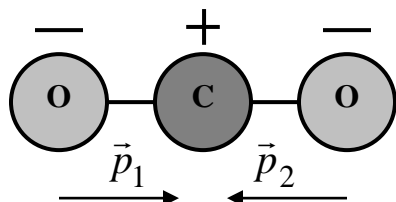


### Non-Polar and polar molecules

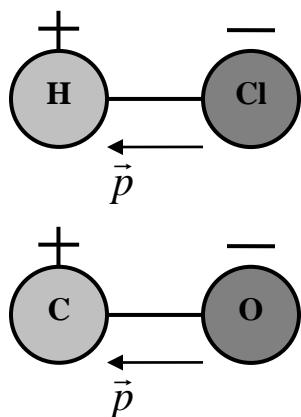
A molecule can be treated such that it consists of negative and positive charges of equal amounts so that it remains neutral. From this point of view, there are two types of molecules as discussed below:

**(a) Non-Polar molecules** The molecules in which the centers of gravity of negative and positive charges coincide are known as non-polar molecules. The inherent dipole moment of such molecules is zero.  $\text{H}_2$ ,  $\text{O}_2$ ,  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{C}_6\text{H}_6$ ,  $\text{CS}_2$ , etc are examples of non-polar molecules.



The non-existence of an intrinsic electric dipole moment in non-polar molecules is due to their symmetric structure. As an example, let us consider the case of  $\text{CO}_2$  molecule. The  $\text{CO}_2$  molecule has a linear symmetrical structure. The two C-O bonds in  $\text{CO}_2$  molecule have dipole moments  $\vec{p}_1$  and  $\vec{p}_2$  of equal magnitude directed opposite to each other as shown in Figure on LHS. Thus, the resultant electric dipole moment is zero. Hence  $\text{CO}_2$  molecule is a non-polar molecule

**(b) Polar molecules** The molecules in which the centers of gravity of negative and positive charges do not coincide are known as polar molecules. Since the centers of gravity of negative and positive charges are separated by a distance of molecular dimensions, they form an electric dipole and therefore the inherent dipole moment of such molecules is non-zero.  $\text{H}_2\text{O}$ ,  $\text{CHCl}_3$ ,  $\text{C}_6\text{H}_5\text{Cl}$ ,  $\text{C}_6\text{H}_5\text{NO}_2$ ,  $\text{C}_6\text{H}_5\text{OH}$  etc are examples of polar molecules. The existence of an intrinsic electric dipole moment in polar molecules is due to their asymmetric structure.



As an example, let us consider the case of  $\text{H}_2\text{O}$  molecule. The two H-O bonds in  $\text{H}_2\text{O}$  molecule have dipole moments  $\vec{p}_1$  and  $\vec{p}_2$  of equal magnitude making some angle with horizontal direction on both sides of O atom as shown in Figure on LHS. Thus, the resultant electric dipole moment is non-zero. Hence  $\text{H}_2\text{O}$  molecule is a polar molecule. However, some molecules having symmetric structures are also polar.

For example, let us consider the cases of  $\text{HCl}$  and  $\text{CO}$  molecules. Both have the symmetric structure. In  $\text{HCl}$  molecule, the electron pair of the H-Cl bond lies more toward the Cl atom than toward the H atom. The  $\text{HCl}$  molecule, therefore, behaves like an electric dipole having a dipole moment  $\vec{p}$  directed from Cl atom to the H atom. In the same manner,  $\text{CO}$  molecule is an electric dipole having a dipole moment  $\vec{p}$  directed from O atom to the C atom.

Fig. 5.11

### Dielectrics

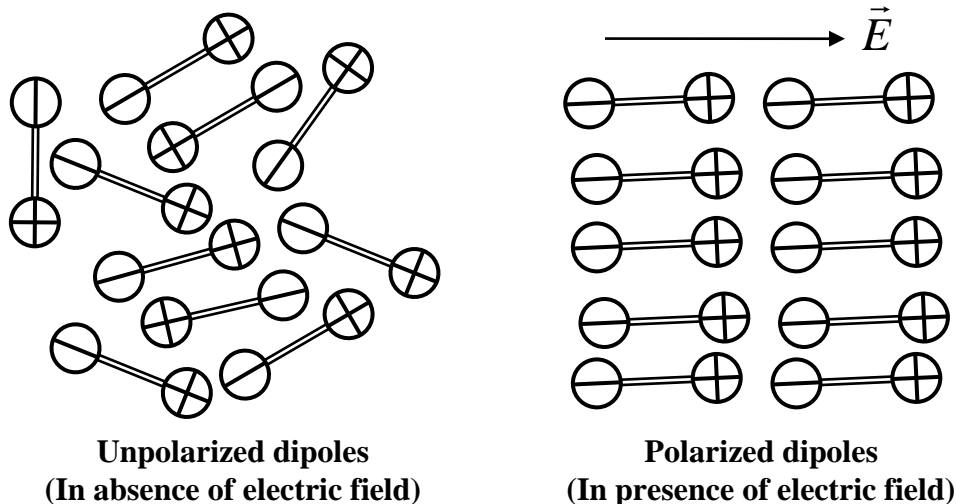
We know that the insulators are materials that have no free electrons and so they can not conduct electric current in the presence of the electric field. The insulators whose behavior gets modified in the external electric field are known as dielectrics.

