

Dielectric materials

1.

- (*) Matter polarization and Relative permittivity.

In this chapter, we discuss about.

- Relative permittivity.
- Dipole moment and Electronic polarization.
- Polarization vector 'p'
- Local field E_{loc} and Clausius-Mosotti Equation.

- (**) Relative permittivity.

Consider a parallel plate capacitor (rectangular plates), with the area of the plates as $a\text{m}^2$ each, a distance 'd' meter apart in vacuum. The capacitance of the capacitor is,

$$C_0 = \frac{\epsilon_0 a}{d} \quad (I)$$

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where,

ϵ_0 = dielectric constant or permittivity of vacuum = 8.854×10^{-12} farad/meter. If the space between the plates is filled with a dielectric material, the capacitance of the capacitor increases and is given by,

$$C = \frac{\epsilon_0 \epsilon_r a}{d} \quad (II)$$

Where,

ϵ_r = Relative dielectric constant of the dielectric material.

= 1 for vacuum.

= 1.0006 for air.

Thus, the capacitance of the capacitor is directly proportional to the relative dielectric constant.

From (i) & (ii).

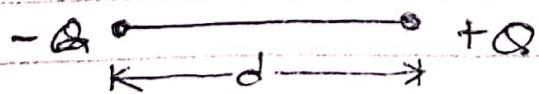
$$\frac{C}{C_0} = \frac{\epsilon_0 \epsilon_r a}{d} = \epsilon_r$$

$$\therefore \epsilon_r = \frac{C}{C_0}$$

Hence, relative permittivity can be determined by measuring the capacitance with vacuum as dielectric and then material as dielectric.

* Dipole moment and electronic polarization.

The dipole moment is established by two charges of equal magnitude but of opposite polarity. Separated by a distance 'd' apart.



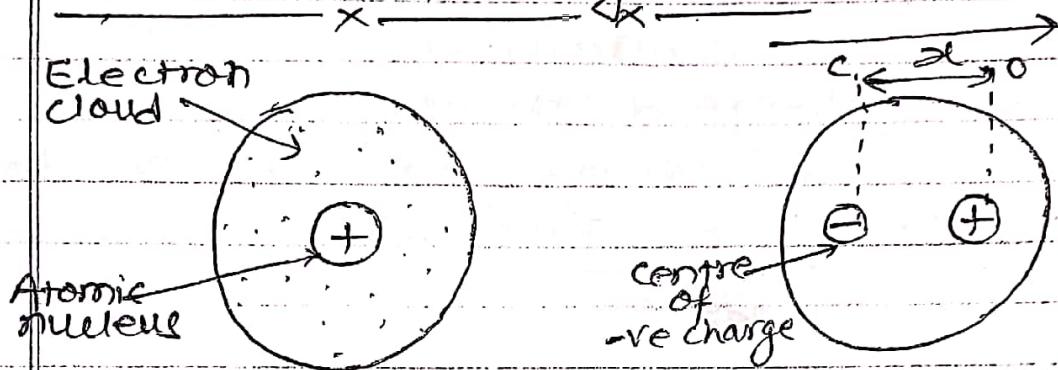
$$\vec{P} = Q \vec{d}$$

Hence, an electric dipole moment is simply a separation between a negative

and positive charge of equal magnitude Q .

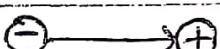
The region that contains the $+Q$ and $-Q$ charges has net zero charge.

(*) Electronic polarization.



A neutral atom
in $E=0$

produced dipole
moment in a field



p_{induced}

→ The net charge within a neutral atom is zero.

→ The centre of negative charge of the electron coincides with the positive nuclear charge which means that the atom has no net dipole moment.

Now when this atom is placed in an external electric field, it will develop an induced dipole moment.

The electrons, being much lighter than the positive nucleus, become easily displaced by the field, which results in the separation of the negative charge from the centre from the positive charge centre.

This separation of negative and positive charges and the resulting induced dipole moment are termed polarization.

