several interatomic distance. The relaxation time for this process is related to the frequency of successful jumps of ions under the influence of the applied field, a typical being 10^2 Hz. Corresponding, space charge polarization occurs at power frequency (50-60 Hz).

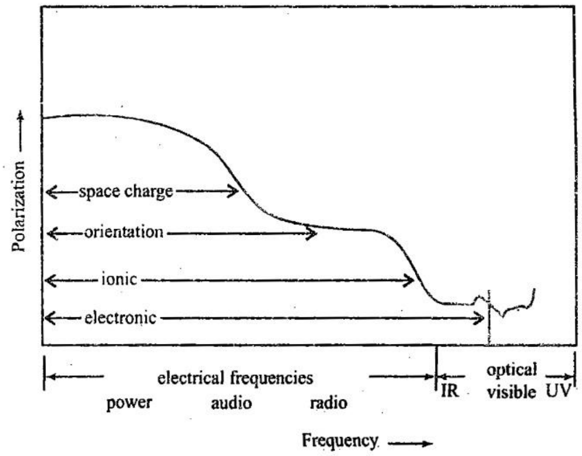


Fig illustrates all the four types of polarization at different frequency ranges.

i) At optical frequency (~ 10^{15} H z) electronic polarization alone is present.

ii) At ~ 10^{13} H z range ionic polarization occurs in addition to electronic polarization.

iii) At $10^{6 \text{ to }} 10^{13}$ H z range ionic contribution due to orientation polarization gets added.

iv) At 10^2 H z range space charge polarization also contributes

TEMPERATURE DEPENDENCE OF POLARIZATION:

The electronic and the ionic Polarizabilities are practically independent of temperature for normal temperature whereas orientation polarization and space charge polarization are affected by temperature.

In orientation polarization, the randomizing action of thermal energy decreases the tendency of the permanent dipoles to align themselves in the applied field. This results in a decrease in the dielectric constant with increasing temperature

In space charge polarization the increase of temperature facilitates the diffusion of ions. Thermal energy may also aid in overcoming the activation barrier for the orientation of polar molecules in the direction of the field. In such a case relative dielectric constant may increase with increase of temperature.

1.4. INTERNAL FIELD (OR) LOCAL FIELD AND DEDUCTION OF CLAUSIUS – MOSOTTI RELATION

When a dielectric material is kept in an external field it exerts a dipole moment in it. Therefore two field are exerted viz,

(i) Due to external field

(ii) Due to dipole moment.

*This long range of coulomb forces which is created due to the dipoles are called as internal field or local field. This field is responsible for polarizing the individual atoms or molecule*s.

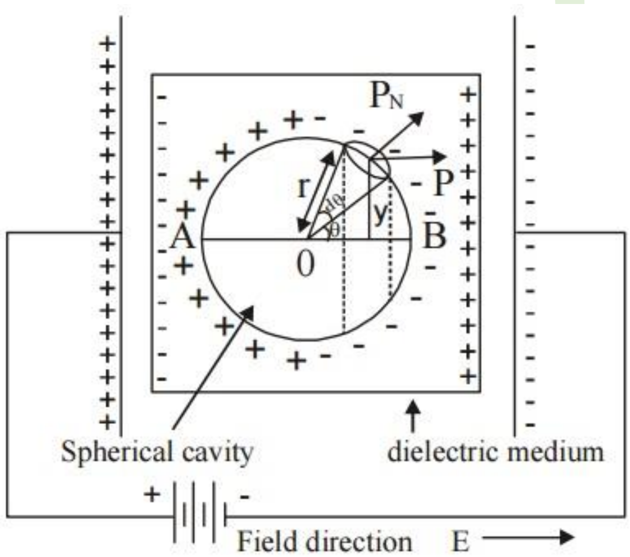
Lorentz Method for Finding Internal Field

Let us assume a dielectric material kept in an external field. Consider an imaginary sphere in the solid dielectric of radius 'r'.

Here the radius of the sphere is greater than the radius of the atoms. i.e., there are many atoms dipoles within the sphere. A small elements ring is cut with thickness ds. Let y be the radius of the small ring as shown in fig.

The electric field at the center of the sphere is called internal field, which arise due following four factors.

$$E_{int}=E_1+E_2+E_3+E_4 \quad \text{...........(1)}$$



Where ,

E_1 → Field due to the charge on the plates. (Externally applied)

E_2 → Field due to polarization charges on the plane surface of the dielectric.

E_3 → Field due to polarized charged include at the spherical surface.

E_4 → Field due to atomic dipoles inside the sphere considered.

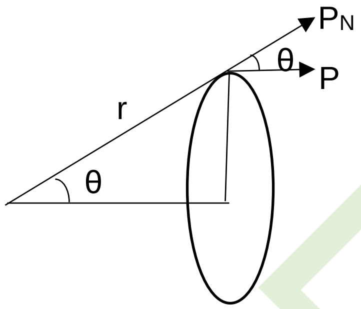
Macroscopically, we can take E= E_1+E_2. (i.e.) the field externally applied (E_1) and the field include on the plane surface of the dielectric (E_2) as a single field (E).

If the dielectric is highly symmetric then the dipoles will cancel with each other therefore we can take E_4 =0

Therefore, Equation (1) becomes, $E_{int} = E + E_3$ ………….(2)

To find E_3

In the elements ring, let ‘q’ be the charge on the area ds. Polarization is defined as the surface charge per unit area. If P is the components of polarization perpendicular to the area as shown in fig



Here $P_N = P \cos\theta = \frac{Q'}{ds}$

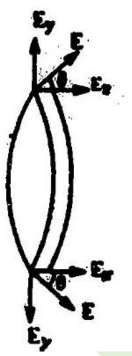
(Or) Charge on ds is $q' = P \cos\theta \, ds$ ……………. (3)

Electric field intensity at ‘C’ due to charge q’ (Coulomb’s law) is given by

$E = \frac{q'}{4\pi\varepsilon_0 r^2}$ Substituting for q' from equation (3) , we have

$E = \frac{P\cos\theta}{4\pi\varepsilon_0 r^2} ds$

The above intensity is along the radius ‘r’. resolving the intensity into two components as shown in below figure.



Component parallel to the field direction $E_x = E\cos\theta$

$$\therefore E_x = \frac{P\cos^2\theta \, ds}{4\pi\varepsilon_0 r^2}$$

Component perpendicular to the field direction

$E_y = E\sin\theta$

$$\therefore E_y = \frac{P\cos\theta\sin\theta \, ds}{4\pi\varepsilon_0 r^2}$$

The perpendicular components are in opposite direction and hence cancel each other. So the parallel components are along taken into consideration.

If the total surface area of the ring is consider as dA then

$E_x = \frac{P\cos^2\theta dA}{4\pi\varepsilon_0 r^2}$ ....(4)

Where,

dA=circumference × thickness

dA=2πy × dS

Since y = r sin θ and dS = r d θ, we can write

dA = 2πr sin θ × rd θ

(or) dA = 2πr^2 sin θ d θ ....(5)

Substituting equation (5) in equation (4), we get

Electric field intensity due to the elements ring =$\frac{p\cos^2\theta\sin\theta d\theta}{2\varepsilon_0}$ ...... (6)

Electric field intensity due to the whole sphere can be derived by integration equation (6) with the limits 0 to Л

$E_3 = \int_0^\pi \frac{p\cos^2\theta\sin\theta d\theta}{2\varepsilon_0}$ .... (7)

(or) $E_3 = \frac{2}{3}\left[\frac{P}{2\varepsilon_0}\right]$ $\left[\because \int_0^\pi \frac{\cos^2\theta\sin\theta d\theta}{2\varepsilon_0} = \frac{2}{3}\right]$

(or) $E_3 = \left[\frac{P}{3\varepsilon_0}\right]$ .... (8)

Substituting equation (8) in equation (2), we can write

$\therefore E\frac{P}{3\varepsilon_0}_{int}$ ....(9)

Where E_{int} is called internal field or Lorentz field

CLAUSIUS - MOSOTTI RELATION

We know $\vec{D}$= ε E = ε_0 E + p (or) E (ε - ε_0) = P .... (10)

Substituting equation (9) in equation (8), we get

$$\therefore E\frac{P}{\varepsilon - \varepsilon_0}\frac{P}{3\varepsilon_0}_{int}$$

(or) $\therefore E\frac{P[3\varepsilon_0 + (\varepsilon - \varepsilon_0)]}{3\varepsilon_0(\varepsilon - \varepsilon_0)}_{int}$

(or) $\therefore E\frac{P(2\varepsilon_0 + \varepsilon)}{3\varepsilon_0(\varepsilon - \varepsilon_0)}_{int}$ .... (11)

We know polarization P = Nα E_i

$\therefore E \frac{P}{N\alpha_{int}}$ ………………… (12)

Comparing equation (10) and equation (11) we get,

$$\frac{P}{N\alpha} = \frac{P(2\varepsilon_0+\varepsilon)}{3\varepsilon_0(\varepsilon-\varepsilon_0)}$$

(or) $\frac{N\alpha}{3\varepsilon_0} = \frac{(\varepsilon-\varepsilon_0)}{(2\varepsilon_0+\varepsilon)}$

(or) $\frac{N\alpha}{3\varepsilon_0} = \frac{\varepsilon_0\left(\frac{\varepsilon}{\varepsilon_0}-1\right)}{\varepsilon_0\left(\frac{\varepsilon}{\varepsilon_0}+2\right)}$

(or) $\frac{N\alpha}{3\varepsilon_0} = \frac{(\varepsilon_r-1)}{(\varepsilon_r+2)}$

The above equation is called Clausius – Mossitti Relation.

