Conduction in Polymers and Ionic Materials

Ionic Materials

- In ionic materials, the band gap is large and only very few electrons can be promoted to the valence band by thermal fluctuations.
- Cation and anion diffusion can be directed by the electric field and can contribute to the total conductivity: $\sigma_{total} = \sigma_{electronic} + \sigma_{ionic}$
- High temperatures produce more Frenkel and Schottky defects which result in higher ionic conductivity.

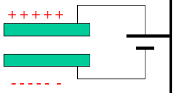
Polymers

- Polymers are typically good insulators but can be made to conduct by doping.
- A few polymers have very high electrical conductivity - about one quarter that of copper, or about twice that of copper per unit weight.

Capacitance

When a voltage V is applied to two parallel conducting plates, the plates are charged by +Q, –Q, and an electric field E develops between the plates.

The charge remains on the plates even after the voltage has been removed.



The ability to store charge is called **capacitance** and is defined as a charge Q per applied voltage V:

$$C = Q / V \quad \text{[Farads]}$$

For a parallel-plate capacitor, C depends on geometry of plates and material between plates

$$C = \varepsilon_r \varepsilon_o A / L = \varepsilon A / L$$

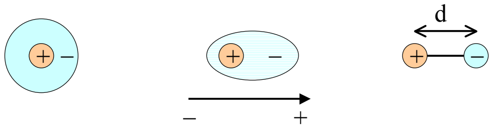
where A is the area of the plates, L is the distance between plates, ε is the **permittivity** of the dielectric medium, ε_o is the permittivity of a vacuum (8.85×10^{-12} F/m^2), and ε_r is **relative permittivity (or dielectric constant) of the material**, $\varepsilon_r = \varepsilon / \varepsilon_o = C / C_{vac}$

Dielectric Materials

The dielectric constant of vacuum is 1 and is close to 1 for air and many other gases. But when a piece of a dielectric material is placed between the two plates in capacitor the capacitance can increase significantly.

$C = \varepsilon_r \varepsilon_o A / L$ with ε_r = 81 for water, 20 for acetone, 12 for silicon, 3 for ice, etc.

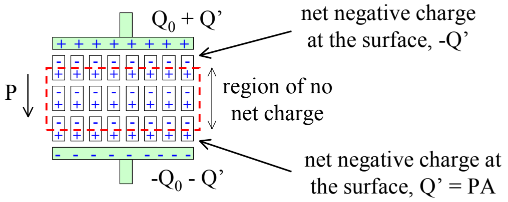
A **dielectric material** is an insulator in which **electric dipoles** can be induced by the electric field (or permanent dipoles can exist even without electric field), that is where positive and negative charge are separated on an atomic or molecular level



Magnitude of electric dipole moment is $p = q\,d$

Dielectric Materials

Dipole formation and/or orientation along the external electric field in the capacitor causes a charge redistribution so that the surface nearest to the positive capacitor plate is negatively charged and vice versa.



Dipole formation induces additional charge Q' on plates: total plate charge $Q_t = |Q+Q'|$.

Therefore, $C = Q_t / V$ has increased and dielectric constant of the material $\varepsilon_r = C / C_{vac} > 1$

The process of dipole formation/alignment in electric field is called **polarization** and is described by $P = Q'/A$

Dielectric Materials

In the capacitor **surface charge density** (also called **dielectric displacement**) is

$$D = Q/A = \varepsilon_r \varepsilon_o E = \varepsilon_o E + P$$

Polarization is responsible for the increase in charge density above that for vacuum

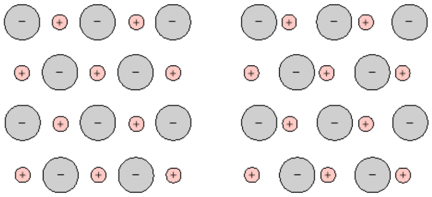
Mechanisms of polarization (dipole formation/orientation)

- **electronic** (induced) polarization: Applied electric field displaces negative electron "clouds" with respect to positive nucleus. Occurs in all materials.
- **ionic** (induced) polarization: In ionic materials, applied electric field displaces cations and anions in opposite directions
- **molecular** (orientation) polarization: Some materials possess permanent electric dipoles (e.g. H_2O). In absence of electric field, dipoles are randomly oriented. Applying electric field aligns these dipoles, causing net (large) dipole moment.

$$P_{tptal} = P_e + P_i + P_o$$

Mechanisms of polarization

electronic polarization



ionic polarization

molecular (orientation) polarization

Dielectric strength

Very high electric fields (>10^8 V/m) can excite electrons to the conduction band and accelerate them to such high energies that they can, in turn, free other electrons, in an avalanche process (or electrical discharge). The field necessary to start the avalanche process is called **dielectric strength** or breakdown strength.

Piezoelectricity

In some ceramic materials, application of external forces produces an electric (polarization) field and vice-versa

Applications of **piezoelectric** materials is based on conversion of mechanical strain into electricity (microphones, strain gauges, sonar detectors)

Piezoelectric materials include barium titanate $BaTiO_3$, lead zirconate $PbZrO_3$, quartz.

Summary

Make sure you understand language and concepts:

- Acceptor state
- Capacitance
- Conduction band
- Conductivity, electrical
- Dielectric constant
- Dielectric displacement
- Dielectric strength
- Diode
- Dipole, electric
- Donor state
- Doping
- Electrical resistance
- Electron energy band
- Energy band gap
- Extrinsic semiconductor
- Fermi energy
- Forward bias
- Free electron
- Hole
- Insulator
- Intrinsic semiconductor
- Ionic conduction
- Junction transistor
- Matthiessen's rule
- Metal
- Mobility
- MOSFET
- Ohm's law
- Permittivity
- Piezoelectric
- Polarization
- Polarization, electronic
- Polarization, ionic
- Polarization, orientation
- Rectifying junction
- Resistivity, electrical
- Reverse bias
- Semiconductor
- Valence band