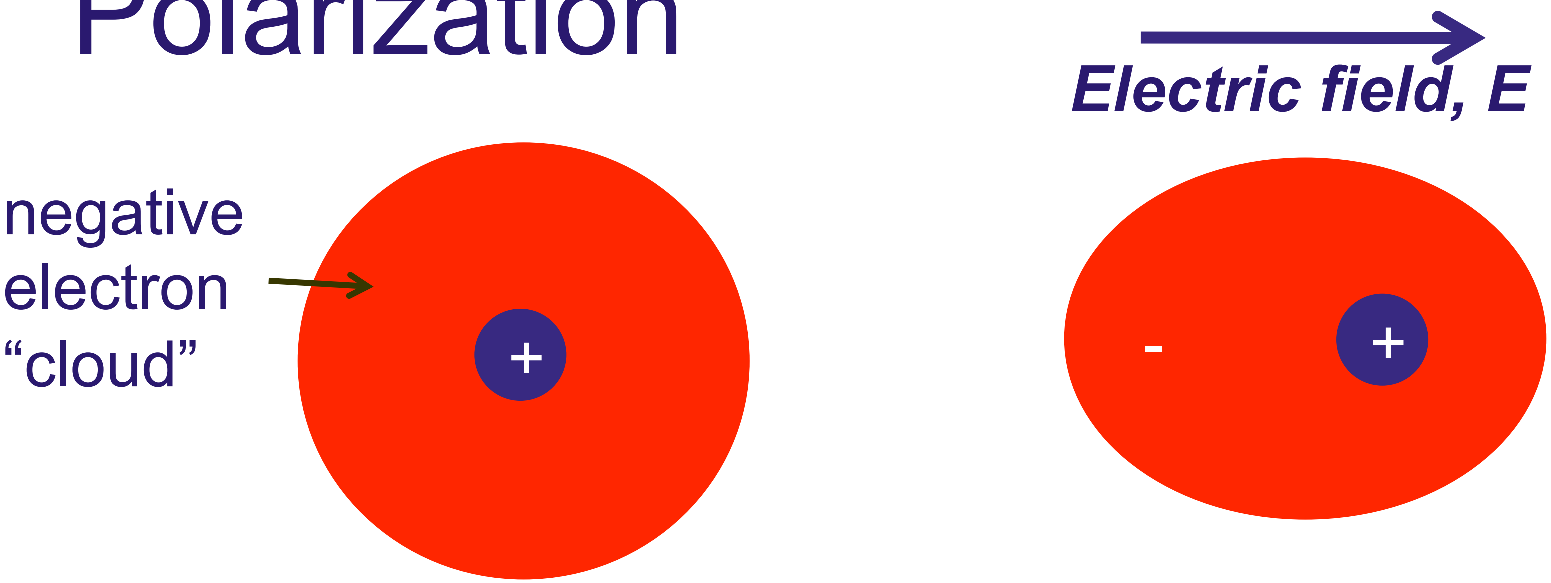
Lecture 2

- Insulator Review
- Polarization & Capacitors
- Conduction in Solids

Insulators

- Insulators – large amount of energy is required to promote electrons to the conduction band so that they can move around freely i.e. to break one of the bonds – the electron charge remains in the chemical bonds
- e.g. NaCl (salt), Al_2O_3 (aluminium oxide), C (diamond) etc.
- Insulators are used as dielectrics in capacitors and insulation between conductors

Polarization



- When an insulating solid is subject to an electric field, ***E***, there is a tendency for the positive and negative charge in the atoms to displace relative to one another so the solid has an *electric dipole moment*. The dipole moment per unit volume is the *polarization* ***P***.

$$\boldsymbol{P} = \varepsilon_0 \chi_e \boldsymbol{E}$$

ε_0 = permittivity of free space χ_e = electric susceptibility

Permittivity

- **Permittivity** ε - is an important physical property of a solid (dielectric medium) It is a measure of the ability of the material to polarize in response to the field and thereby reduce the total electric field inside the material.
- We usually compare the permittivity of a material to that in free space (i.e. vacuum), ε_0 (= 8.8× 10^{-12} F/m), through the relative permittivity, ε_r ($\varepsilon = \varepsilon_0 \varepsilon_r$)
- The permittivity of air is similar to the permittivity of free space (vacuum) so $\varepsilon_r = 1$ for air

