Classification of substance

(i) Conductor

(ii) Dielectric or Insulator ($\sigma = 10^{-18}$ Sm)

(iii) Semiconductor for substance ($\sigma = 10^{7}\,\Omega m^{-1}$ to $10^{-13}\,\Omega m^{-1}$)

Dielectric

A dielectric is a material which contain no free charge carrier so that no current can flow through it. σ is poor for dielectric and it is zero for ideal dielectric. ($E_g \geq 3eV$)

Concept of Capacitance

When charge is given to a conductor, its potential increases.

The increase in potential of conductor is directly proportional to the charge given to it.

$$V \propto Q$$

$$Q \propto V$$

$$Q = CV$$

C is constant depends on

(i) size of conductor

(ii) Shape of conductor

(iii) Surrounding medium and presence of other neighbouring conductor

C is called capacitance of conductor

the C does not depends on charge existing on conductor

$$C = \frac{Q}{V}$$

Capacitance of conductor
C is the ratio of charge given to it and rise in potential of conductor

If $V = 1$ volt

then $C = Q$

Capacitance of conductor is numerically equal to the charge required to be given to conductor, which raises its potential by 1 volt.

S.I unit of C is coulomb/volt called farad

$$1 \text{ farad} = \frac{1 \text{ coulomb}}{1 \text{ volt}}$$

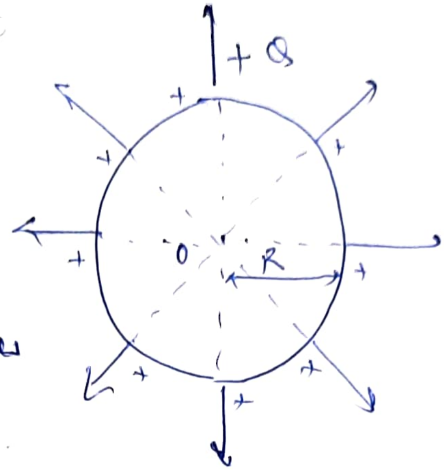
The capacitance of a conductor is 1 farad if 1 coulomb of charge raises its potential by 1 volt.

Farad is very long (large) unit, therefore unit used are microfarad (μF) and picofarad (PF)

Thus the capacitance of a conductor is its capacity of collecting of charge.

Capacitance of an Isolated spherical conductor

let radius of conductor is R placed in air and Q charge is given to it then charge spreads on the surface of conductor such that the potential on each point of conductor becomes same. the surface of conductor becomes equipotential surface..



Assuming charge (+Q) situated at O of sphere, the potential at surface is

$$V = \frac{1}{4\pi\epsilon_0}\frac{Q}{R}$$

Capacitance of sphere

$$C = \frac{Q}{V} = \frac{Q}{\frac{1}{4\pi\epsilon_0}\frac{Q}{R}}$$

$$C = 4\pi\epsilon_0 R$$

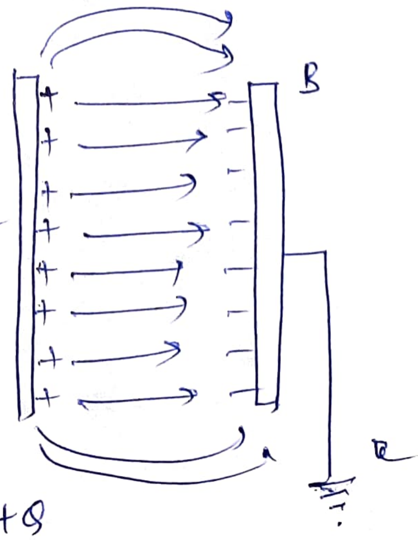
$$C \propto R$$

C depends on R

Parallel plate capacitor with Dielectric

It consist of two plane metallic plates A and B placed parallel to each other

let plate A is given +Q charge outer surface of B earthed, when Q is given to A, the charge −Q is induced at inner surface of B and a charge +Q at outer surface, the +Q charge is transferred to earth. Thus net charge on plate



A is +Q and on plate B is −Q.