Measurement of dipole moment

The dipole moment of the molecule can be found using the clausius – Mossitti relation by multiplying equation (12) by the molar volume (M_A/ρ)

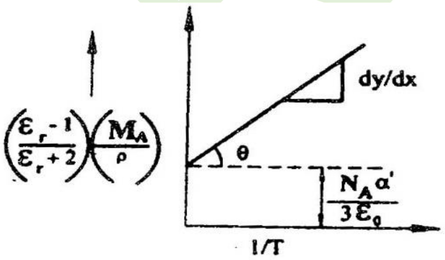
Molar polarization P_m= $\left(\frac{N\alpha}{3\varepsilon_0}\right) \times \left(\frac{M_A}{\rho}\right) = \left(\frac{\varepsilon_r-1}{\varepsilon_r+2}\right) \times \left(\frac{M_A}{\rho}\right)$ …………………(13)

we know Avogadro's number $\frac{nM_A}{N_A} = \rho$

Equation (13) can be written as

$$\boldsymbol{P_m = \frac{N_A\alpha}{3\varepsilon_0} = \left(\frac{\varepsilon_r-1}{\varepsilon_r+2}\right) \times \left(\frac{M_A}{\rho}\right)}$$ ……………….(14)

We know $\alpha = \alpha' + \frac{\mu^2}{3K_BT}$ and $\alpha_e + \alpha_i = \alpha'$



Therefore slope $\frac{dy}{dx} = \frac{N_A\mu^2}{3\varepsilon_0}$

$$\mu^2 = \left(\frac{dy}{dx}\right)\left(\frac{3\varepsilon_0}{N_A}\right)$$

(or)

$$\mu = \sqrt{\left(\frac{dy}{dx}\right)\left(\frac{3\varepsilon_0}{N_A}\right)}$$

Thus the dipole moment of the molecule can be measured by finding the slope. In any case if the dipole moment is zero, i.e., if =0, the graph will become a straight line parallel to x axis, which implies that the polarization is independent of temperature.

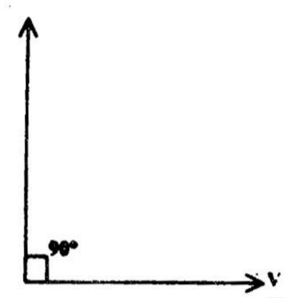
1.5. DIELECTRIC LOSS

If a dielectric is subjected to an electric field, the electrical energy is absorbed by the dielectric and certain quantity of electrical energy is dissipated in the form of heat energy. This is known as dielectric loss.

The dielectric loss can occur both in direct and alternating voltages. The dielectric loss is less in direct voltage than that of alternating voltages.

Loss in purified Gas

If an alternating voltage is applied across the capacitor having vacuum (or) purified gas then the resulting current leads the applied voltage by 90^0 ,as shown in fig . if 'I' leads 'V' exactly by 90^0 , we can say that no electrical energy is lost.



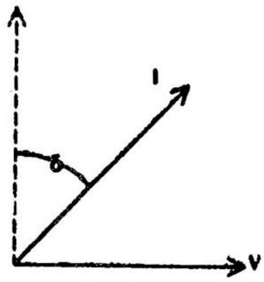
Explanation

We know power loss P_L=VI cos θ

When θ=90^0 : P_L=0

Loss in commercial dielectric

Now, when a practical dielectric is present the current leads the voltage by (90-∂),then it shows that there is some loss on electric energy and ∂ is called loss angle,as shown in fig



Explanation

In this case the power loss P_L =VI cos θ

Since θ =90 ^{0}- , we have P_L=VI cos (90^0-δ)

P_L=VI sin θ ……………………………(1)

We know V=IR

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

If the capacitive reactance is Xc then we can write,

$$I = \frac{V}{X_C} \quad \text{…………………………(2)}$$

Substituting equation (2) in equation (1),we get,

Power loss $P_L=V^2$ sin Xc

We know frequency $f = \frac{1}{2\pi RC}$

$$f = \frac{1}{2\pi X_c C}$$

$$X_c = \frac{1}{2\pi f C}$$

Substituting equation (4) in equation (3),we get P_L=2лfC V^2 sin δ

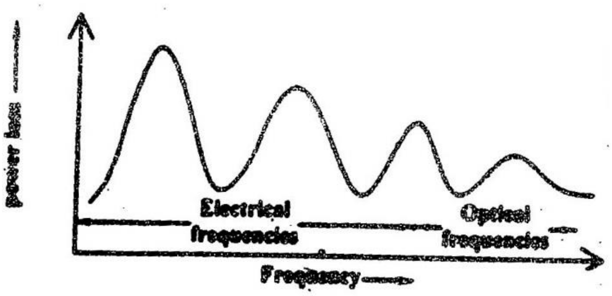
If is very small, then sin δ = tan δ

Power loss P_L=2л fC V^2 tan δ

Here tan is called the power factor of the dielectric. If f,C,V are constants, then

$P_{L\infty}$ tan δ

Naturally the power loss varies with frequency. The power loss at various frequency ranges is shown in fig



In the electrical frequency regions the power loss is high, due to the diffusion of ions from one equilibrium position to another.

In the optical region the power loss is less because here the dielectric loss is associated with the electrons.

1.6. GAUSS LAW AND ITS BOUNDARY CONDITIONS

Gauss law is the basic law of electrostatic interaction

Statement

The total Electric flux (Φ) or the Total Normal Electric Induction (TNEI) of the electric field $\vec{E}$ over any closed surface is equal to $\frac{1}{\varepsilon_0}$ times the total charge enclosed by the surface.

$$\therefore \boldsymbol{\phi} = \oint_S \vec{\boldsymbol{E}}.\boldsymbol{d}\vec{\boldsymbol{s}} = \frac{\sum \boldsymbol{q}}{\boldsymbol{\varepsilon_0}}$$

Explanation

This law relates the flux through any closed surface and net charge enclosed within the surface. Hence Σq is the net charge inside the closed surface. This closed surface is called "Gaussian surface". From this law it is seen that flux of $\vec{E}$ through a closed surface *S* depends only on the value of the net charge inside the surface and not on the location of the charges.

Case (i): When the electric charge is situated inside the closed surface

Let a point charge +q is placed at a point 'O' inside a closed surface 'S' as shown in figure. Let *dS* be a small area element at a distance *r* from *q*. The component of the electric field $\vec{E}$ normal to this surface is E cos θ. The electric flux (dΦ) over the surface is given by

$d\Phi = \vec{E}.d\vec{s}$ (1)

(or) $d\Phi = E \cos\theta \, dS$ (2)

Where 'θ' is the angle between $\vec{E}$ and $d\vec{s}$.

The electric field due to charge *q* at point P on the surface placed at a distance *r* is given by

$\boldsymbol{E} = \frac{\boldsymbol{1}}{\boldsymbol{4\pi\varepsilon_0}}\frac{\boldsymbol{q}}{\boldsymbol{r^2}}$ (3)

Substituting equation (3) in equation (2) we get

$\therefore d\phi = \frac{q}{4\pi\varepsilon_0}\left(\frac{dS\cos\theta}{r^2}\right)$ (4)

Here $\left(\frac{dS\cos\theta}{r^2}\right) = d\omega$ is the solid angle subtended by the area dS at O.

$\therefore d\phi = \frac{q}{4\pi\varepsilon_0}d\omega$ (5)

Hence the total flux through the entire closed surface is given by

$$\phi = \oint_S d\phi = \frac{q}{4\pi\varepsilon_0}\oint_S d\omega$$

$\therefore \phi = \frac{q}{\varepsilon_0}$ (6)

This law holds even if there are several charges $+q_1$, $+q_2$, $+q_3+$...... inside the surface as shown in Figure

$$\therefore \text{Total flux } \phi = \frac{1}{\varepsilon_0}q_1 + \frac{1}{\varepsilon_0}q_2 + \frac{1}{\varepsilon_0}q_3$$

$$\text{(or) } \phi = \frac{1}{\varepsilon_0}(q_1 + q_2 + q_3 + ..)$$

$$\therefore \phi = \frac{1}{\varepsilon_0}\sum q$$

$$\therefore \phi = \oint_S \vec{E}.d\vec{s} = \frac{\sum q}{\varepsilon_0} \quad (7)$$

Case (ii) For the charge outside the sphere

Let the charge *+q* be situated outside the closed surface at point *O*. Let a small solid angle *dω* from an elementary core cut the closed surface at two elements of area dS_1 and dS_2 at A and B. Magnitude of the flux through dS_1 and dS_2 are equal.