Thus an atom is said to be polarized if it possess an effective dipole moment that is if there is a separation between the centre of the negative and positive charge distribution α :

The induced dipole moment depends upon the electric field causing it:

$$\therefore P_{\text{ind}} = \alpha E$$

where α is a coefficient called the polarizability of the atom.

Since the polarization of a neutral atom involves the displacement of electrons α' is called electronic polarization, and denoted as α_e .

(*) Polarization Vector (P)

When a material is placed in an electric field, the atoms and molecules of the material become polarized so that we have a distribution of dipole moments in the material. We can visualize this effect with the insertion of dielectric slab into the parallel plate capacitor.

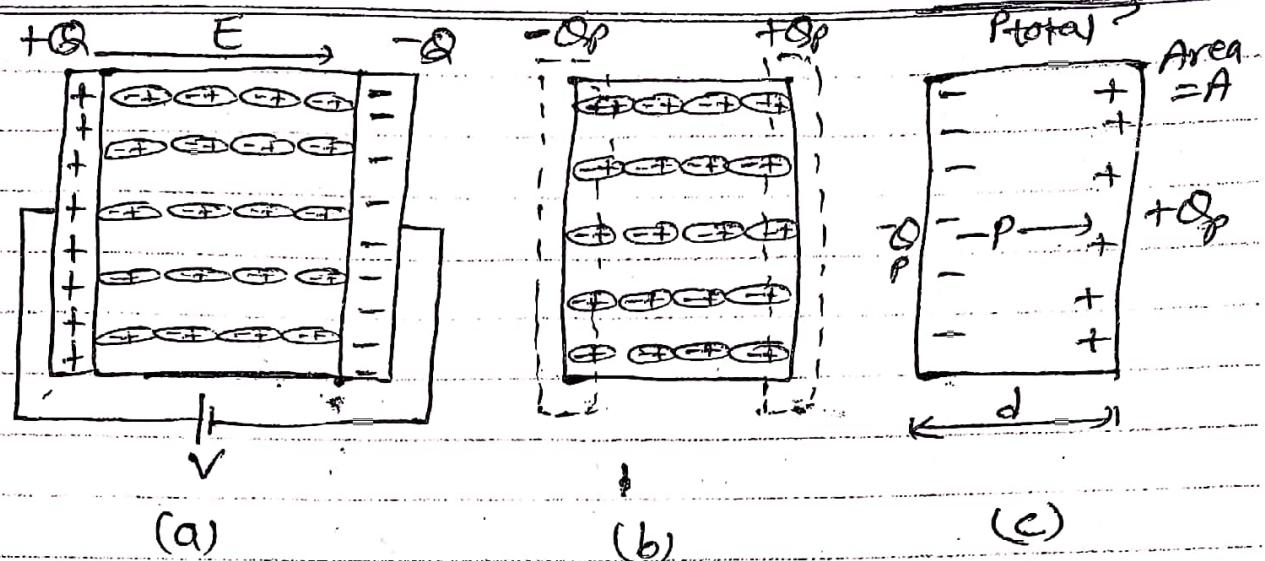


fig !:- When a material is placed in an electric field, the atoms and molecules of the material become polarized so that, we have a distribution of dipole moments in the material.

- All dipole ends of opposite charge inside the material will cancel but there will be an uncompensated surface charge on the plates; positive on one side and negative on the other plate i.e. $+Q_p$ and $-Q_p$.
- We see that charges $+Q_p$ and $-Q_p$ appear on the opposite surfaces of a material when it becomes polarized in an electric field. These charges are bound and are a direct result of the polarization of the molecules. They are termed surface polarization charges.

→ We represent the polarization of a medium defined as the dipole moment per unit volume.