Suppose A is area of each plate

d is separation b/w plate

K is dielectric constant of medium filled b/w plate

If σ is charge density then

$$\sigma = \frac{Q}{A}$$

The $\vec{E}$ b/w plates

$$E = \frac{\sigma}{K\epsilon_0}$$

ϵ_0 is permittivity of free space

Potential difference b/w plate

$$V_{AB} = Ed = \frac{\sigma d}{K\epsilon_0}$$

then

$$V_{AB} = \frac{Qd}{A\epsilon_0 K}$$

Capacitance of capacitor

$$C = \frac{Q}{V_{AB}} = \frac{Q}{\frac{Qd}{K\epsilon_0 A}}$$

$$C = \frac{K\epsilon_0 A}{d}$$

C ~~depend~~ is

(i) directly proportional to A
$C \propto A$

(ii) $C \propto \frac{1}{d}$

(iii) $C \propto K$

(iv) independent of metal plates

Definition of Dielectric constant

$$C_0 = \frac{\epsilon_0 A}{d}$$

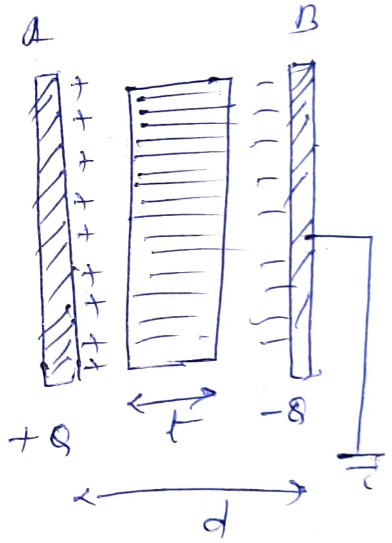
$$\frac{C}{C_0} = k \qquad k \text{ is dielectric constant}$$

$$C = k C_0$$

for air of vacuum $k = 1$

k is defined as the ratio of capacitance of capacitor filled with medium to the capacitance of same capacitor filled with air or vacuum.

Capacitance of a parallel plate capacitor when partly filled with dielectric substance



let Area of plates is A
separation b/w plates is d
the dielectric slab of dielectric constant K and thickness $t (< d)$
is placed b/w plate
the thickness of air is $d - t$

If charge ~~Q is given~~ on plate A is +Q
and on B is −Q

Surface charge density

$$\sigma = \frac{Q}{A}$$

E b/w plate in air

$$E_1 = \frac{\sigma}{\epsilon_0} = \frac{Q}{\epsilon_0 A}$$

E b/w plate in slab

$$E_2 = \frac{\sigma}{K \epsilon_0} = \frac{Q}{K \epsilon_0 A}$$

Potential b/w plates

V_{AB} = workdone in carrying unit positive charge from one plate to another plate

$= \Sigma E x$ (E is not constant b/w plate)

$= E_1 (d-t) + E_2 t$

$= \frac{Q}{\epsilon_0 A}(d-t) + \frac{Q}{K\epsilon_0 A} t$

$$V_{AB} = \frac{Q}{\epsilon_0 A}\left[d-t+t/K\right]$$

Capacitance

$$C = \frac{Q}{V_{AB}} = \frac{Q}{Q/\epsilon_0 A\,(d-t+t/K)}$$

$$C = \frac{\epsilon_0 A}{d-t+t/K} = \frac{\epsilon_0 A}{d-t(1-1/K)}$$

As $K>1$, then C is increases

Special case

(i)

Energy stored in ~~an electric~~ capacitor field in the presence of a dielectric

let charge on capacitor is built up on capacitor if small charge brings up at a time.

when charge has reached a value q and potential V and let final values are q_0 and V_0

when additional charge dq is brought on capacitor then work done

$$dW = V\,dq = CV\,dV \qquad (q = CV$$

Therefore work done in charging the capacitor to a potential V_0 is

$$W = \int dW = \int_0^{V_0} CV\,dV = C\left[\frac{V^2}{2}\right]_0^{V_0}$$

$$= \frac{1}{2} C V_0^2$$

this work is stored in form of energy in the dielectric and it increases the internal energy of molecules