Flux through dS_1 is inward and flux through dS_2 is an outward flux. Therefore total flux through dS_1 and dS_2 shall be written as

$$\text{Total flux} = -\frac{q}{4\pi\varepsilon_0}d\omega + \frac{q}{4\pi\varepsilon_0}d\omega = 0 \quad (8)$$

The entire closed surface can be considered to be made of pairs of elements like dS_1 and dS_2. Thus from equation (8) we can see that the total flux due to charge outside is zero.

Uses:

It is used to find the electric field. If, the charge distribution is so symmetric, by constructing a closed surface, the electric field can be find out

Gauss law is one of the fundamental equations of electromagnetic theory. I.e., it is one of the Maxwell's equations

One can derive Coulomb's law from Gauss law. So Gauss law is more fundamental than coulomb's law.

1.7. DIELECTRIC BREAKDOWN

The main purpose of dielectric is to store electrical energy and act as insulator. When the dielectric is subjected to a heavy voltage, beyond certain value, it loses its insulation property because electrons start jumping from valence band to the conduction bend. *Hence, a dielectric material loses its resistivity and permits very large current to flow through it. This is known as dielectric break down or failure.*

The magnitude of dielectric field strength at which dielectric breakdown occurs is called dielectric strength. It is the breakdown voltage per unit thickness of the material.

1.8. Types of Dielectric Breakdown

There are various types of dielectric breakdowns as mentioned below;

1. Intrinsic or Zener breakdown
2. Thermal breakdown
3. Discharge breakdown
4. Chemical and electrochemical breakdown ,
5. Defect breakdown.

1. Intrinsic breakdown

In a dielectric, the charge displacement increases with increasing field strength. Beyond a critical value of the field strength, there is an electric breakdown due to the physical determination of the dielectric material. When the applied electric field is large, some of the electrons in the valence band cross over the conduction band gap giving rise to large conduction currents. Under this condition, the strength of the local field is of the order of I mega volt cm^{-1}. *Thus, the liberation or movement of electrons from valence band is called internal field emission of electrons and this breakdown is called the intrinsic breakdown or Zener breakdown.*

The electrons moving under the high accelerating electric force collide with the atoms or molecules. They release more electrons and holes by breaking covalent bonds between them. Thus, the current density increases. The covalent bonds between atoms or molecules are broken continuously and finally dielectric breakdown occurs. These types of breakdowns is called Avalanche breakdown. Impurities in the dielectric material create additional energy levels in the energy gap and so they help the intrinsic breakdown to occur at lower applied voltage.

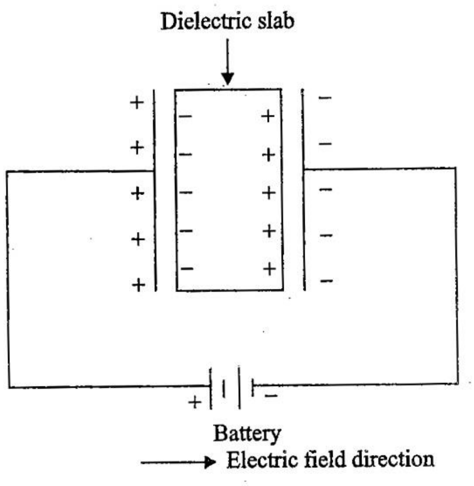


Fig. 5.11. Intrinsic Breakdown

Characteristics

1.This can occur even at lower temperatures.

2.This requires relatively large electric fields.

3.Generally, this kind of breakdown occurs in thin samples.

4.This does not depend on the electrodes configuration and shape of the

material.

2. Thermal breakdown

This is due to the attainment of excessive temperature in dielectric. The electrical energy loss has to be dissipated as heat and if the heat dissipated is less then the heat generated there is a progressive increase in the temperature of the dielectric which eventually results in local melting. During that time enormous current will flow through the material and immediately dielectric breakdown will occur.

Characteristics

1. This can occur only at high temperatures.
2. The strength of the electric field to create dielectric breakdown depends upon the materials size and shape.
3. The breakdown time is of the order of few milliseconds.
4. Since the dielectric loss is directly proportional to frequency, the electric field strength to create this dielectric breakdown will be smaller for alternating fields and higher for d.c. fields.

3. Discharge breakdown

This discharge breakdown occurs when the insulator contains occluded gas bubbles as shown in fig. *since gases require small ionization potential than solids, the gaseous atoms ionize first and the gaseous ions bombard in the solid dielectric causing electrical deterioration. This type of breakdown is called discharge breakdown.*

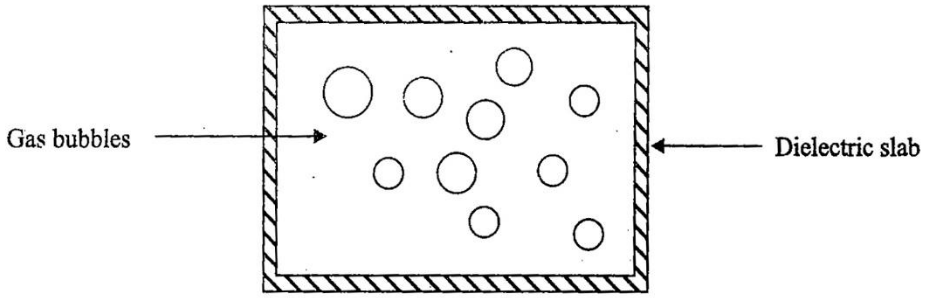


Fig. 5.12. Discharge Breakdown

Characteristics

1. This can occur at low voltages where, there, are large numbers of occluded gas bubble in the insulating material.
2. When discharge takes place at a point, the surrounding places are burnt and hence, their electrical properties are affected. Thes, the life of the insulating material depends upon the

number of discharges which are taking place inside the material. Thus, it depends upon the applied voltage.

4. **Chemical and electrochemical breakdown**

Chemical and electrochemical breakdown is very much related to thermal breakdown. Temperature rise in an insulating material accelerates the chemical deterioration. When temperature rises, mobility of ions increases and hence electrochemical reaction taken place. when ionic mobility increases leakage current also increases and this leads to dielectric breakdown. Field induced chemical reaction gradually decreases the insulation resistance and finally results in breakdown. Not only by the application of electric field but also by so many ways the chemical reaction can occur.

Characteristics

1. Electrochemical breakdown is determined by the leakage current, density of ions, temperature and permanent dipoles in the material.
2. To reduce electrochemical reactions, the foreign materials would not be mixed with pure insulating materials.
3. Electrochemical reactions are accelerated by high temperatures. So, to avoid break down insulating materials should not be operated at high temperatures.
4. If there are layers of materials with permanent dipoles on the insulating materials, then they may be large leakage current which leads to break down. Therefore, the materials having permanent dipole moment should not be used as high temperature insulating materials.

5. Defect breakdown

If the surface of the dielectric material has defects such as cracks and porosity, as shown in fig. Then, impurities such as dust or moisture collect at these discontinuities leading to breakdown. Also, if it has defect in the form of strain inside the material, that region will also break on application of electric field.

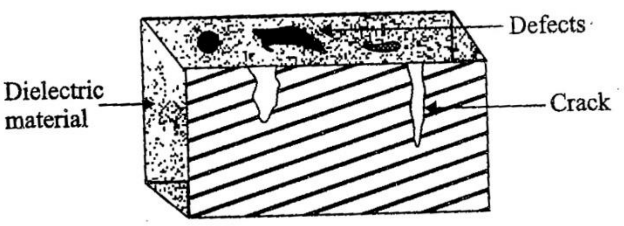


Fig. 5.13. Defects and Cracks in Dielectric Material

1.9. Remedies to Avoid Breakdown Mechanisms

In order to avoid the breakdown mechanisms in the dielectric materials, the following points should be satisfied:

1 It must have low dielectric loss and less density.

2 It should be fire proof and resistive to oils, liquids, and gases.

3 It must possess high resistivity and dielectric strength.

4 It should be in pure form i.e., defect free.

5 It must have small thermal expansion and sufficient dielectric strength.

1.10 Classification of insulating materials

There are three types of insulating materials namely (i) Solid insulating materials (ii) liquid insulating materials and (iii) gaseous insulating materials.

1.10.1 Solid insulating materials

(a) Mica

It is made of silicate aluminum with silicates of soda potash and magnesia.

Properties

(i) It is crystalline in nature
(ii) It can be split into thin sheets easily
(iii) It is rigid and strong
(iv) It has high dielectric strength and low power loss
(v) Its dielectric constant varies from 5 to 7
(vi) Its dielectric strength varies from 500 to 1000 kV/mm.