Dielectrics, are thus, a special type of electrical insulators, which is highly resistant to electric current. When a dielectric medium interacts with an applied electric field, charges are redistributed within its atoms or molecules. This redistribution can alter the shape of an applied electrical field both inside the dielectric medium and in the region nearby. When two electric charges move through a dielectric medium, the interaction energies and forces between them are

reduced. When an electromagnetic wave travels through a dielectric, its speed slows and its wavelength shortens.

### Dielectric polarization

When a dielectric is placed in an external electric field, its molecules acquire an electric dipole moment along the external field. This phenomenon, in which the dipole moments align along the direction of the electric field, is known as dielectric polarization.



To understand dielectric polarization in detail, let us consider a dielectric molecule having polar molecules. In the absence of an external field, the polar molecules acting as individual dipoles are randomly distributed as shown in the above Figure. Hence the net electric dipole moment of the dielectric remains zero. When an external field is applied across the dielectric, the molecules (or dipoles) tend to align in the direction of the field (see RHS Figure). Hence a net dipole moment is produced in the dielectric.

The change in the behavior of a dielectric in an external electric field can be explained in terms of dielectric polarization. When a polar or non-polar molecule is placed in an electric field, the small displacements produce in the centers of gravity of negative and positive charges. In this situation, non-polar molecules possess an induced dipole moment. On the other hand, polar molecules possess an induced dipole moment with their permanent dipole moment. For both types of molecules, the orientation of resultant dipole moment in the external form will be such as to set or tend to set the axis of dipoles along the lines of force.

### Some important dielectric parameters

#### Dielectric constant

The relative dielectric constant of a material under given conditions is a measure of the extent to which it concentrates electrostatic lines of flux. It is the ratio of the amount of stored electrical energy when a potential is applied, relative to the permittivity of a vacuum. It is also called relative permittivity.

The dielectric constant is represented as  $\epsilon_r$  or  $K$ . Mathematically, it can be expressed as

$$K = \epsilon_r = \frac{\epsilon}{\epsilon_0}$$

Here  $\epsilon$  is the electric permittivity of the material, and  $\epsilon_0$  is the electric permittivity of vacuum. The Dielectric constant  $K$  of a medium can also be defined as the ratio of the capacitance  $C$  of a parallel plate capacitor filled with the given dielectric material to its capacitance  $C_0$  in the vacuum (i.e., without dielectric material between its plates).

$$K = \frac{C}{C_0}$$

### (b) Electric polarization vector

The electric polarization vector (or polarization density)  $\vec{P}$  is the vector field that expresses the density of permanent or induced electric dipole moments in a dielectric material. The polarization vector  $\vec{P}$  is defined as the dipole moment per unit volume. The SI unit of measure is coulombs per square meter.

When a dielectric material is placed in an external field, then its molecules gain a dipole moment and the dielectric is said to be polarized. For a linear isotropic dielectric, the electric dipole moment per unit volume or polarization vector  $\vec{P}$  is proportional to the strength  $\vec{E}$  of the applied external field, i.e.,

$$\vec{P} \propto \vec{E}$$

or 
$$\vec{P} = \chi_e \vec{E}$$

Here  $\chi_e$  is the constant of proportionality. It is known as electric susceptibility of the dielectric material. It is a dimensionless scalar quantity. Its value for vacuum is 0. Its unit is  $\text{Coul}^2 / \text{N-m}_2$ .

### (c) Free charge density and bound charge density

Electric polarization corresponds to a rearrangement of the bound electrons in the material, which creates an additional charge density, known as the bound charge density  $\rho_b$ . Mathematically, it can be expressed as

$$\rho_b = -\nabla \cdot \vec{P} \quad \text{--- (1)}$$

so that the total charge density is given by

$$\rho = \rho_f + \rho_b \quad \text{--- (2)}$$

where  $\rho_f$  is the free charge density (describing charges brought from outside).