we know

$$C = \frac{\epsilon_0 A K}{d}$$

$$V_0 = Ed$$

Therefore

$$W = \frac{1}{2}\left(\frac{\epsilon_0 A K}{d}\right) V_0^2$$

$$= \frac{1}{2}\epsilon_0 K \cdot Ad \left(\frac{V_0}{d}\right)^2$$

$$= \frac{1}{2}\epsilon_0 K A d E^2$$

Ad is ~~the~~ volume of dielectric region

the energy density u (energy per unit volume)

$$u = \frac{\frac{1}{2}\epsilon_0 K A d E^2}{Ad} = \frac{1}{2}\epsilon_0 K E^2$$

$$u = \frac{1}{2}\epsilon_0 K E^2$$

Energy stored in a capacitor

Let capacitance of capacitor is C

total charge is Q. in small installment

let at the instant charge on capacitor is q

and potential difference is V

If a further charge dq is given to the capacitor

the work done against the potential difference is

$$dW = V dq = \frac{q}{C} dq \qquad \left[V = \frac{q}{C}\right]$$

therefore total amount of work done in charging

the capacitor from charge 0 to Q is

$$W = \int_0^Q \frac{q}{C} dq = \frac{1}{C}\left[\frac{q^2}{2}\right]_0^Q = \frac{Q^2}{2C}$$

we know $Q = CV_0$ (final potential difference V_0)

$$W = \frac{(CV_0)^2}{2C} = \frac{1}{2}CV_0^2$$

this is energy stored in capacitor

for parallel plate capacitor

$C = \epsilon_0 A/d$ and field $E = \frac{V_0}{d}$

then

$$W = \frac{1}{2}\frac{\epsilon_0 A}{d}(Ed)^2 = \frac{\epsilon_0 E^2}{2} A \cdot d$$ (Ad is volume of b/w plates)

then energy per unit volume

or energy density $u = \frac{\epsilon_0 E^2}{2}$

Polar and non-polar molecules

Non-polar molecules

A molecule in general may be regarded as having its positive charge concentrated as nuclear points and entire electronic structure of molecule as forming a single cloud of negative charge of smoothly varying density.

A molecule in which the centre of positive charge and negative charge coincide ~~for~~ and thus for which the inherent dipole moment is zero is called non-polar molecule.

Such as H_2, O_2, CO_2, CH_4, CCl_4, C_6H_6, C_6H_{12}, CS_2 etc.

Polar molecules

There are molecules for which the distribution of two kinds of charges are different so that the positive and negative charges are centred at point separated by a distance of molecular dimensions forming an electric dipole.

Therefore these possess a net inherent dipole moment and are called ~~electric dipole~~ polar molecules

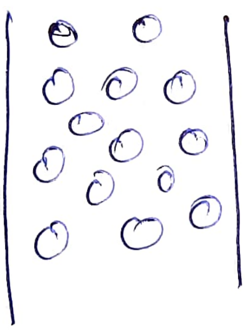
such as H_2O, HCl, $CHCl_3$, NH_3, C_6H_5Cl, $C_6H_5NO_2$ etc.

Polarization of dielectric

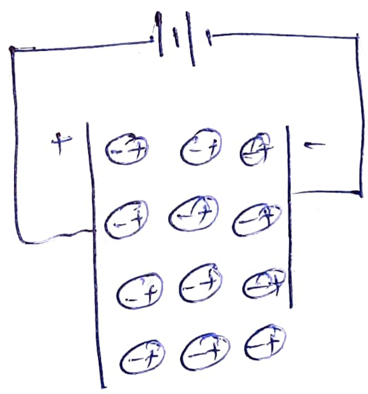
When a polar or a non-polar molecule is place in an external electric field the small displacement of the orbital electrons will cause the distance b/w the centre of positive and negative charges to alter. Thus non-polar molecules becomes induced dipoles whereas polar molecules which are already dipoles will be oriented by field, and may have resultant dipole moment modified since they possess

(i) permanent dipole moment
(ii) induced dipole moment.