Uses

1. It is sued as insulator in commutator segment
2. It is used as a separator in electrical machines, switch gears, heating devices, iron boxes, hot plates as insulator
3. It is used in the form of tapes in high voltage alternators

(b) Asbestos

It is a naturally occuring mineral material of fibrous structure made of magnesium silicate

Properties

(i) It has high dielectric loss
(ii) It possess low dielectric strength
(iii) Can withstand high temperature

Uses

1. It is used in electrical machines to withstand high temperature
2. It is used in the form of paper, tape, cloth and board for insulation
3. It is used to manufacture panel boards, insulating tubes, cylinders, etc.,
4. It is used in ovens, iron boxes, etc.,

5. It is applied in switching devices and in circuit breakers

(c) Poly Vinyl Chloride (PVC)

It is produced by treating acetylene and hydrogen chloride in the presence of a catalyst at a temperature of about 50º C.

Properties

(i) It has good mechanical and electrical properties
(ii) It is non-corrosive

Uses

(i) It is used in the manufacturing of PVC films, tapes and pipes.
(ii) It is used as insulation for batteries, conductors and cables.

(d) Rubber

it is made of organic polymers may be natural or synthetic. The synthetic rubber is made by co-polymerization of iso-butane and iso-propane.

Properties

(i) It has good electrical and thermal properties
(ii) Its dielectric constant varies between 2.5 and 5.
(iii) Synthetic rubber is applicable for high temperature ranges.
(iv) It possess high tensile strength

Uses

1. It is used as insulating materials for electric wires, tapes, coating, transformers, etc.,
2. It is used in the construction of storage battery housings.

(e) Ceramic materials (Potter's earth (clay))

These materials are produced by mixing finely ground clay and metal oxide with water to make it as a paste and is shaped to our requirements. It is dried and then heated to a very high temperature (1200ºC to 1700ºC).

In general, they are non-metallic organic compounds such as silicates, aluminates, oxides, carbides, nitrates and hydrates.

Properties

(i) They are hard, dense and brittle
(ii) They are available both in crystalline and amorphous forms
(iii) The dielectric constant varies from 4 to 10.
(iv) They have excellent dielectric and mechanical properties
(v) They can withstand very high temperature and very high voltage

Uses

1. They are used in plug holders and cathode heaters
2. They are used vacuum type ceramic metal seals
3. They are used for the manufacture of switches, plugs, fuse holds, sockets etc.,
4. They also has applications in electric stoves, kettles, etc.,

(f) Glass

Glass is an inorganic material made by the fusion of different oxides. Examples: silicon oxide, zinc oxide, zinc oxide and magnesium oxide.

Properties

(1) It is brittle and hard
(2) It has low dielectric loss and has good mechanical strength
(3) They are highly chemical resistant to most corrosive agents
(4) It act as a good insulator with good appearance
(5) It is insoluble in water

Uses

1. They are applied in manufacture of capacitors
2. It is used in radio and television tubes, electrical lamps and laminated boards
3. Toughened glass is used for insulation in extra high voltage lines i.e., above 100 Kilovolts.

1.10.2. Liquid Insulating Materials

Liquid insulating materials can be divided into three groups.

(i) Mineral insulating oils: Transformer oil, cable oil, capacitor oil, etc.,
(ii) Synthetic insulating oils: Askarels, arclors, sovol and sovtol.
(iii) Miscellaneous insulating oils: Vegetable oils, Vaseline and silicon liquids.

Generally liquid dielectric materials have moderate dielectric strengths. But insulating liquids improve the insulating properties of other solid materials (especially fibrous materials) by eliminating the other gases. They offer good heat dissipation media and facilitate cooling's of the windings which emit heat due to losses in the windings. They are sometimes required for extinguishing arcs in certain applications like circuit breakers.

(i) Mineral insulating oils

This oil is obtained from crude petroleum by distillation. This oil is used to transfer heat by convection from windings and core to the cooling surfaces. It is used to maintain the insulator of the windings. Now a days synthetic oil is used as an insulator in transformers in the place of transformer oil (mineral oil) because synthetic oil are very much resistant to oxidation to oxidation and to fire hazards.

Properties

(i) It possesses high oxidation resistance and good thermal stability
(ii) It has high dielectric strength and high viscosity

Uses:

They are used in transformers and capacitors

(iii) Synthetic Insulating Oils

When we compare this with mineral insulating oil, the properties are degraded. Askarels have thermal stability up to 110ºC and are manufactured from chlorinated hydro-carbons.

Properties

- **(i)** These oils are very cheap and non-inflammable
- **(ii)** They have longer life and safer in operating conditions.

Uses

They are used as coolant and insulant in high voltage transformers.

(iii) Miscellaneous Insulating Oils

Silicon liquids are costly and they have stability up to 200ºC. Vaseline has high viscosity and high dielectric constant. It is used for impregnation of papers used in capacitors.

Properties

- **(i)** The dielectric strength of these liquids is same as that of mineral oils
- **(ii)** The power factor is very low

Uses

1. They are used in High Voltage (H.V.) transformers
2. They are used to increase the surface resistivity of ceramic insulators.

1.10.3. Gaseous Insulating materials

(i) Vacuum

Vacuum means free space without air. So creating a vacuum place is a type of insulation.

Uses

it is used in (i) X-ray tubes (ii) Electronic valves (iii) Particle accelerators (iv) Microwave tubes (v) Low-loss capacitors, etc.,

(ii) Air

Air is a naturally occuring dielectric. The atmospheric gas consists of a number of gases say N_2, O_2, He, CO_2, Ne, etc.,

Properties

- (i) The dielectric ions of air is almost zero (tan σ = 0)
- (ii) The dielectric strength of air ranges from 3 to 5 kV/mm

Uses

- (i) They act as insulators in switches, plugs and various electrical machines
- (ii) They are used in low voltage applications
- (iii) They are also used in over head transmission lines

(iii) Nitrogen

Nitrogen is the important gaseous dielectric used after air.

Properties

- **(i)** It is chemically inert gas
- **(ii)** It prevent oxidation
- **(iii)** It reduces damage to the apparatus used

Uses

- (i) They are used in high voltage gas filled pressure cables
- (ii) They also has applications in capacitors

(iv) Sulphur Hexafluoride

When Sulphur is burnt in the atmosphere of fluorine, Sulphur hexafluoride is produced.

Properties

- (i) It is highly stable
- (ii) It has high dielectric strength

Uses

- (i) It is used as a constant in X-ray tubes
- (ii) It is used in transformers, electrical switches, etc.,

1.11. Capacitor or condenser

A *capacitor* or a condenser is a device which essentially consists of two conducting surfaces separated by an insulating material (called dielectric) say oil or mica. The capacitance of a capacitor increases with the presence of dielectric.

Capacitance (or) Capacity (c)

The capacitors have a property known as capacitance (or) capacity. The property of a capacitor to store electrical energy is called as capacitance. *Hence the capacitance of a capacitor is defined as the amount of charge required to create a unit potential difference between the plates.*

If the charge of q coulomb is given to one of the two plates of a capacitor and if a potential of V volts is established between the two, then its capacitance is $C = \frac{q}{V}$ coulomb / volt

The unit of capacitance is coulomb/volt and is also called farad. i.e., 1 farad = 1 coulomb /volt

Thus the unit farad is defined as the capacitance of a capacitor which needs a charge of one coulomb to establish a potential difference of 1 volt between the plates.

Definition

A capacitor has a capacity of one farad if one coulomb of charge is transferred from one conductor to the other, when the difference of potential between the two conductor is one volt.

Since the unit of capacitance farad is too large, for practical purposes much smaller units like microfarad (or) picofarad is used.

1 μf = 10^{-6} farads; 1 pf = 10^{-12} farads

1.12. Principle of a capacitor

Principle

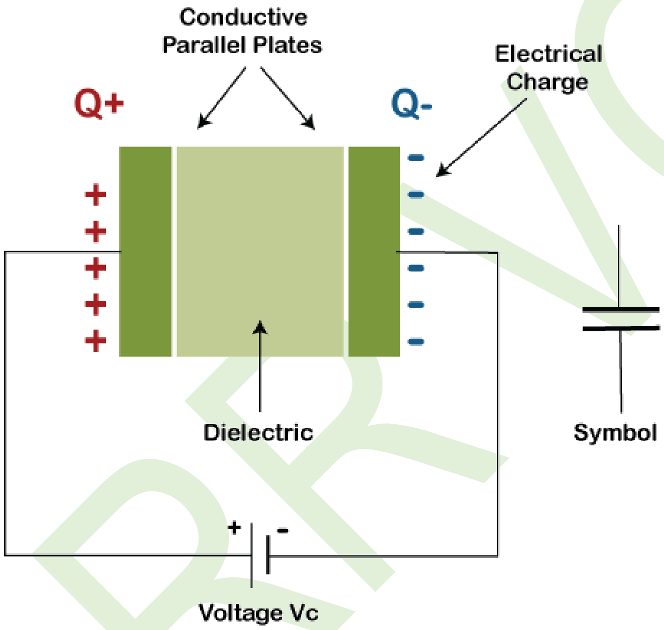
A capacitor consists of two conductors, one charged and the other usually earth connected. The conducting surfaces may be in the form of either circular, rectangular or spherical. The purpose of a capacitor is to store electrical energy by an electrostatic stress in the dielectric. A parallel plate capacitor is shown in figure.