At the surface of the polarized material, the bound charge appears as a surface charge density

$$\vec{\sigma}_b = \vec{P} \cdot \hat{n} \quad \text{--- (3)}$$

Here  $\hat{n}$  is a unit vector pointing outwards perpendicularly to the surface. If  $\vec{P}$  is uniform inside the material, this surface charge is the only bound charge.

### (d) Electric displacement vector

From the above discussion, it is clear that the magnitude of polarization vector  $\vec{P}$  can be expressed as the surface charge density of bound charges, i.e.,

$$P = \sigma_b \quad \text{--- (1)}$$

Analogous to Eq. (1), we can define a vector known as the electric displacement vector  $\vec{D}$ , which is expressed as surface charge density of free charges, i.e.,

$$D = \sigma_f \quad \text{--- (2)}$$

In physics, the electric displacement field or electric flux density  $\vec{D}$  is a vector-valued field that accounts for the effects of bound charges within materials. “D” stands for “displacement”, as in the related concept of displacement current in dielectrics.

### (e) Electric permittivity

For a linear isotropic dielectric, the electric displacement vector or electric flux density  $\vec{D}$  is proportional to the strength  $\vec{E}$  of the applied external field, i.e.,

$$\vec{D} \propto \vec{E}$$

or 
$$\vec{D} = \epsilon \vec{E}$$

Here  $\epsilon$  is the constant of proportionality. It is known as the electric permittivity of the dielectric material. It is a dimensionless scalar quantity. Thus, the electric permittivity  $\epsilon$  of dielectric material can be expressed as the ratio of electric flux density  $\vec{D}$  to electric flux density  $\vec{E}$  i.e.,

$$\epsilon = \frac{\vec{D}}{\vec{E}}$$

### 5.17 Polarizability of a dielectric

The induced dipole moment  $\vec{p}$  of each atom (or ion or molecule) of dielectric material in the presence of an external electric field is proportional to its strength  $\vec{E}$ , i.e.,

$$\vec{p} \propto \vec{E}$$

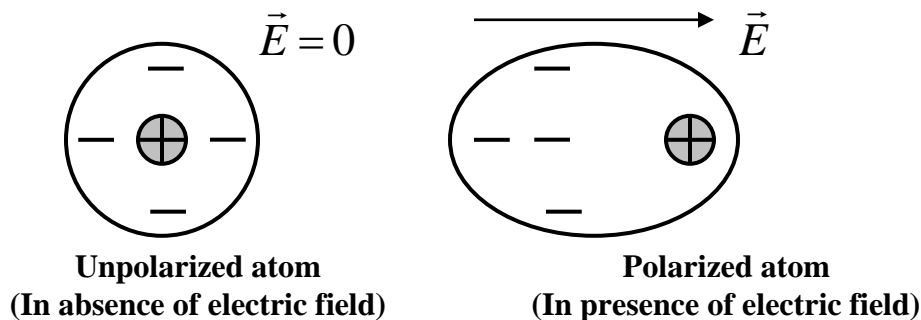
or 
$$\vec{p} = \alpha \vec{E}$$

Here  $\alpha$  is the constant of proportionality. It is known as the polarizability of the dielectric material. The polarizability can be divided into the following three main categories:

#### (a) Electronic polarizability

The electronic polarizability  $\alpha_e$  arises due to the displacement of the electron clouds of an atom relative to its nucleus in the presence of an external electric field as shown in Figure 5.17.

The dielectric polarization  $\alpha_e$  of a material at optical frequencies results from electronic polarizability. The order of electronic polarizability  $\alpha_e$  is  $1.6 \times 10^{-39} \text{ F m}^2$ .



For calculating the effect of electronic polarization, We consider an idealized atom with perfect spherical symmetry having a point-like charge  $+ze$  in the nucleus and the exact opposite charge  $-ze$  homogeneously distributed in the volume of the atom, which is given by

$$V = \frac{4}{3} \pi R^3 \quad \text{--- (1)}$$

Here  $R$  is the radius of the atom

The charge density  $\rho$  of the electrons then is

$$\rho = \frac{3ze}{4\pi R^3} \quad \text{--- (2)}$$

The positive charge in the nucleus and the center of the negative charges from the electron “cloud” will thus experience forces in the different directions and will become separated. The separation distance  $d$  will have a finite value because the separating force of the external field is exactly balanced by the attractive force between the centers of charge at the distance  $d$ .

