EEE6212 "Semiconductor Materials" -Conduction Processes

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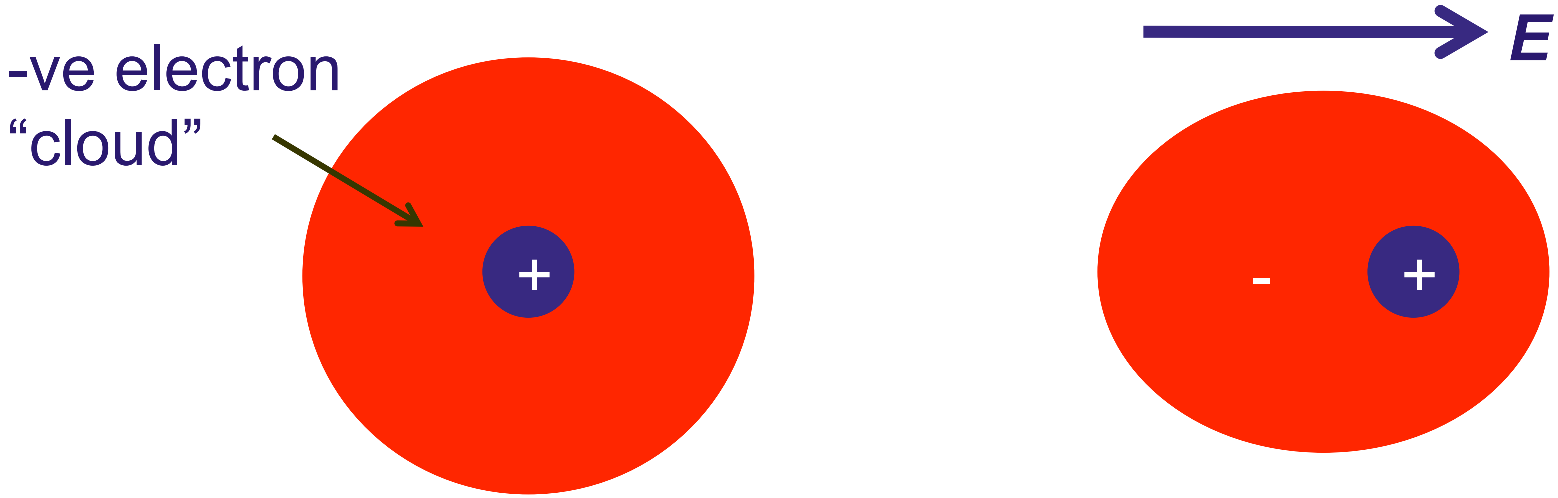
Polarization



- When a system is subject to an electric field, ***E***, there is a tendency of the +ve and –ve charge to displace relative to one another so the system has an electric dipole moment. The dipole moment per unit volume is the polarization ***P***. See EEE101.

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

ε_0 = permittivity of free space, χ_e = electric susceptibility

Permittivity and Susceptibility

- **Electric susceptibility χ_e** - measure of how easy it is to polarize a dielectric in response to an electric field
- **Permittivity, ε ,** is a physical property of a solid (dielectric medium). Measure of the ability of the material to polarize in response to the field, and thereby reduce the total electric field inside the material. It is a measure of how easily the material "permits" the electric field to propagate.
- We usually compare the permittivity of a material to free space (i.e. vacuum) ε_0 (= 8.8×10^{-12} F/m) through the relative permittivity ε_r
- The permittivity of air ~ permittivity of free space so $\varepsilon_r = 1$ for air