Polarization vector,

$$\mathbf{P} = \frac{1}{\text{volume}} [P_1 + P_2 + P_3 + \dots + P_N]$$

where P_1, P_2, \dots, P_N are the dipole moments induced at N molecules in the volume. If P_{av} is the average dipole moment per unit volume then,

$$\mathbf{P} = N \cdot P_{av}$$

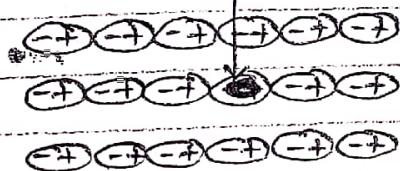
where, N is the number of molecules per unit volume.

(*) Local field E_{loc} and Clausius-Mossotti Equation.

The field experienced by a charge from its surrounding molecules is called Local electric field E_{loc} .

E_{loc} depends not only on the free charges on the plates but also on the arrangement of all the polarized molecules around the point.

E_{loc} will depends upon the amount of polarization, the material has experienced. The greater the polarization, the greater is the local field.



The local field E_{loc} , acting on a

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molecule, increases with polarization as,

$$E_{\text{loc}} = E + \frac{P}{3\epsilon_0}$$

(iii) where

$E + \frac{P}{3\epsilon_0} = E$ = Applied electric field,

P = polarization

Clausius-Mossotti Equation:

(Relationship between macroscopic factor (ϵ_r) and microscopic factor (α_e)).

(i) Clausius-Mossotti equation for electronic polarization.

We know that,

$$E_{\text{local}} = E + \frac{P}{3\epsilon_0} \quad (i) \quad | E = \text{Applied field}$$

And the induced polarization is now given by,

$$P = \alpha_e E_{\text{local}}$$

Hence, polarization due to N molecules,

$$P = Np = N\alpha_e E_{\text{local}} = N\alpha_e \left(E + \frac{P}{3\epsilon_0} \right)$$

$$\Rightarrow P = N\alpha_e E + \frac{N\alpha_e P}{3\epsilon_0}$$

$$\text{or } P = \frac{N\alpha_e E}{1 - N\alpha_e} \quad (II)$$

$\boxed{\beta^2 + \gamma^2 = 3\epsilon_0}$

Also we have,

$$P = \epsilon_0 \chi S E \quad (III)$$

where χ = dielectric susceptibility.

Now, from Equations (II) & (III),

$$\epsilon_0 \chi S E = N\alpha_e E$$

$$\frac{\epsilon_0 \chi S}{3\epsilon_0} (1 - N\alpha_e) = N\alpha_e$$

$$\text{or, } \epsilon_0 \chi (1 - N\alpha_e) = N\alpha_e$$

$$\text{or, } \frac{\epsilon_0 \chi - N\alpha_e \chi}{3} = N\alpha_e \quad (I)$$

$$\text{or, } N\alpha_e + N\alpha_e \chi = \frac{\epsilon_0 \chi}{3}$$

$$\text{or, } N\alpha_e (1 + \frac{\chi}{3}) = \frac{\epsilon_0 \chi}{3}$$

$$\text{or, } N\alpha_e (\frac{\chi + 3}{3}) = \frac{\epsilon_0 \chi}{3}$$

$$\text{or, } N\alpha_e = \frac{\chi}{\chi + 3}$$

We know $\chi = \epsilon_r - 1$

$$\text{or, } \frac{N\alpha_e}{3\epsilon_0} = \frac{\chi}{\chi + 3} = \frac{\epsilon_r - 1}{\epsilon_r + 2} \quad (IV)$$

Eqn (IV) is called the Clausius-Mossotti

Equation, which relates relative permittivity and electronic polarizability more accurately.

In terms of optical frequency, the Clausius-Mossotti equation is given by,

$$\frac{N\alpha_e}{3\epsilon_0} = \frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{n^2 - 1}{n^2 + 2} \quad (V)$$

Since $\epsilon_r = n^2$

(2) Clausius-Mossotti equation for ionic polarization

Ionic polarizability is denoted by α_i .