Let *A* be the charged conductor and *B* the earth connected conductor. In the absence of B, let the charge on *A* be +*q* and the potential *V*. Therefore the capacity of the conductor A = q/V.. If B is kept near A, the electrostatic induction takes place, the free +ve charge flows to the earth and *B* will have the bound -ve charge. Consequently, the potential of A decreases and its capacity increases.

This is because with the presence of *B*, the amount of workdone in bringing a unit +ve charge from infinity to *A* decreases there be force of repulsion due to *A* and force attraction due to *B*.

So the resultant force of repulsion on a unit +ve charge is reduced and the constant of workdone is reduced. Hence the potential of *A* decreases and therefore the capacity of *A is increased.*

In actual practice, a dielectric will be present in between the two conductors (plates) to form capacitors (or) condensors.



1.13. Typical capacitor construction and types

Capacitor can be classified into three categories

(a) Capacitors with solid dielectric
(b) Capacitors with air as the dielectric
(c) Electrolytic capacitors

Examples for capacitors with solid dielectric

The Leyden Jar, Mica capacitor, Paper capacitor

Examples for capacitors with air dielectric

Variable air capacitor

The commonly used capacitors are as follows

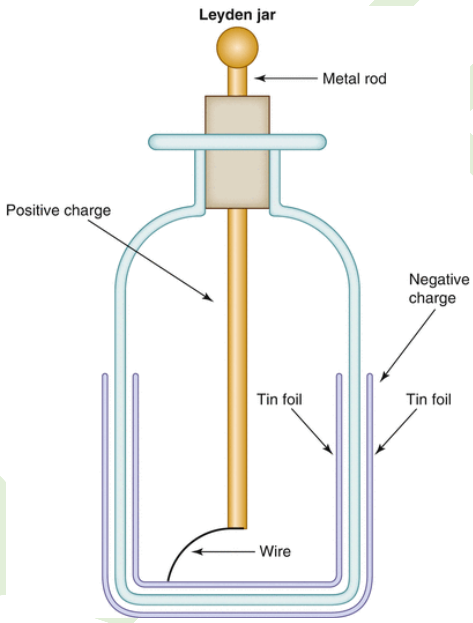
Mica capacitors, ceramic capacitors, paper capacitors and Electrolyte capacitors.

Some of the various types of capacitors are explained below:

(a) The Leyden Jar: (with solid dielectric)

This is a form of parallel plate capacitor. It consists of a glass jar (or) bottle which is coated with tin foil up to about two thirds of its height on the outer and inner surfaces of the glass jar. If the jar is held on hand the outer coating is earth connected.

The inner coating is charged with +ve (or) -ve electricity. The contact with the inner coating is obtained with the help of a brass rod ending in a chain on one side and a knob on the other side as shown in figure.



Here the inner and the outer coatings serve as the two plates of a capacitor and the glass in between serves as the dielectric. This is similar to a parallel plate capacitor and the capacity of the Layden jar is $C = \frac{\varepsilon_0 \varepsilon_r A}{d}$ where ε_r is the specific inductive capacity of glass, *A* is the overlapping area of tine foils between the inner and the outer coating and *d* is the thickness of glass. Although its capacity is small, it is able to withstand high potential differences. It is a type of fixed capacitor.

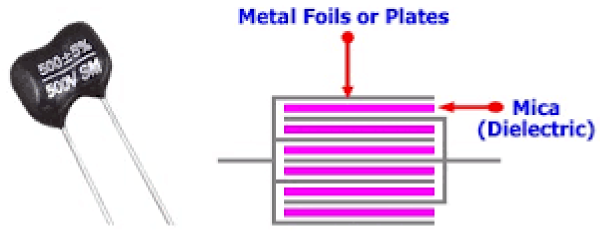
(b) Mica capacitor (with solid dielectric)

These are multiple type consisting of a series of plates. Alternative plates being connected together and separated by thin mica sheets. *The assembly is housed in a metal or ebonite case having two wire ends to which the two sets of plates are connected.*

Silver-mica capacitors have silver films deposited on thin mica dielectric sheets. Mica capacitors have very low power factors on a.c. and are suitable for use at radio frequencies.

The total capacity of such a capacitor is given by $C = \frac{N\varepsilon_0\varepsilon_r A}{d}$ where *N* is the number of capacitors grouped in parallel, ε_r is the specific inductive capacity of mica, *A* is the area of each coating of tin foil and *d* is the thickness of each mica sheet.

These type of capacitors are used in high voltage circuits where the insulation is important.



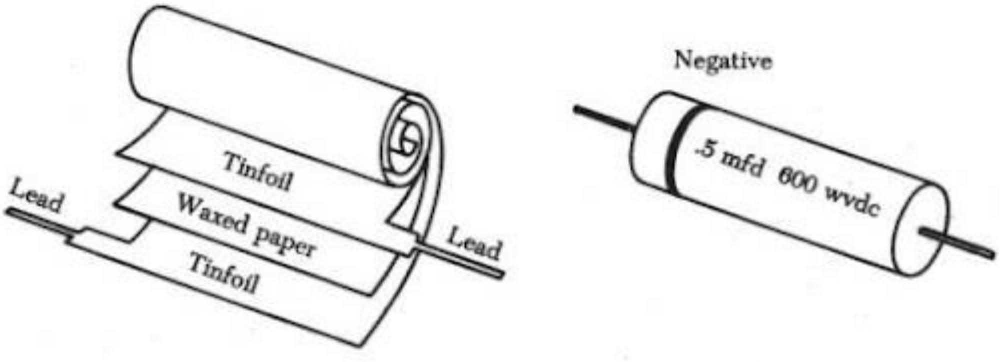
Mica capacitor

(c) Ceramic capacitor

In this type the discs of ceramic material are coated with metallic silver on opposite faces. The ceramic disc acts as the dielectric and silver coating are plates. These have very low power factor which decreases with increase in frequency and suitable for shortwave radio circuits. The ceramic and mica capacitors are more costly.

(d) Paper capacitors

In this a thin long strip of paraffin waxed paper is kept in between the coatings of tin (or) aluminium foil and rolled into a cylinder
The strips are tightly rolled and the whole capacitors is dipped in paraffin (or) oil. This is just a parallel plate capacitor where the plates viz, the tin or aluminium foils with the dielectric in between are rolled up so as to occupy a very small space as shown in figure. With paraffin waxed paper the thickness of the dielectric is very small and hence the capacity of the capacitor is very high. These capacitors are very cheap. The dielectric constant of paper is about 3.5. These are suitable in audio frequency circuits as by-pass or coupling capacitors.



(e) Variable air capacitor

This type of capacitor is commonly used in wireless sets and electronic circuits. It consists of two sets of Aluminium plates. One set of plates is fixed (A) and the other set of plates can be rotated (B), by a knob (K) attached to it.

The capacity of the capacitor can be uniformly varied by rotating the knob. The air between the plates acts as the dielectric and smaller the air gap the larger will be the capacity of the capacitor.

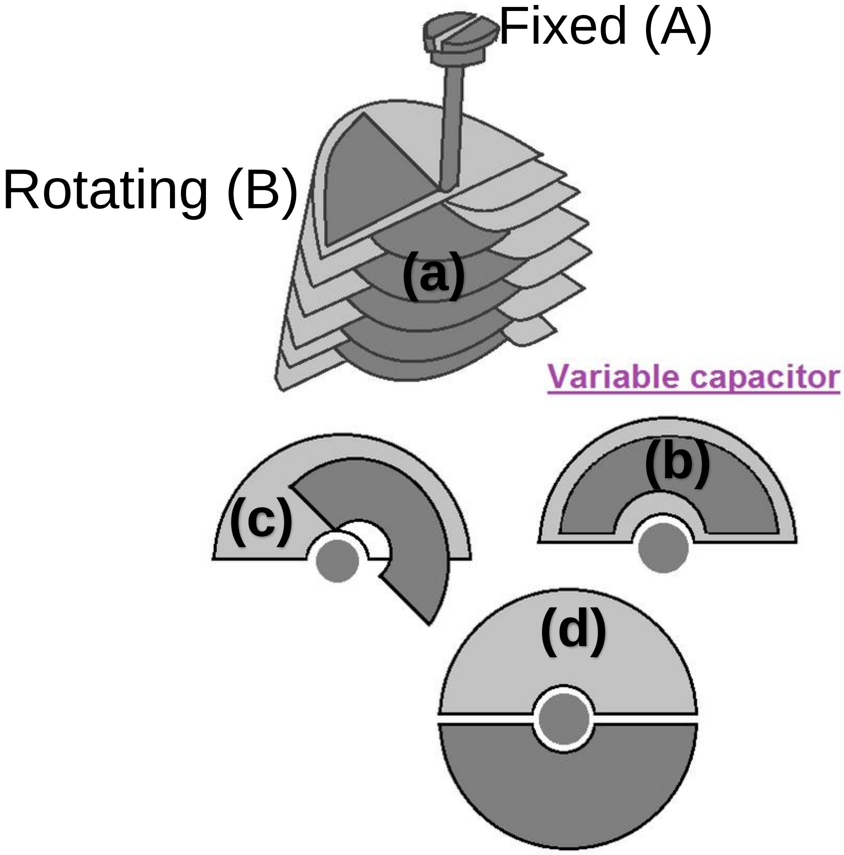


Figure b, c and d show the variation in the area of overlap between the plates A and B.

