EE334 – Electrical Properties of Materials

26 Lecture: pp. 168-177 4-6, 4-7, 4-8

Electrical types of materials;

1 Conductors – metals - high conductivity $\sigma >> 1$

2 Dielectrics – Insulators low conductivity $\sigma << 1$

3 Semiconductors – between the two

Perfect Conductor ➔ σ = infinity

Perfect insulator ➔ $\sigma = 0$

Homogeneous material: does not vary from point to point.

Isotropic material: parameters are independent of direction

What parameters

ε: electric permittivity

μ: magnetic permeability

σ: electrical conductivity

Why do conductors conduct? (Loose e- in outer shell)

Are these loosely attached e- stationary? (No)

How are they moving?

(Orbits, thermally driven, Brownian motion, catch and release by atoms)

What causes a current?

(Net drift of electrons, V=iR, potential difference causes an electric field, electric field causes a force on the e-, F=-qE)

F=ma➔a=F/m➔a=qE/m constant acceleration, getting faster and faster

Why don't the e- fly out of the wire? e- collide with atoms, slows them down, get net effective velocity (u_e)

$\vec{J} = \rho_V u_e$ the current density is the volume of charge times the drift velocity.

Conservation of momentum: the force times the time between collisions must be equal to the momentum

$\vec{F} = \dfrac{m\vec{u}_e}{\tau} = -e\vec{E}$ solve for the drift velocity: $\vec{u}_e = \dfrac{-e\tau}{m_e}\vec{E}$

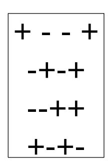
Sub this into the current density expression

$\vec{J} = \rho_V \left(\dfrac{-e\tau}{m_e}\right)\vec{E}$ the charge in a given volume is the number of electrons times the charge of an electron

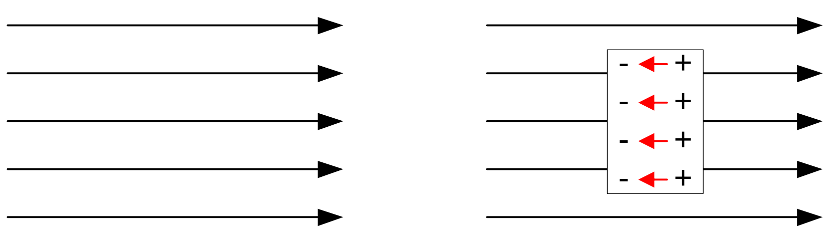
$\vec{J} = \left(\dfrac{Ne^2\tau}{m_e}\right)\vec{E} \Rightarrow \sigma\ \vec{E}$ point form of Ohm's Law(V=iR, i=V/R)

σ is the conductivity of the material, depends on the number of electrons, and the time between collisions with atoms, different for different materials

What happens when a perfect conductor is placed in an external E-field?



Charge migration



1 Charge migration
2 Induced surface charge
3 Induced internal field cancels external field

Inside a perfect conductor:

$\vec{E} = 0$ $\rho_V = 0$ $V_{ab} = 0$

Semiconductors

What are they? (allowed empty bands)

Why do we use them? (Can engineer them to have different properties)

n-type made by doping semiconductor crystal with atoms that have an extra free electron

p-type made by doping semiconductor crystal with atoms short an electron (holes)

by adding different materials to different regions can create an engineering circuit (p-n junction that has useful properties.

Places in the crystal lattice that are short an electron are called holes. These holes drift with an applied E-field just like electrons.

$$\vec{u}_h = \mu_h \vec{E}$$

The hole drift velocity is proportional to the electric field, the proportionality constant is the hole mobility, similarly the electron velocity is proportional to the electric field scaled by the electron mobility.

$$\vec{u}_e = \mu_e \vec{E}$$

It is easier for the electrons to move through the lattice than holes, so the mobility of electrons is larger than the mobility of holes.

$$\mu_h < \mu_e$$

There is also a current associated with the movement of holes

$$\vec{J}_h = \rho_h \vec{u}_h$$

The total current in a semiconductor is the sum of the hole and electron currents.

$$\vec{J}_T = \vec{J}_e + \vec{J}_h = \left(-\rho_e \mu_e + \rho_h \mu_h\right)\vec{E} = \sigma \vec{E}$$

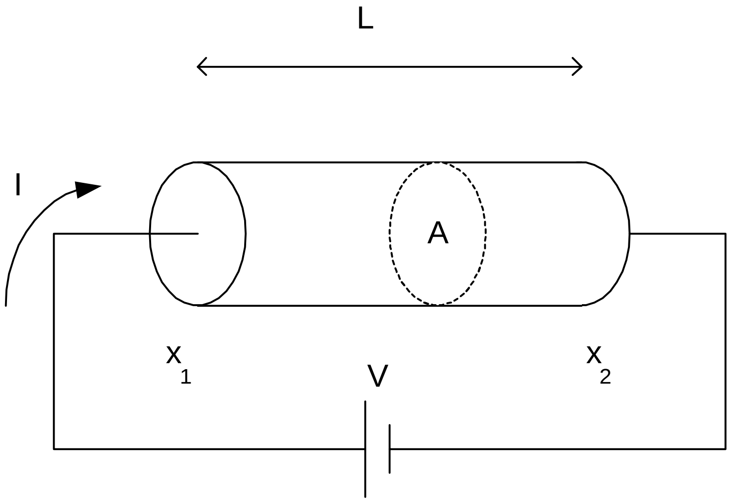
The conductivity of a semiconductor is from both electron and hole movement

$$\sigma = \left(-\rho_e \mu_e + \rho_h \mu_h\right) = \left(N_e \mu_e + N_h \mu_h\right)$$

The conductivity is related to the resistivity by: $\sigma = \dfrac{1}{\rho_c}$

Can use to calculate the resistance of a material.