Hence, same as the electronic polarizability, the Clausius-Mossotti Equation is given by,

$$\frac{N\alpha_i}{3\epsilon_0} = \frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{x}{x+3} \quad (VI)$$

Hence the total polarization in air is given by $(\alpha_e + \alpha_i)$. So the Clausius-Mossotti Equation becomes,

$$\frac{N(\alpha_e + \alpha_i)}{3\epsilon_0} = \frac{x}{x+3} = \frac{\epsilon_r - 1}{\epsilon_r + 2} \quad (VII)$$

(Q) Types of polarization mechanisms.

There are a number of polarization mechanisms that may contribute to the relative permittivity.

(1.) Electronic polarization

(2.) ~~Electronic polarization~~

(2.) Orientational polarization.

(3.) Ionic polarization.

(4.) Interfacial polarization.

The Clausius-Mossotti Equation is capable of handling and defining the microscopic and macroscopic factor for electronic and ionic polarization only.

(1.) Electronic polarization.

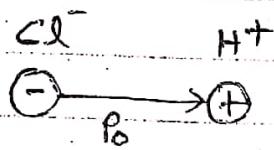
→ discussed already;

The Clausius-Mossotti Equation due to electronic polarizability α_e is given by,

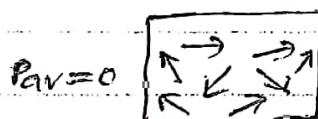
$$\frac{N\alpha_e}{3\epsilon_0} = \frac{\chi}{\chi + 3} = \frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{n^2 - 1}{n^2 + 2}$$

(2) orientational polarization (dipolar)

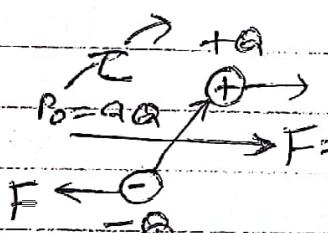
Certain molecules possess permanent dipole moments. For e.g. HCl molecule shown in fig. below has a permanent dipole moment P_0 from the Cl^- ion to the H^+ ion.



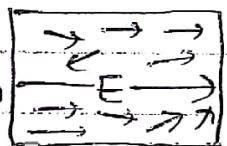
(a)



(b)



(c)



(d)

In the liquid or gas phases, these molecules, in the absence of an electric field, are randomly oriented, as a result of thermal agitation as shown in fig (b).

When an electric field E is applied, E tries to align the dipoles parallel to itself, as depicted in fig (c). The Cl^- & H^+ charges experience forces in opposite directions. But the nearly bond between Cl^- & H^+ hold them together, which means that the molecule experiences a torque (τ) about its centre of mass. This torque

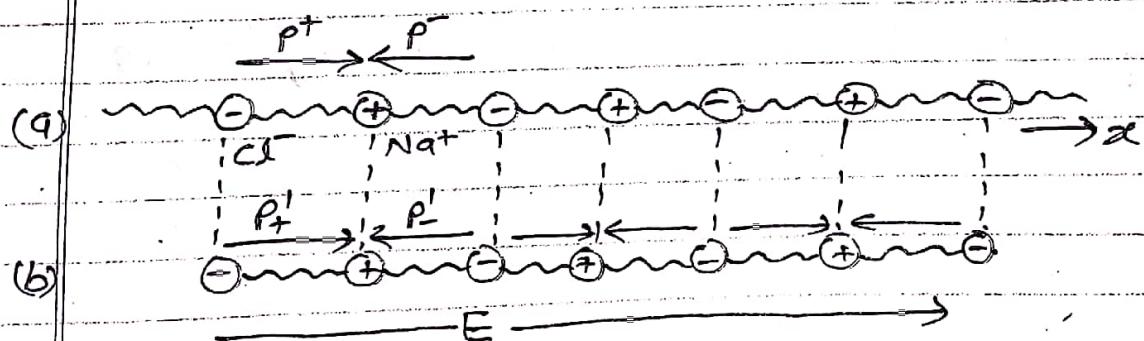
acts to rotate the molecule to align P_0 with E . If all the molecules were to simply rotate & align with the field, the polarization of the solid would be,

$$P = N P_0$$

Where, N is the number of molecule per unit volume.

(3) Ionic polarization.