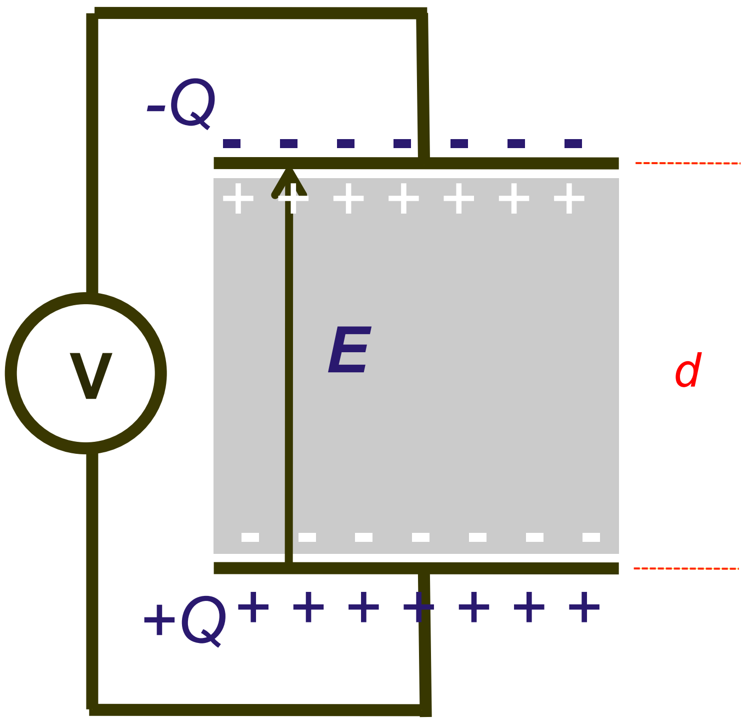
Polarization Mechanisms

- **Electronic or Induced Polarization** (last slide but one). Occurs in all dielectric materials – it has a fast frequency response to applied alternating E field ~10^{15} s^{-1} (easy to move light electrons as the field is reversed)
- **Molecular or Ionic Polarization** – In ionic crystals e.g. NaCl (salt) E field can shift sub lattice of Na^+ and Cl^- ions. Moderate frequency response ~10^9 s^{-1} (more difficult to move atoms or molecules as electric field is reversed)
- **Orientational Polarization** – can have a permanent dipole within a molecule (polar molecule) – e.g water, not important for solids.

The total polarization in a substance is the sum of all 3 components.

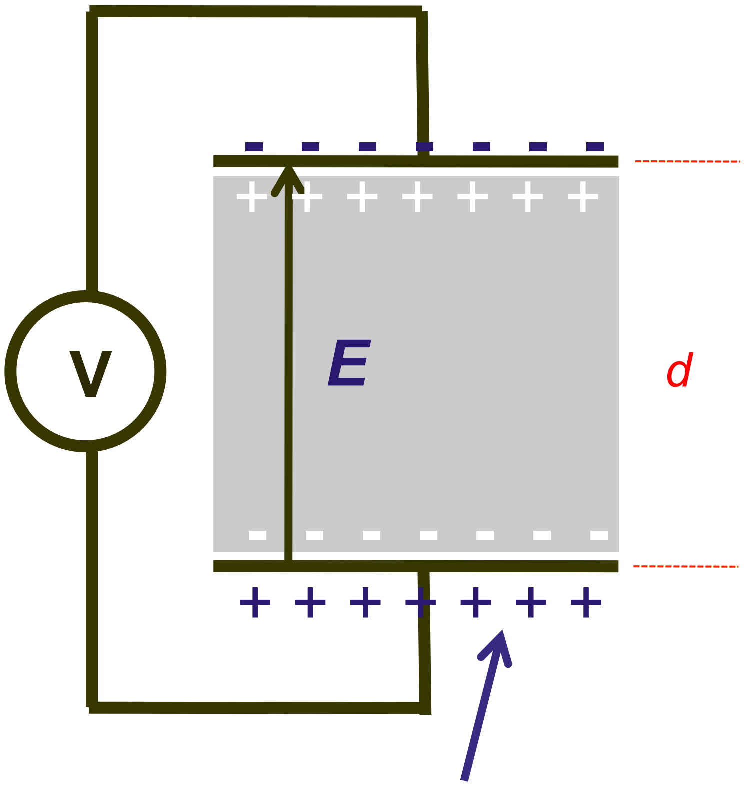
Changing polarisation direction in response to a changing E field takes energy – this energy loss appears as heat in solid and adds a resistive component to the equivalent impedance in capacitors.