In an electrical field  $E$ , a force  $F_e$  acts on pint charge  $+ze$ , which is given by

$$F_e = zeE \quad \text{--- (3)}$$

Here, we have to take into account the Coulombic attraction between point charge  $+ze$  and homogeneously distributed charge  $-ze$ . We may divide the force on charged particles on any place inside a homogeneously charged sphere into the force from the inside sphere and the force from the hollow outside sphere. Electrostatics teaches us, that a sphere charged on the outside has no field in the inside, and therefore no force. Thus we indeed only have to consider the charge inside the sphere.

The Coulombic attractive force  $F_c$ , is given by

$$F_c = \frac{1}{4\pi\epsilon_0} \cdot \frac{q_1 q_2}{d^2} \quad \text{--- (4)}$$

Here  $q_1 = +ze$  (Charge at the center of the nucleus)

and  $q_2 = \rho \frac{4}{3}\pi d^3$  (The fraction of the charge of the electrons contained in the sphere with radius  $d$ )

Then Eq. (4) becomes

$$F_c = \frac{1}{4\pi\epsilon_0} \cdot \frac{(+ze) \left( \frac{4}{3}\rho\pi d^3 \right)}{d^2}$$

or  $F_c = \frac{z\rho ed}{3\epsilon_0} \quad \text{--- (5)}$

Using Eq. (2) in (5), we have

$$F_c = \left( \frac{z^2 e^2}{4\pi\epsilon_0 R^3} \right) d$$

Equating  $F_e$  with  $F_c$  gives the equilibrium distance  $d_E$ , i.e.,

$$zeE = \left( \frac{z^2 e^2}{4\pi\epsilon_0 R^3} \right) d_E$$

or  $d_E = \frac{4\pi\epsilon_0 ER^3}{ze} \quad \text{--- (6)}$

The induced dipole moment  $p$ , is, then given by

$$p = ze d_E \quad \text{--- (7)}$$

Using Eq. (6) in (7), we have

$$p = ze \frac{4\pi \epsilon_0 E R^3}{ze} = 4\pi \epsilon_0 E R^3$$

The polarization  $P$  is given by

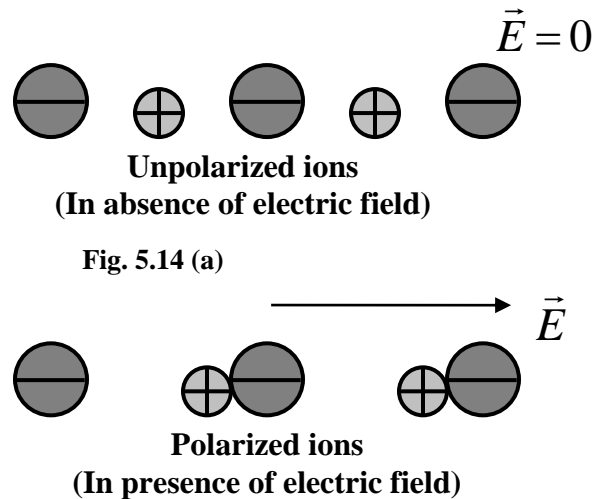
$$P = N p = 4\pi \epsilon_0 N E R^3$$

Where  $N$  is the density of the dipoles.

### (b) Ionic polarizability

The ionic polarizability  $\alpha_i$  arises due to the displacement of the one type of charged ions relative to other types of charged ions in a solid in the presence of an external electric field as shown in Figure 5.14.

Consider a simple ionic crystal, e.g. NaCl. Each  $\text{Na}^+\text{-Cl}^-$  pair is a natural dipole, no matter how you pair up two atoms. The polarization of a given volume, however, is exactly zero because for every dipole moment there is a neighboring one with the same magnitude, but opposite sign. In an electric field, the ions feel forces in opposite directions. For a field acting as shown, the lattice distorts a little bit. The  $\text{Na}^+$  ions moved a bit to the right, the  $\text{Cl}^-$  ions to the left. The dipole moments between adjacent NaCl pairs in field direction are now different and now there is a net dipole moment in a finite volume.



The contribution of ionic polarizability is significant at low frequencies. As an example,  $\epsilon \approx 5.6$  for NaCl at low frequencies whereas at optical frequencies  $\epsilon \approx 2.5$ . This difference is due to the contribution of ionic polarizability  $\alpha_i$ .

### (c) Dipolar or orientation polarizability

The dipolar or orientation polarizability  $\alpha_d$  arises due to the alignment of the polar molecules of a dielectric material in the presence of an external electric field. In other words, the process of orientation of permanent dipole moments along the axis of the applied electric field is called orientational polarization.