This type of polarization occurs in ionic crystals such as NaCl, KCl & LiBr. Consider the one dimensional NaCl crystal depicted as a chain of alternating Na^+ & Cl^- ions as in fig (a) below:



In the absence of an applied, the solid has no polarization because the dipole moments of equal magnitude are lined up head to head and tail to tail so that the net dipole moment is zero.

The dipole moment P_+ in the positive α direction has the same magnitude as P_- in the negative α direction so the net dipole moment,

$$P_{\text{net}} = P_+ - P_- = 0.$$

In the presence of field E along the α direction, however the Cl^- ions are pushed in the $-\alpha$ direction and the Na^+ ions in the $+\alpha$ direction about their equilibrium positions. Consequently the dipole moment P_+ in the $+\alpha$ direction increased to P'_+ , as shown in fig.(b).

The net dipole moment per ion pair is now $(P'_+ - P'_-)$. which depends on the electric field E . Thus the induced average dipole moment per ion pair P_{av} depends on the field E . The ionic polarization α_i is defined in terms of the local field experienced by the ions,

$$P_{\text{av}} = \alpha_i E_{\text{loc}}$$

The larger the α_i the greater the induced dipole moment. Generally α_i is larger than the electronic polarization α_e by a factor of 10 or more. which leads to ionic solids having large

Clausius-Mosotti eqⁿ for
ionic polarization

classmate

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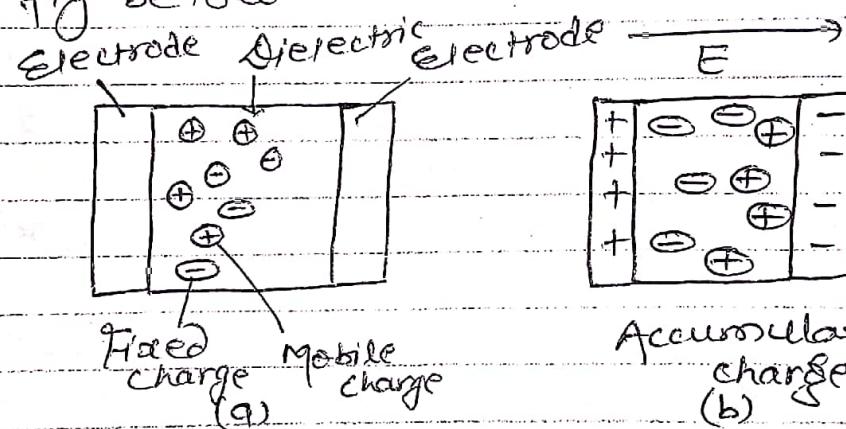
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$$\frac{N\alpha_i}{3\epsilon_0} = \frac{\chi}{\chi+3} = \frac{\epsilon_r - 1}{\epsilon_r + 2}$$

dielectric constant.

(4) Interfacial polarization

Interfacial polarization occurs whenever there is an accumulation of charge at an interface between two materials or between two regions within a material. The simplest example is interfacial polarization due to accumulation of charges in the dielectric near one of the electrodes as depicted in fig. below.



Invariably materials, however perfect, contain crystal defects, impurities, & various mobile charge carriers such as electrons (e.g. from donor-type impurities), holes, or ionised host or impurity ions.

In above example, in fig(a), the ~~interfacial~~ material has an equal number of positive and negative ions, but the positive ions are assumed to be far more mobile. Under the presence of an

applied field, these positive ions migrate to the negative electrode. The positive ions, however, cannot leave the dielectric & enter the crystal structure of the metal electrode.



Total Polarization.

In the presence of electronic, ionic and dipolar polarization mechanism, the average induced dipole moment per molecule will be the sum of ~~the~~ all the contributions in terms of the local field.

$$\bar{\mu}_{av} = \alpha_e E_{loc} + \alpha_i E_{loc} + \alpha_d E_{loc} \quad (1)$$

Each effect adds linearly to the net dipole moment per molecule, a fact verified by experiments. Interfacial polarization cannot be simply added to the above eq'(1) as $\alpha_{if} E_{loc}$ because it occurs at interfaces & cannot be put into an average polarization per molecule in the bulk.