Dielectric Capacitor



- Charge, Q, on plates maintains ***E***-field
- Capacitance is defined as $\boldsymbol{C = Q/V}$ (Farads) i.e. a measure of the "capacity" to store charge, Q, per unit voltage, V, across the plates
- When the ***E***-field is applied to the inserted dielectric, a polarization occurs which appears as extra charge on surface of dielectric
- The displaced surface charge induces equal and opposite ***extra*** charge (over and above that without the dielectric) on the capacitor plates
- Hence capacitance increases with dielectric insert

Dielectric Capacitor



Charge increases due to dielectric

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

$$C = \frac{\varepsilon A}{d}$$

for a parallel plate capacitor

$$where\ \varepsilon = \varepsilon_0 \varepsilon_r$$

For no dielectric, $C = \frac{\varepsilon_0 A}{d}$ *hence capacitance is enhanced by* ε_r*.*

A = area of plates
d = separation of plates
ε_r = relative permittivity of dielectric

Dielectric Breakdown

- What is it? - sudden increase in current above a critical electric field (e.g. in a capacitor)
- It is a limitation of the dielectric – capacitor or insulator becomes a short circuit i.e. conducts electric current
- Can be reversible & non-reversible (latter is catastrophic)
- Breakdown driven by the ***E***-field can be ~ 10^9 Vm^{-1} (very high)
- Ideally breakdown field should be as high as possible to enable large voltages to be applied to capacitors

Ideal Capacitor Dielectric

- High ε_r for large capacitance in a small area
- Breakdown only at very high fields (high voltage capability)
- Low cost
- Manufacturability into thin films
- Reliability

Capacitor Example

Q- A parallel plate capacitor has a spacing of 100 µm with air between the plates. If a dielectric film of relative permittivity ε_r =10 is placed between the plates what should the new spacing be to leave the capacitance unchanged?

$$C = \frac{\varepsilon_0 \varepsilon_{r1} A}{d_1} = \frac{\varepsilon_0 \varepsilon_{r2} A}{d_2}$$

giving –

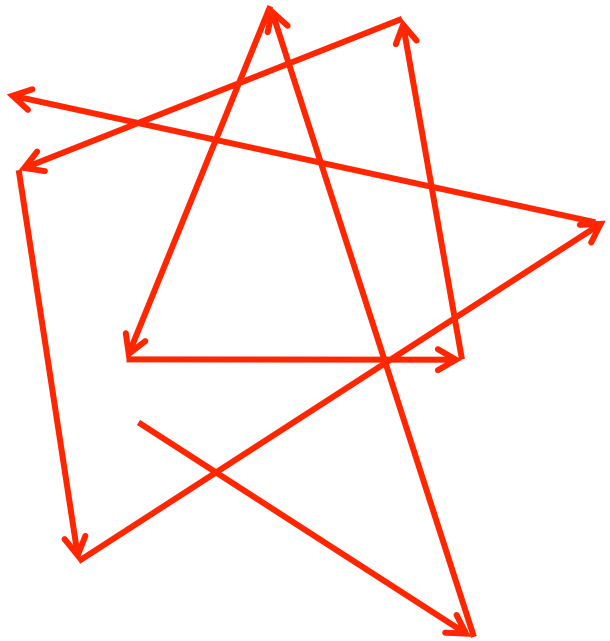
$$d_2 = \frac{\varepsilon_{r2}}{\varepsilon_{r1}} d_1 = \frac{10}{1}.1\mathrm{x}10^{-4}$$

$$d_2 = 1\mathrm{mm}$$

Where d_1 *and* d_2 are the distances between the plates without and with the dielectric