Figure b corresponds the maximum capacity where the sets of plates overlap with each other

Figure d corresponds to the minimum capacity where the rotating plates are completely rotated out of fixed plates

If the total number of plates is *n* then number of capacitors will be *n-1.* Hence the total capacitance of such a variable capacitor is $C = \frac{(n-1)\varepsilon_0 \varepsilon_r A}{d}$ farads.

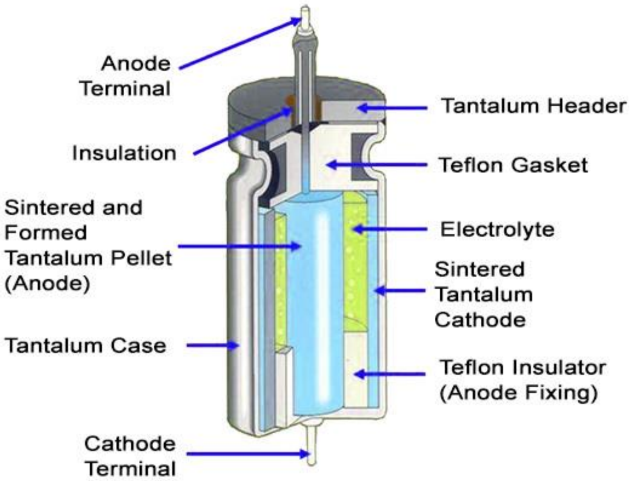
The symbols have their usual meanings.

(f) Electrolytic capacitor

These are of two types (i) Wet type (ii) Dry type.

(i) Wet type

A wet type electrolytic capacitor consists of two aluminium electrodes. A and C dipped in a solution of ammonium borate as shown in figure.



The plate A serve as anode and C serve as cathode. On passing a d.c. a very thin film of aluminium oxide is formed on the anode. This film is an insulator. The arrangement can now be used as a capacitor with anode as one plate, the solution as the other plate, and the aluminium oxide film as dielectric. Since the dielectric layer is very thin, the capacitance of this arrangement is very large. This capacitor can be used only in d.c. circuits and cant be used in a.c. circuits.

(ii) Dry type

In dry type, +ve and -ve electrodes of aluminium foil are separated by a porous paper or by a cotton gauze saturated with either a viscous liquid or paste containing the electrolyte. This is formed into a roll and housed in a cardboard box, which is usually waxed. These have very high capacitance and hence used in filter circuits in radio etc.,

(g) Guard ring capacitor

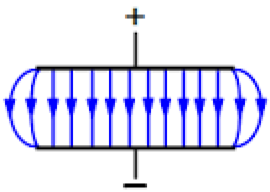


Figure 2

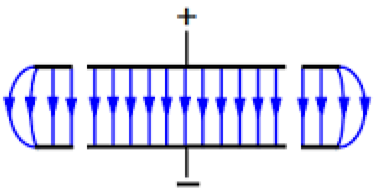


Figure 3

The guard ring capacitor is the modified form of parallel plate capacitor to reduce the 'edge effect' (or) fringing effect of the field near the edges of the parallel plate capacitor

In guard ring capacitor, the electric field is uniform even at edges of the parallel plates. In this capacitor a ring *G* is used around the plate A and it is in plane with it. The inner diameter of *G* is slightly longer than the diameter of A. The air gap between A and G is very small as shown in figure *b*. The diameter of the plate *B* is equal to the outer diameter of G. The field between A and B is uniform throughout the common are between them. The irregularity in the field occurs at the outer edge of the guard ring.

The effective area of the plate is given by A' = Area of the plate A+1/2

Area of the circular gap between A and G

$C = \frac{\varepsilon_0 \acute{A}}{d}$ farad.

This is used as an absolute standard of capacitance.

Note: Edge effect (or) fringing effect: In a parallel plate capacitor the electric field between the plates is not uniform near the edges. This is called the edge effect (or) fringing effect.

1.11 APPLICATIONS OF DIELECTRIC MATERIALS (CAPACITORS AND TRANSFORMERS)

The dielectric materials has three major applications

(a) It is used as a dielectric medium in capacitors.

(b) It is used as insulating materials in transformers.

(c) It is used in industries and dielectric heating.

(a) **Dielectrics in capacitors**

For dielectrics to be used in capacitors, it should possess the following properties.

Properties:

1. It must have dielectric constant.
2. It should possess high dielectric strength.
3. It should have high specific resistance.
4. It should also have low dielectric loss.

Uses:

1. Thin sheets of papers filled with synthetic oils are used as dielectrics in the capacitors.

2. Tissues papers and polypropylene films filled with dielectrics are used in power capacitors.

3. Mica is used as dielectrics in discrete capacitors.

4. An electrolytic solution of solution phosphate is used in wet type electrolytic capacitors.

5. An electrolytic paste made up of ammonium tetra borate and glycol is used in Dry type electrolytic capacitors.

6. Ceramic materials such as Barium titan ate and calcium titan ate are used in disc capacitors and high frequency capacitors respectively.

(b) Insulating materials in transformers

For dielectric to act as insulating materials, it should posses the following properties.

Properties:

1. It should have low dielectric constant.

2. It should possess low dielectric loss.

3. It must have high resistance.
4. It must possess high dielectric strength.
5. It should have adequate chemical stability.
6. It must have high moisture resistance etc.

Uses:

1. Ceramics and polymers are used as insulators.

2. Paper, rubber, plastics, waxes etc are used to form thin films, sheets, tapes, rods, etc.

3. PVC,(poly vinyl chloride) is used to manufacture pipes, batteries, cables etc.

4. Glass, mica, asbestos, alumina are used in ceramics.

5. Porcelain is used in high voltage power lines.

6. Liquid dielectrics such as petroleum oils, silicone oils are widely used in transformers, circuit breakers, etc.

7. Mineral insulating oils obtained from crude petroleum by distillation is used as transformers oils, because of high resistive to oxidation and fire hazards.

8. Synthetic oils such as askarels, sovol, etc are used as a coolant and insulant in high voltage transformers.

9. Gases such as vacuum air, nitrogen, sulphur hexa fluoride are used in X-ray tubes, sitches, high voltage gas filled pressure cables, coolants respectively.

(c) Dielectrics in industries and dielectric heating

(i) Industrial applications

1. Dielectrics possessing piezo-electric is used in gas lighters, microphones, phonographs, etc.

2. Dielectric possessing inverse piezo-electric effect is used in quartz watches, ultrasonic dryers, cleaning the semiconductor wafers, ultrasonic transducer etc.

(ii) Dielectric heating

Dielectric heating is the process of heating the insulating materials at a very high voltage under suitable frequency at which the dielectric loss becomes maximum, so that the dielectric loss will come out in the form of heat. Hence adequate heating was done at high voltages.

1. dielectric heating is the principle used in microwave ovens.
2. dielectric heating is also used in the dehydration of food , tobacco, etc

1.11 GENERAL APPLICATIONS

The following are the some of the applications of the dielectric materials:

1. Quartz crystal is used for the preparation of ultrasonic transducers, crystal oscillators, delay lines, filters etc.,
2. Barium titanate is used for the preparation of accelerometers.
3. Lead zirconate titanate ($PbZr_xTi_{1-x}O3$) is used for the preparation of earphones, microphones, spark generators (gas lighter, car ignition), displacement transducer, accelerometers etc.,

Uses

1. Porcelain is used in high voltage power lines.
2. Liquid dielectrics such as petroleum oils, silicone oils are widely used in transformers, circuit breaker etc.
3. Mineral insulating oil is used as transformer oil, because of high resistive to oxidation and fire hazards.

1.12 Piezoelectricity and Piezoelectric crystals

Piezoelectricity

When mechanical stress is applied on dipolar crystals, electricity is produced due to the displacement of dipoles. This phenomenon is called piezoelectricity and those crystals that exhibits this property are termed as piezoelectric crystals.

