EEE105 - Electronic Devices
Lecture 3

Insulators (or Dielectrics)

(CAL: INSUL – Insulators)

In an insulator, few if any electrons can escape from their bonds and become free to conduct.

A large energy is required to break the electrons free from the crystal bonds. This requires one to heat up the material till it is extremely hot (often the material will melt/decompose first!) or use very deep ultra-violet (UV) light.

A key application of Insulators is to place them between conductors to prevent shorting. Another is their use in Capacitors, because of POLARISATION.

See also EEE101, EEE220

Briefly: The electric field between two capacitor plate with a voltage applied causes a separation of charges in the atoms

The dielectric in an electric field experiences a polarisation. This will appear as a displaced surface charge (not mobile) opposite to the plate charge. However in a capacitor we need a certain amount of total charge to get the right field on the capacitor. This means that we need ***more charge*** on the plates

As $C = Q/V$

This means that C must increase with the dielectric present:

$$C = \frac{\varepsilon A}{d} \quad , \quad \varepsilon = \varepsilon_0 \, \varepsilon_r$$

Where A is the area of the capacitor plates and d the plate separation. The dielectric has a relative permittivity greater than 1, which causes the capacitance to increase.

Insulators and Capacitance

From above we can see that the presence of a dielectric between two parallel plates will modify its capacitance. The modification depends on the type of distortion that the electric field induces. In particular the value of ε_r is frequency dependent.

The frequency response for electronic changes (to the electron cloud around an atom) can be very fast (around 10^{15} s^{-1}). For ionic changes (where ionically bound atoms move) it is a slower (around 10^9 s^{-1}) and for structural dipoles, where the molecules may have to move the frequency is much slower at around 10^4 s^{-1}.

Rotating dipoles takes energy – which gives a loss which can appear as a resistive component to the impedance.

Another issue in considering Dielectrics in capacitors is breakdown. Under high E fields the few free electrons (and there will always be some) can be accelerated to high enough velocities such that when they collide with other electrons they are released from their bonds to. This process leads to a rapid rise in the density of free electrons and hence a rapid rise in current.

These breakdown Electric fields can vary widely with materials, but values of up to 10^9 Vm^{-1} have been observed.

The key issues in choosing suitable dielectrics for capacitors are:

Capacitor Example

A parallel plate capacitor has a spacing 100 μm between the plates, with air between them. If a dielectric of relative permittivity $\varepsilon_r = 10$, is to be placed between the plates, what should the spacing be changed to to leave the capacitance unchanged. The dielectric has a breakdown field of 50 MVm^{-1}, what is the maximum voltage that can be applied across this capacitor

Answer

To carry out the first part we need to use the relationship $C = \varepsilon_0 \varepsilon_r A \big/ d$. In state '1' the capacitor has no dielectric between the plates and in state '2' the dielectric is placed between the plates and *d* adjusted so that C remains the same.

To calculate the breakdown voltage, then we need to consider the field between the capacitor plate. There may be charges in the dielectric but overall the material will be neutral, hence the charge density ρ will be zero. From Poisson's Equation the field must therefore be a constant. As E between the plates we need simply to know at what voltage across the capacitor the breakdown field value is exceeded:

Conductivity in Solids

(CAL: physcon(a), physcon(b), driftsim, physcon(c))

In a solid free electrons are always moving around the crystal lattice. They move in one direction until they hit something (and impurity atom, crystal defect, or a lattice vibration) and then they set of in a new direction. So an electrons path will look like a RANDOM walk:

The energy that causes this motion is from the thermal energy of the system. This is the electron's thermal motion.

Thermal motion is random, so there is no NET (or average) motion of the electrons from one part of the material to another. Hence the current flowing = zero.

In order to obtain a net flow of current, we need to either:

Applying an Electric Field

When we apply an electric field the electrons, in addition to having thermal motion, are also accelerated in the field:

Note: Electrons are –ve charged so they accelerate in the opposite direction to the field. Hence there is now a net movement of electrons from left to right.

Therfore a current is flowing from

The extra velocity caused by the field (the average velocity of the electrons, or the velocity of the electron population, is called the ***drift velocity.***

In reality the thermal velocity (v_{th}) is much larger than the drift velocity (v_d). However, v_d leads to "***drift current"*** which the one we can measure and hence is the one we are interested in.

Key Points to Remember:

1. In an insulator charges cannot move freely, but their positions can be distorted if a field is applied.
   a. This distortion leads to a surface charge which opposes the applied field
   b. This effect leads to an increase in capacitance, as ε_r increases.
2. In a conducting material electrons are moving randomly about, changing direction when they collide
   a. However there is not NET movement of electrons therefore the current is zero
3. A net motion of free charges (= a current) can be obtained by either
   a. Applying an Electric field or having a concentration gradient in the charge density
4. Electron motion is in the OPPOSITE direction to current flow.