(*) Dielectric contact.

A rigid contact placed between the two parallel conductor is known as dielectric contact. Dielectric is a material in which energy can be stored by the polarization of the molecules. It is a material that increases the capacitance or charge storage capacity or ability of a capacitor. Ideally, it is a non-conductor of electrical charge, so that an applied field does not cause a flow of charge but instead relative displacement of opposite charges and hence polarization of the medium.

(**) Dielectric loss.

Dielectric loss is the electrical energy lost as heat in the polarization process in the presence of an applied ac field. The energy is absorbed from the ac voltage and converted to heat during the polarization of the molecules. It should not be confused with conduction loss (σE^2 or V^2/R).

(**) Dielectric breakdown.

A defining property of a electric medium is not only its ability to increase capacitance, but also an

equally important its insulating behaviour or low conductivity so that the charges are not simply conducted from one plate of the capacitor to the other through the dielectric. Dielectric materials are widely used as insulating medium between conductors at different voltages to prevent the ionization of air and hence current flow overs between conductors. The voltage across dielectric material & hence the field within it cannot however be increased without limit.

Eventually a voltage is reached that causes a substantial current to flow between the electrodes which appears as a short and between the electrodes and leads to what is called dielectric breakdown.

(*) Dielectric strength

The dielectric strength is the maximum field that can be applied to an insulating medium without causing dielectric breakdown. It is denoted by E_{br} . The dielectric strength of solid depends on molecular structure, impurities in the material, sample geometry, nature of the electrodes, temperature,

ambient conditions duration and frequency of applied field.

(x) Piezoelectricity.

Certain crystals for example quartz (crystalline SiO_2) and BaTiO_3 becomes polarized when they are mechanically stressed. charges appear on the surfaces of the crystal as depicted in fig (a) & (b).

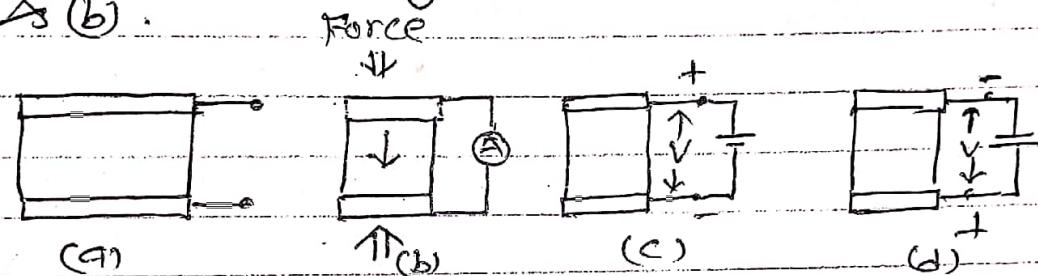


fig: piezoelectric effect.

Appearance of surface charges leads to a voltage difference between the two surfaces of the crystal. The same crystals also exhibit mechanical strain or distortion when they experience an electric field as shown in fig (c) & (d). The direction of mechanical deformation (eg. extension or compression) depends on the direction of the applied field, or the polarity of the applied voltage. The two effects are complementary & define piezoelectricity.

(*) Ferroelectricity:

Certain crystals are permanently polarized even in the absence of an applied field. The crystal already possess a finite polarization vector due to the separation of positive & negative charges in the crystal. These crystals are called ferroelectric.

Eg:- Barium titanate ($\text{BaTiO}_3 \Rightarrow \text{Ba}^{2+}, \text{O}^{2-}, \text{Ti}^{4+}$)

The temperature (critical) above which the ferroelectric property is lost is called Curie temperature.

#

Macroscopic effects on Dielectric materials.

As we know, the dielectrics are the materials which do not conduct electricity. There are very few free electrons in the conduction band at normal temperature and moderate electric field. The energy gap between the valence band and conduction band is the order of 10eV.

