Lecture 17: Dielectric Materials
They are of great importance in electronics industry.

-How do we define an insulator?
  • Energy gap of $\approx 2.5$ eV
  • Materials in which electron-holes are less, not created by visible light (400nm-700nm) $\approx 3eV$
-What is the reason behind wide gap??

Dielectric Constant ($\mathcal{E}$):

![Diagram of capacitor with conductive plates and dielectric](image)

This capacitor is comprised of two parallel plates, each of area $A$, and separated by a dielectric with dielectric constant $\mathcal{E}$.

The plates have a charge density $\pm \rho = \pm Q/A$

Assuming that the plate dimensions are $>> d$, the electric field near midpoint $(d/2)$ between the plates will be uniform with magnitude $E = \rho/\mathcal{E}$

$$V = \int_0^d Edz = \int_0^d \frac{\rho}{\mathcal{E}} dz = \frac{\rho d}{\mathcal{E}}$$

The capacitance $C = \frac{\mathcal{E}A}{d}$

Thus, we measure the capacitance in vacuum and get $C_0$. We then measure it again with the dielectric of interest between the two plates to get $C_r$.

Then, $\mathcal{E} = C_r/C_0$
Example:
When you apply a voltage to two parallel plates separated by distance L, the resulting electric charges remain on the plates even after removing the voltage. We define that by

\[
C = \frac{Q}{V}
\]

C = capacitance

\(C \propto \frac{A}{L}\)

It also depends on the material between the plates

In vacuum, \(C = \varepsilon_0 \frac{A}{L}\) \hspace{1cm} (eq 1)

\(\varepsilon_0\) : Permittivity of free space (universal constant) = 8.85 \(\times 10^{-12}\) F/m

In the presence of dielectric material
\(C = \varepsilon_r \varepsilon_0 \frac{A}{L}\) \hspace{1cm} (eq 2)

\(\varepsilon_r\) : Dielectric constant (relative permittivity)

Using eq 1 & eq 2:
The capacitance increased after a dielectric material is introduced.

**Explain:**

The atom is represented by a positively charged core and a negatively charged electron cloud. By applying electric field, the charges are displaced → Formation of an electric dipole

The electric dipole moment

\[ P = Q \cdot \delta \]

**Polarization:** The process of formation of an electric dipole (or alignment of an existing dipole) under the influence of an external electric field. This causes redistribution of charges.
Look to the direction of the external electric field and the direction of polarization, it is clear that $E$ has been decreased by polarization:

$$E = \frac{E_{\text{vacuum}}}{\mathcal{E}}$$

$E$: after dielectric metal
$\mathcal{E}$: Dielectric constant

Type of Polarization
1. Electric polarization
2. Molecular polarization
3. Dipolar polarization
4. Space charge polarization: long range charge migration

Their effects can be added
Note: Dielectric constant is frequency dependent

**Frequency Dependence:**
Relaxation time: Reorientation of the dipole in response to an electric field is characterized by relaxation time ($\tau$):

- Electric polarization:
  $\tau$ is small- fast response
- Ionic polarization:
  Slow
- Molecular Polarization:
  Much slower
- Space charge polarization:
  Very slow ($\tau$ very large)
$\alpha$: stands for polarization

- When relaxation time $\tau$ is much faster than the frequency of the applied electric field, polarization occurs instantaneously.
- When $\tau$ is much slower than the frequency, no polarization occurs.
- When $\tau$ and the frequency of the applied field are the same, a dielectric ion will happen (excitation energy is absorbed)

Note: It is very important to know the frequency for dielectric ions for the material
Ferroelectric

In most dielectric materials (insulating dense solids) the polarization is either ionic or electronic.

Ferroelectric material: Ionic contribution is the largest and it has two of the following conditions
1. Contains ions displace in response to an electric field
2. The displacements line up in the same direction
3. The displacements do not disappear after removing the electric field
Some ferroelectric materials develop a spontaneous polarization without an external applied electric field. In some materials, polarization does not vanish after removing the electric field (remnant polarization). It can only remain removed by inverting the electric field, a hysteresis loop is obtained.

What is the implication of that?

Note: Direction of polarization is reversible
Note: Ferroelectrics do not usually contain iron. Why are they called ferroelectric?

Critical Temperature (Curie): similar to ferromagnetic. Above the critical temperature, ferroelectric effects are gone and the material becomes dielectric. Range of Curie temperature: $-200^\circ$C to $640^\circ$C

Use of ferroelectrics
- Multilayer capacitors
- Random Access Memory

Example: Material exhibits a spontaneous polarization: $\text{BaTiO}_3$ (Barium Titanate)
Why these materials possess spontaneous polarizations? In their crystal structure, the positive and negative ions are slightly displaced from their symmetrical positions, which lead to a permanent ionic dipole moment. A large number of these dipoles line up.
Ionic Conductions

The movement of some negative and positive charged ions (jump from lattice site to another lattice site under the influence of an electric field).

Conductivity $\sigma$: $\sigma_{ion} = N_{ion}e\mu_{ion}$

It depends on vacancy concentrations, so ions can jump:

(Mobility) $\mu_{ion} = \frac{De}{K_B T}$  (Einstein Relation)

$D$: Diffusion coeff.
$T$: temperature
$K_B$: Boltzman constant