Piezoelectric crystals

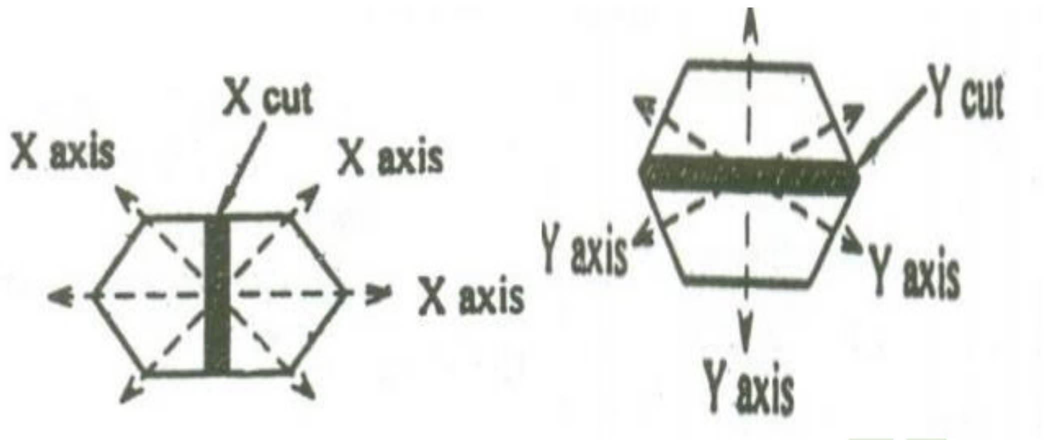
The crystal which produces piezo-electric effect and converse piezo-electric effect are termed as *piezo-electric crystals.*

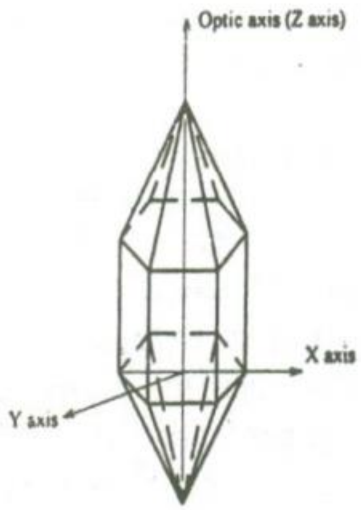
Examples

Quartz, Topaz, Tourmaline Barium titanate, Rochelle salts, Lead titanate, etc., are some of the examples for piezoelectric crystals.

Quartz crystal

A typical example for a piezoelectric crystal (Quartz) is as shown in Fig. It has an hexagonal shape with pyramids attached at both ends. It consists of 3 axes, viz., (i) optic axis (Z-axis), which joins the edges of the pyramid (ii) Electrical axis (X-axis), which joins the corners of the hexagon and (iii) mechanical axis (Y-axis), which joins the centre (or) sides of the hexagon as shown in figure.





X-cut and Y-cut crystals

X-cut crystal:

When the crystal is perpendicular to the X-axis as shown in figure. When it is called X-cut crystal. Generally X-cut crystals are used to produce longitudinal ultrasonic waves.

Y-cut crystal

When the crystal is cut perpendicular to the Y-axis as shown in figure then it is called Y-cut crystal.

Generally, Y-cut crystals produces transverse ultrasonic waves.

Piezoelectric effect

When pressure or mechanical force is applied along certain axis (mechanical axis) with respect to optic axis of the crystals like quartz, tourmaline, Rochelle salts etc., then equal and opposite charges are produced along the perpendicular axis (electrical axis) with respect to optic axis of the crystal as shown in figure. This effect is called piezoelectric effect.

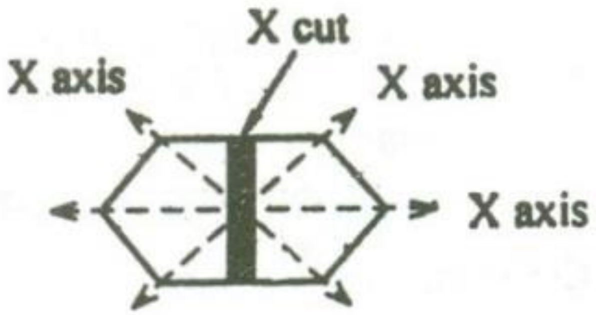


Figure 1.4.2

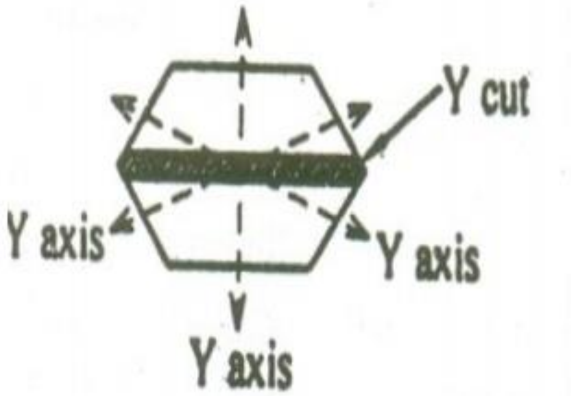


figure 1.4.3

Inverse piezoelectric effect

When potential difference (or) *e.m.f.* is applied along certain axis (electrical axis) with respect to optic axis of the piezoelectric crystals then the crystal starts vibrating along the perpendicular axis (Mechanical axis) with respect to the crystal as shown in figure. This effect is called as inverse piezoelectric effect.

Properties

(1) Piezoelectricity phenomenon exists due to crystal anisotropy (amorphous materials are not piezoelectric)
(2) Piezoelectricity and pyroelectricity have linear effect, whereas ferroelectricity has non-linear effects.
(3) Piezoelectric effect- when mechanical pressure is applied at the opposite ends, electric charges are produced at the other ends.
(4) Inverse piezoelectric-Electric field is applied at the opposite faces, then mechanical deformation is produced at the other opposite faces.

Applications

(i) Piezoelectric crystals are used in microphones, ultrasonic devices, sonar detector etc.,
(ii) Piezoelectric crystals acts as a transducer and is used to generate ultrasonic waves.

1.13. Pyroelectricity and Pyroelectric crystals

Pyro means heat, some piezoelectric crystals when heated, then it produces electricity to a small extent and this phenomenon is called pyroelectricity. The crystals that exhibits this phenomenon are called pyroelectric crystals.

Examples

Tourmaline, Gallium nitride, Cesium nitrate ($CsNO_3$), Lithium tantalite ($LiTaO_3$) are some of the examples of pyroelectric crystals.

Properties

(iii) Pyroelectric crystals will have unidirectional polarization
(iv) These crystals are non-centro symmetric in nature.

Applications

(i) The Pyroelectric crystals are used in IR detectors, elements.
(ii) These are also used in temperature sensors.

Question(s) and answer (s)

Part A – 2 marks

1. What is meant by polarization in dielectrics? (or) Define electric polarization.

The process of producing electric dipoles inside the dielectric when placed in external electric field (E) is called electric polarization.

i.e., The induced dipole moment (μ) = αE. Where α is electric polarizability.

2. Mention any two active and passive dielectrics with their applications (or) Compare active and passive dielectrics.

Sl.No	Active dielectrics	Passive dielectrics
1.	Dielectrics which can easily adapt itself to store the electrical energy in it is called active dielectrics	Dielectrics which restricts the flow of electrical energy in it are called passive dielectrics
2.	**Examples:** Piezo electric, Ferroelectrics, Pyroelectrics	**Examples:** glass, mica, plastic
3	It is sued in the production of ultrasonics	It is used in production of sheets, pipes, etc.,

3. Define electronic polarization

When a dielectric material is kept in external field (E), the positive and negative charges in the dielectrics moves in opposite direction, thereby creating a dipole moment. This process is known as electronic polarization.

The induced dipole moment $\mu = \alpha_0 E$. where α_e – permittivity of free space

4. Define local (or) internal field in dielectric

When a dielectric is kept in an external electric field (E), two fields are exerted due to (i) external field and (ii) dipole moment created. These long range of coulomb forces which are created due to the dipoles are called internal field (or) local field in dielectric.

It is given by $E_{int} = E + \frac{P}{3\varepsilon_0}$ where P – polarization; ε_0 – permittivity in free space

5. What is meant by dielectric loss and loss tangent? Why it occurs?

When a dielectric material is subjected to electric field, the electrical energy is absorbed by the dielectric and certain amount of electric field is dissipated in the form of heat energy. This loss in energy in the form of heat is called dielectric loss. The power loss $P_L \propto \tan\delta$, where tan δ is called loss tangent and δ is called loss angle. This dielectric loss mainly occurs due to the imaginary part of complex dielectric constant.

6. What is meant by dielectric breakdown and dielectric strength

Dielectric breakdown: When external field applied to a dielectric material is greater than the critical field, the dielectric losses its insulating property and becomes conducting. Therefore, a large current flow through the material, this phenomenon is called dielectric break down

Dielectric strength: It is minimum strength (voltage) required per unit thickness of the dielectric material to produce dielectric breakdown.

7. Explain electrochemical breakdown in dielectric

This type of breakdown occurs due to the presence of coirs and their mobility. These impurities causes leakage current and energy loss in the materials. Thus, when the temperature of the dielectric material is increased due to the presence of coirs the chemical reaction is accelerated and hence the material becomes conducting, causing electrochemical breakdown.