The orientation of induced dipoles or permanent dipoles in external electric field will be such as to set or tend to set the axis of dipole along the line of force. This phenomenon is called electric polarization

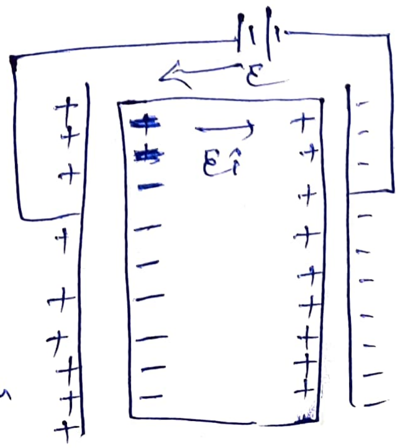


In absence of field



In presence of field.

Effect of polarization on electric field with in dielectric



When no field is applied the molecules do not show any polarity since either they are unelectrified non-polar molecules or they are polar molecules, which will be oriented at random and in such large no. of molecules that resultant field due to all is zero.

Resultant field

$E_R = E - E_i$

Electronic, atomic, ionic, and orientational polarization

(i) Atomic polarization also called Electronic polarization

When a dielectric is placed in the electric field, there is a displacement of electron-cloud relative to the nucleus of atom. This causes an induced dipole moment in atoms or molecule. This phenomenon is called electronic or atomic polarization. Example noble gases

(ii) Ionic polarization

When a dielectric made of molecule having ionic character is placed in the external electric field, the separation b/w positive and negative charges is altered. This ~~is~~ causes an induced dipole moment in molecules. This phenomenon is called ionic polarization

Example ~~Nacl~~ NaCl

(iii) Orientational (or dipole) polarization

When a dielectric made of molecules having randomly oriented permanent dipole moments is placed in an external electric field, the molecule as a ~~or~~ whole may rotate about the axis of geometry so that the dipole align along the field direction. This is referred as dipolar or orientational polarization

Example HCl, H_2O etc.

thus total dielectric polarization is

$$P = P_e + P_i + P_o$$

Electric Polarization vector

when dielectric is placed in electric field so that a dipole moment is induced in it and it is said to be polarized.

The polarization of an dielectric depends on the total electric field inside the medium

If $\vec{E}$ is average electric field acting on the molecule or atom then average dipole moment induced in each molecule or atom is directly proportional to effective field. i.e.

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

$$\vec{P} = \epsilon_0 \alpha \vec{E}$$

where α is a constant called molecular or atomic polarisability and depends on dielectric constant of material

$$\alpha = \frac{\vec{P}}{\epsilon_0 E}$$

$P \rightarrow C\,m$
$E \rightarrow N/C$
$\epsilon_0 = C^2/NM^2$

Unit of α is that volume (m^3)

If n is no. of molecules per unit volume.

then total induced dipole moment per unit volume

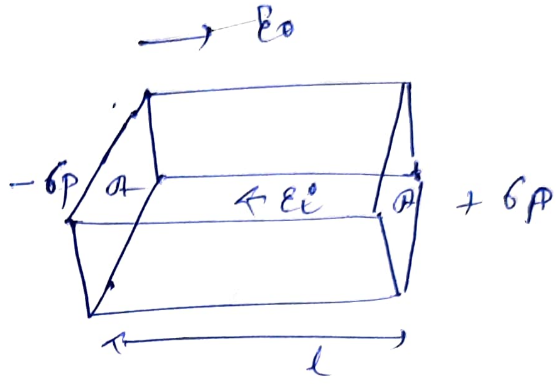
$$= n \epsilon_0 \alpha E$$

thus the total induced dipole moment per unit volume is called polarization and it is represented by P

$$\vec{P} = \frac{P}{V} = n\epsilon_0 \alpha \vec{E}$$

$V \rightarrow$ volume of dielectric

Consider the rectangular block of polarized dielectric of length l and area A.



E_0 is applied electric field.

field E_i is induced due to the separation of positive and negative charges.

let $-\sigma_p$ and $-\sigma_p$ be charge density of induced charge on the faces of rectangular

then induced charge on each face

$$Q = \sigma_p A$$

Total induced dipole moment ($= Ql$)

$$= \sigma_p A l$$

volume of dielectric block $= Al$

Then polarization = induced dipole moment per unit volume

$$\vec{P} = \frac{\sigma_p A l}{A l}$$

$$P = \sigma_p$$

Thus electric polarization also be defined as the surface charge density induced at the ~~surface~~ faces which are perpendicular to the direction of applied field.