Look at a bar of length L and cross sectional area of A, and place a potential across the material



Can calculate the potential across the bar and the current through the bar.

$$V = V_2 - V_1 = -\int_{x1}^{x2} \vec{E} \cdot d\vec{l} = E_x L$$
$$I = \int_A \vec{J} \cdot d\vec{S} = \int_A \sigma \vec{E} \cdot d\vec{S} = \sigma \; E_x A$$

Apply Ohm's Law: V=IR➔R=V/I

$$R = \frac{V}{I} = \frac{E_x L}{\sigma E_x A} = \frac{L}{\sigma \; A} \qquad (\Omega)$$

This assumes a uniform cross section if it varies over the length you must leave it in the integral form and integrate over the changing cross section.

$$R = \frac{\int \vec{E} \cdot d\vec{l}}{\int \sigma \; \vec{E} \cdot d\vec{S}}$$

The reciprocal of the resistance is the conductance (G)

$$G = \frac{1}{R} = \frac{\sigma \; A}{L}$$

Joule's Law

The energy required to move an electron (or hole) is the force times the distance or:

$$\Delta W = \vec{F}_e \cdot \Delta L$$

The power is the time rate of change of the energy. If both holes and electrons are considered then:

$$\Delta P = \frac{\Delta W}{\Delta t} = \vec{F}_e \cdot \frac{\Delta L_e}{\Delta t} + \vec{F}_h \cdot \frac{\Delta L_h}{\Delta t} = \vec{F}_e \cdot \vec{u}_e + \vec{F}_h \cdot \vec{u}_h$$
$$= \left(\rho_{Ve}\vec{E} \cdot \vec{u}_e + \rho_{Vh}\vec{E} \cdot \vec{u}_h\right)\Delta V = \left(\vec{E} \cdot \vec{J}\right)\Delta V$$

$$P = \int_V \left(\vec{E} \cdot \vec{J}\right) dV \qquad (W)$$

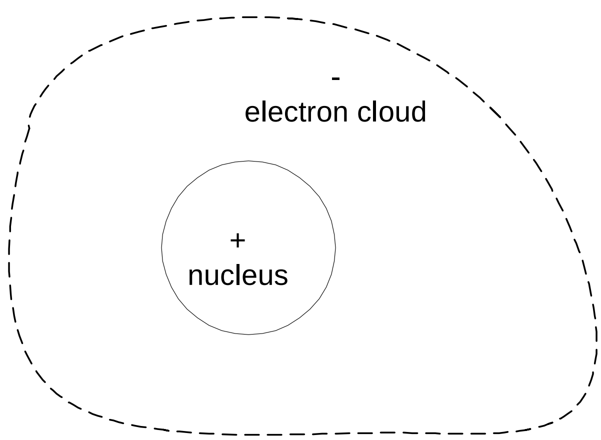
for uniform cross section $\quad dV = d\vec{S} \cdot d\vec{L}$

$$P = \int_L \vec{E} \cdot d\vec{L} \int_A \vec{J} \cdot d\vec{S}$$

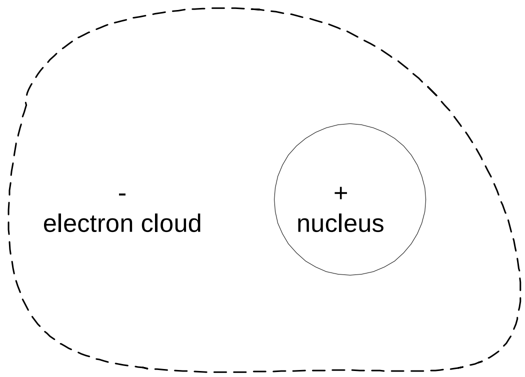
$$P = VI = I^2 R$$

Dielectric (insulators)

No mobile electrons



In an external electric field



can be modeled as a electric dipole therefore polarizes the atom. This perturbs the relationship between D and E

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P}$$

P is the electric polarization of the material.

If

1	linear	$\lvert\vec{P}\rvert \propto \lvert\vec{E}\rvert$
2	isotropic	$\vec{P} \parallel \vec{E}$
3	homogeneous	$\varepsilon \neq \varepsilon(x,y,z), \quad \mu \neq \mu(x,y,z), \ \sigma \neq \sigma(x,y,z)$

Then

$\vec{P} = \varepsilon_0 \chi_e \vec{E}$ $\qquad \chi_e \qquad$ Electric susceptibility

measure of how well does the material polarize in an external field.

$$\vec{D} = \varepsilon_0 \vec{E} + \varepsilon_0 \chi_e \vec{E} = \varepsilon_0 (1 + \chi_e) \vec{E} = \varepsilon \vec{E}$$
$$\varepsilon = \varepsilon_0 (1 + \chi_e) = \varepsilon_0 \varepsilon_r$$

the total permittivity is the permittivity of free space plus a susceptibility term or the total permittivity is scaled by the relative permittivity.

Free space $\quad \varepsilon_r = 1$
Conductors $\quad \varepsilon_r \sim 1$