8. Mention the various dielectric breakdown mechanisms

(i)Intrinsic break down (ii) Thermal break down (iii) Discharge breakdown (iv) Electrochemical breakdown (v) Defect break down

9. The dielectric constant of water is 80, Is water a good dielectric? Is it useful for energy storage in capacitors? Justify your answer

Though the dielectric constant of water is 80ºC at 20ºC (or) 293 K, it is not a good dielectric material, because of the following reasons. Viz

1. At normal temperature the electrical conductivity of water is very high
2. At normal temperature current lea the voltage by a very less angle. i.e., cosθ is very less. Which leads to very high loss angle (δ) and hence tan δ is very high
3. The dissipation factor and hence the power loss is very high. This, water cannot be used as dielectric for energy storage in capacitors.

10. What are the requirements of good insulating materials?

(i) It should have low dielectric constant
(ii) It should possess low dielectric loss
(iii) It must have high resistance
(iv) It must possess high dielectric strength
(v) It should have adequate chemical stability
(vi) It must have high moisture resistance.

11. What are dielectric materials? Give its properties

Dielectric are non-metallic materials which have permanent electric dipoles (or) has an ability to produce enormous induced dipoles in the presence of external electric field

Properties

(i) It has high specific resistance
(ii) It has negative temperature coefficient of resistance
(iii) Large isolation resistance

12. Define dielectric constant

Dielectric constant (ε_r) is the measure of the polarization produced in the material, It is the ration between the absolute permittivity (ε) and permittivity of free space (ε_0)

13. What are the microscopic polarization mechanism involved in dielectric polarization?

They are four mechanisms involved in electric polarization. (i) Electronic polarization (ii) Ionic polarization (iii) Orientation polarization (iv) Space-charge polarization.

14. What is Ionic polarization?

When the electric field is applied to the ionic solids (dielectric), there is a small displacement between cations and anions in opposite directions.

Induced dipole moment $\mu = \alpha_i E$ where α_i – Ionic polarizability $\boldsymbol{\alpha_i = \frac{e^2}{\omega_0{}^2}\left(\frac{1}{M}+\frac{1}{m}\right)}$

15. What is Orientation polarization?

When the electric field is applied to dielectric polar molecules, the dipole align themselves along the field direction & increases the electric dipole moment due to the orientation of the permanent dipoles by the applied field is called orientation polarization

Orientation polarization (P_0) = $N\alpha_0 E$ $\boldsymbol{\alpha_0 = \frac{\mu^2}{3kT}}$

Where N – Number of atoms; α_0- Orientation Polarizability

16. What is space charge polarization?

When the electric field is applied to dielectric materials ions diffuse towards the electrodes in responsible to the applied field. This results in redistribution of charges in the medium. This phenomenon is called space charge distribution

17. Prove that $\chi_e = \varepsilon_r - 1$?

We know that polarization $\overline{P} = \varepsilon_0 \chi_e E_1$

$\therefore \chi_e = \frac{\overline{P}}{\varepsilon_0 \overline{E}_1}$

$\because \frac{\overline{P}}{\overline{E}_1} = \boldsymbol{\varepsilon_0(\varepsilon_r - 1)}$ (or) $\boldsymbol{\chi_e = \frac{\varepsilon_0(\varepsilon_r-1)}{\varepsilon_0} = \varepsilon_r - 1}$ thus proved.

18. What are the differences between Polar & Non – Polar molecules?

S.No	Polar Molecule	Non – Polar Molecule
1.	These molecules have permanent dipole moments even in the absence of an applied field	These molecules do not have permanent dipole moment
2.	The polarization of polar molecules is highly temperature dependent	The polarization of this kind of molecules is independent of temperature

3.	These molecules do not have symmetrical structure & they do not have centre of symmetry	These molecules have symmetrical structure & they have centre of symmetry
4.	Eg: $CHCl_3$, H_2O, HCl	Eg: CCl_4, CO_2, H_2.

19. Explain electrochemical breakdown in dielectric?

It is similar to thermal breakdown. If the temperature of dielectric increases then mobility of ions will increases & hence insulating resistance decreases, which leads to conducting of dielectrics. This type of breakdown is called electrochemical breakdown.

20. Define Gauss law and write the equation for the total flux, when the charge is placed inside the surface and outside the surface

The total electric flux (φ) or the total normal electric induction of the electric field (E) over any closed surface is equal to $1/\varepsilon_0$ times the total charge enclosed by the surface

$$\therefore \phi = \oint_S \vec{E}.d\vec{s} = \frac{\sum q}{\varepsilon_0}$$

Case (i): When the electric charge is situated inside the closed surface

Hence the total flux through the entire closed surface is given by $\phi = \frac{q}{\varepsilon_0}$

Case (ii) For the charge outside the sphere

Total flux = $-\frac{q}{4\pi\varepsilon_0}d\omega + \frac{q}{4\pi\varepsilon_0}d\omega = 0$

21. What are the uses of Gauss law?

1. It is used to find the electric field. If, the charge distribution is so symmetric, by constructing a closed surface, the electric field can be find out
2. Gauss law is one of the fundamental equations of electromagnetic theory. I.e., it is one of the Maxwell's equations
3. One can derive Coulomb's law from Gauss law. So Gauss law is more fundamental than coulomb's law.

22. Mention some of the solid insulating materials and its uses

(a) Mica

It is made of silicate aluminum with silicates of soda potash and magnesia.

Uses

1. It is sued as insulator in commutator segment
2. It is used as a separator in electrical machines, switch gears, heating devices, iron boxes, hot plates as insulator
3. It is used in the form of tapes in high voltage alternators

(b) Asbestos

It is a naturally occuring mineral material of fibrous structure made of magnesium silicate

Uses

1. It is used in electrical machines to withstand high temperature
2. It is used in the form of paper, tape, cloth and board for insulation

(c) Poly Vinyl Chloride (PVC)

It is produced by treating acetylene and hydrogen chloride in the presence of a catalyst at a temperature of about 50º C.

Uses

(i) It is used in the manufacturing of PVC films, tapes and pipes.

(ii) It is used as insulation for batteries, conductors and cables.

23. Give some of the Liquid Insulating Materials and its uses

(i) Mineral insulating oils

This oil is obtained from crude petroleum by distillation. This oil is used to transfer heat by convection from windings and core to the cooling surfaces. It is used to maintain the insulator of the windings. Now a days synthetic oil is used as an insulator in transformers in the place of transformer oil (mineral oil) because synthetic oil are very much resistant to oxidation to oxidation and to fire hazards.

Uses:

They are used in transformers and capacitors

(iv) Synthetic Insulating Oils

When we compare this with mineral insulating oil, the properties are degraded. Askarels have thermal stability up to 110ºC and are manufactured from chlorinated hydro-carbons.

Uses

They are used as coolant and insulant in high voltage transformers.

24. List some of the Gaseous Insulating materials and its uses

(i) Vacuum

Vacuum means free space without air. So creating a vacuum place is a type of insulation.

Uses

it is used in (i) X-ray tubes (ii) Electronic valves (iii) Particle accelerators (iv) Microwave tubes (v) Low-loss capacitors, etc.,

(ii) Air

Air is a naturally occuring dielectric. The atmospheric gas consists of a number of gases say N_2, O_2, *He*, CO_2, *Ne,* etc.,

Uses

(i) They act as insulators in switches, plugs and various electrical machines

(ii) They are used in low voltage applications

25. Define capacitor and mention its unit.

A capacitor has a capacity of one farad if one coulomb of charge is transferred from one conductor to the other, when the difference of potential between the two conductor is one volt.

Since the unit of capacitance farad is too large, for practical purposes much smaller units like microfarad (or) picofarad is used.

1 μf = 10^{-6} farads; 1 pf = 10^{-12} farads

26. Mention few types of capacitors.

(a) capacitor with solid dielectric (b) capacitor with air as dielectric (c) Electrolytic capacitors

27. Define piezoelectricity and piezoelectric crystals.

When mechanical stress is applied on dipolar crystals, electricity is produced due to the displacement of dipoles. This phenomenon is called piezoelectricity and those crystals that exhibits this property are termed as piezoelectric crystals.

28. Define Pyroelectricity and pyroelectric crystals.

Pyro means heat, some piezoelectric crystals when heated, then it produces electricity to a small extent and this phenomenon is called pyroelectricity. The crystals that exhibit this phenomenon are called pyroelectric crystals.

Part – B questions (16 Marks)

1. **Explain the different types of polarization mechanisms involved in a dielectric material.**
2. **What is meant by local field in dielectric and how is calculated for cubic structure? Obtain Clausius-Mossotti equation and show how it used to determine the dipole moment of a polar molecule.**
3. **Discuss in detail about the various types of breakdown mechanism occurs in dielectric materials.**
4. **Classify the insulating materials and explain the properties and their practical application in detail**
5. **What is meant by capacitor? Describe the typical capacitor construction and applications.**
6. **Explain in detail about the (i) dielectric loss (ii) frequency dependency of polarization in dielectric material**