Free Electrons in Solids

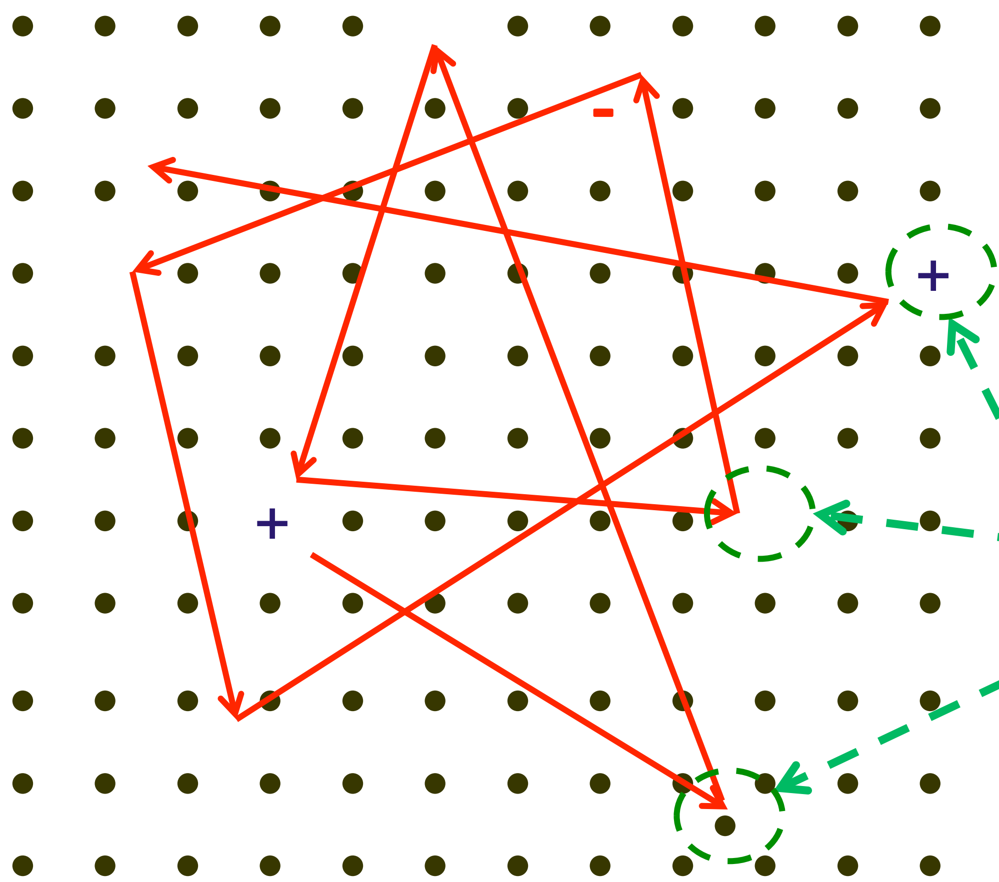
We said before that electrons in the conduction band of a semiconductor crystal can move around freely. What is the detail for this?



Imagine that we can visualise the motion of electrons in a crystal...

- Free electrons have thermal energy and move rapidly around the crystal in a random fashion from one collision to another – similar to Brownian motion for very small particles
- When we observe a large number of carriers we will see there is no net movement of charge in a particular direction – no net current or charge flow

Collisions with what?