The relationship between the electric flux density at a point in a material and electric field strength is given by,

$$\mathbb{D} = \epsilon E$$

where, \mathbb{D} = electric flux density 1 cm^2

ϵ = permittivity of the medium

If $\epsilon = \epsilon_0$ then its value is,

$$\epsilon_0 = 8.854 \times 10^{-12} \text{ F/m}$$

And, $\epsilon = \epsilon_0 \epsilon_r$ for other materials,

where, ϵ_r is the relative permittivity of the material.

When a voltage V is applied across the parallel plates of a capacitor as shown in fig below,

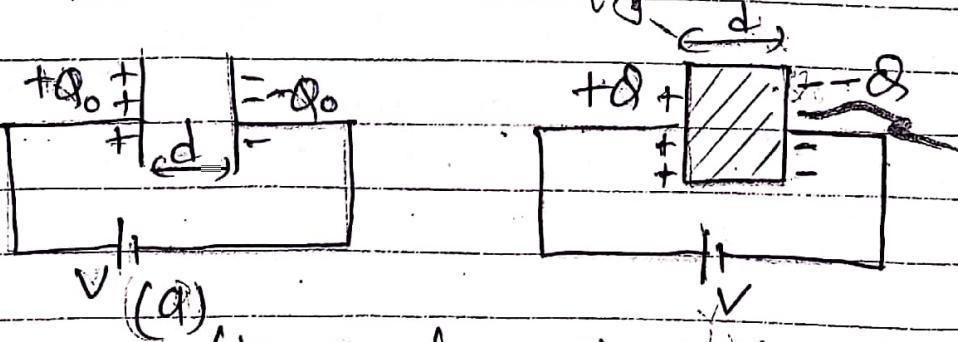


fig: Surface charges on (a) without dielectric
metallic plates (b) with dielectric.

Charges $+Q$ and $-Q$ will be induced on the surfaces of these plates based on the electrostatic induction. The capacitance of the parallel plate capacitor is given by,

$$C_0 = \frac{Q_0}{V_0} \quad \text{--- (i)}$$

When a dielectric material is inserted between these plates then the charges on the surfaces of the plates get increased due to the appearance of the charge on the surface of the dielectric near to the capacitor plates.

In vacuum, the electric flux density is numerically equal to the surface charge per unit area.

$$\text{i.e } \sigma_0 = Q_0 = \epsilon_0 V \quad \text{--- (ii)}$$

Where, d is the distance between two plates and V is the applied potential.

Similarly, when there is a dielectric medium inserted between the plates then the above relationship becomes,

$$\sigma = Q = \epsilon_0 \epsilon_r \frac{V}{d} \quad \text{--- (iii)}$$

The relative permittivity can be defined as the increase in charge stored on the capacitor due to insertion of the medium compare to the charge without medium.



Distribution without (a) no 23 bands are formed
Distribution with (b) 23 bands are formed

22.

$$\epsilon_r = \frac{Q}{Q_0} = \frac{C}{C_0} \quad \text{--- (iv)}$$

Increase in charge density, when a dielectric medium is inserted compared with that without dielectric is caused polarization. This gives the net change in capacitance with dielectric than without dielectric.

i.e $p = \epsilon - \epsilon_0 \doteq Q - Q_0$

or, $p = \epsilon_0 \epsilon_r \frac{V}{d} = \epsilon_0 \frac{V}{d}$

or, $p = \epsilon_0 \frac{V}{d} (\epsilon_r - 1)$

$\therefore p = \epsilon_0 (\epsilon_r - 1) \cdot E \quad \text{--- (v)}$

or, $p = \epsilon_0 \kappa E$

where, $E = V/d$, electric field strength

$\kappa = \epsilon_r - 1$ = Dielectric susceptibility

- bility

p = polarization vector of the material.

Polarization, p can also be defined as the induced charge within the dielectric per unit area.

i.e
$$P = \frac{Q'}{A}$$

where, Q' = induced charge

A = Surface area of the plates