The collisions are not from the crystal lattice itself – they can move freely within a perfect lattice

Collisions are from imperfections in the crystal lattice such as:

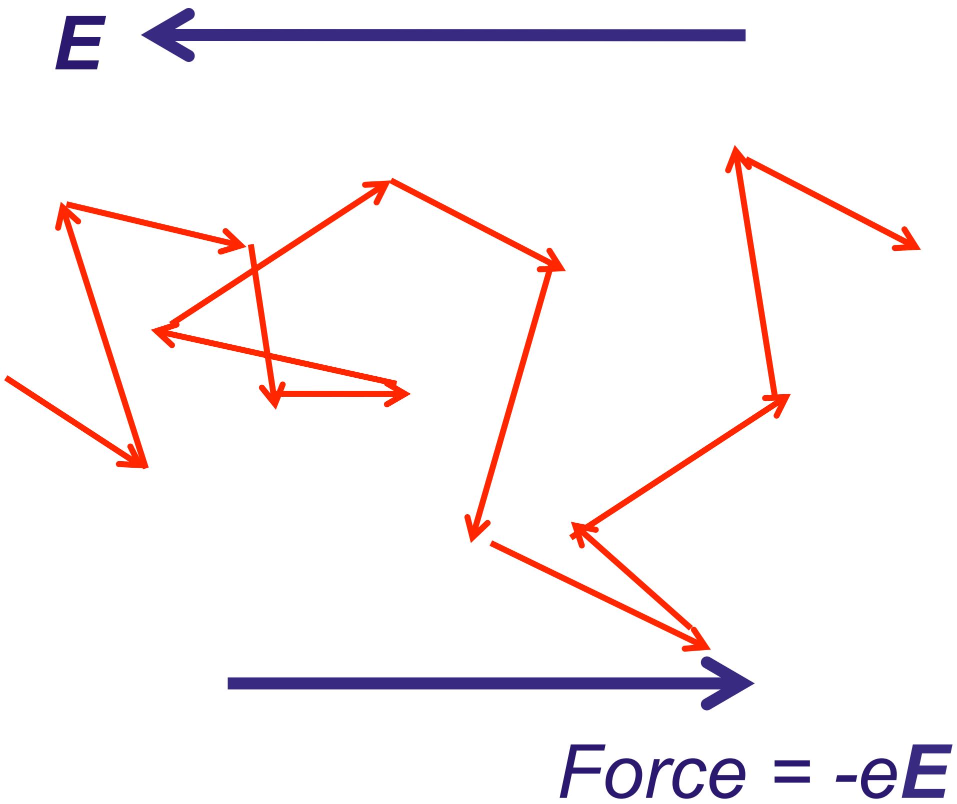
- Ionised (charged) impurities
- Vacancy defects (e.g. missing atoms)
- Interstitial defects (misplaced atoms)
- Phonons (thermal lattice vibrations)

What causes electric current in a conductor?

Three causes of net flow of charge (current).

- An electric potential (voltage) gradient dV/dx (i.e. an ***E***-field)
- An electron density gradient dn/dx (n = electron concentration)
- A temperature gradient dT/dx (T = temperature)

Applying an E-field



Scattering still occurs in an imperfect crystal – when we observe many electrons we see there is net motion of charge with an effective <u>*drift velocity opposite to the electric field*</u>

This arises because the number of random collisions in one direction is greater than in the other direction

This results in a net flow of charge i.e. electric current.

Summary

- In an insulator, electronic charge is bound into the atoms of the lattice and is not free to move around the crystal. However, their position can be distorted relative to the atomic nuclei if an ***E***-field is applied (polarisation)
    - This distortion leads to a surface charge which opposes the applied field
    - A dielectric layer between the plates of a capacitor causes an increase in capacitance by an amount ε_r
- In a conducting material without an electric field applied, electrons are moving randomly with no net movement of charge
- A net motion of free charge (i.e. a current) can be obtained with an applied potential energy (voltage) difference, an electron concentration gradient or a temperature gradient (n.b. potential energy gradient gives an ***E***-field)
- Note: the *convention* is that electron motion is in the opposite direction to current flow