Polarization Mechanisms

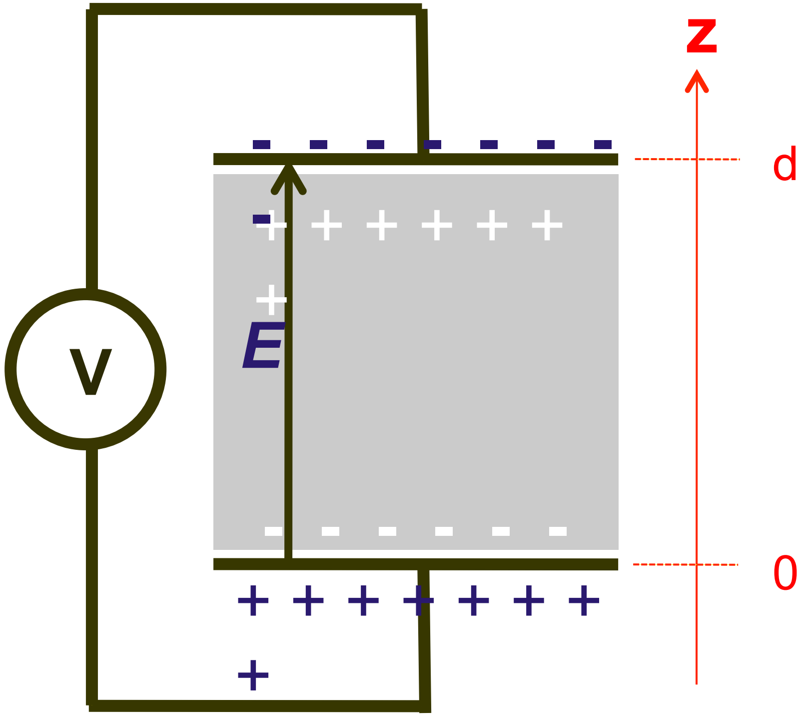
- **Electronic or Induced Polarization** (previous slide). All dielectric materials – fast frequency response ~10^{15} s^{-1}

- **Ionic Polarization** – In ionic crystals e.g. NaCl E field can shift sub lattice of Na^+ and Cl^- ions. Moderate frequency response ~10^9 s^{-1}

- **Orientational Polarization** – can have a dipole within a molecule (polar molecule). E field aligns randomly oriented dipoles causing net polarization. Important for liquids & gases. Slow frequency response ~10^4 s^{-1}

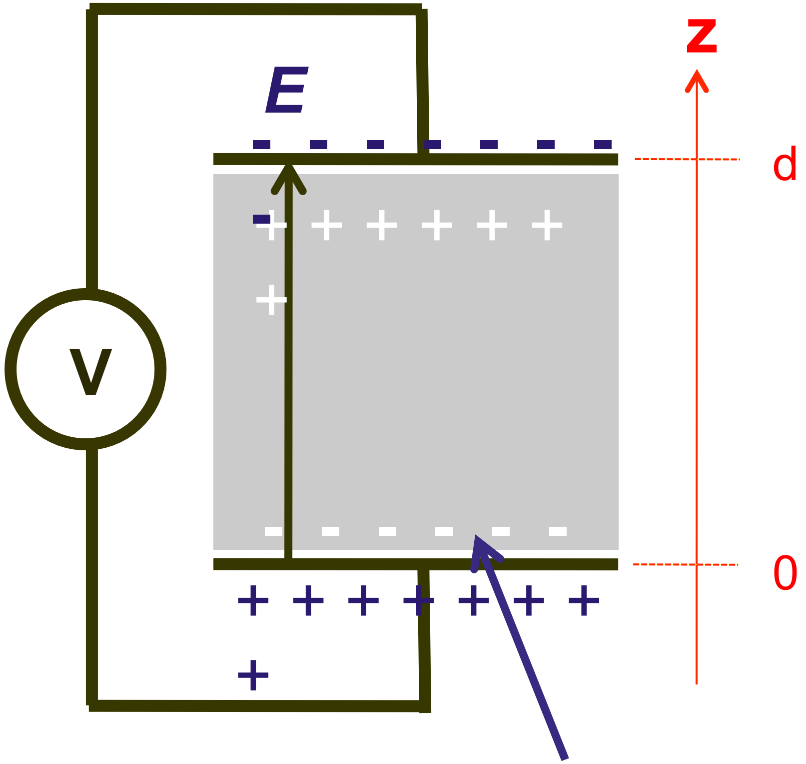
- Moving charge and molecules takes energy – loss appears as resistive component to impedance

Dielectric Capacitor



- In response to an ***E***-field a dielectric produces a polarization
- Displaced surface charge opposite the capacitor plates
- Charge on plates to maintain ***E***-field
- Capacitance, C=Q/V where Q = charge and V = voltage

Dielectric Capacitor



Charge per unit area = ρ

$$V = \int_0^d E\,dz = \int_0^d \frac{\rho}{\varepsilon}\,dz$$

$$= \frac{\rho d}{\varepsilon} = \frac{Qd}{\varepsilon a}$$

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

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

$$\text{where } \varepsilon = \varepsilon_0 \varepsilon_r$$

$\varepsilon_r =$ relative permittivity

Dielectric Breakdown

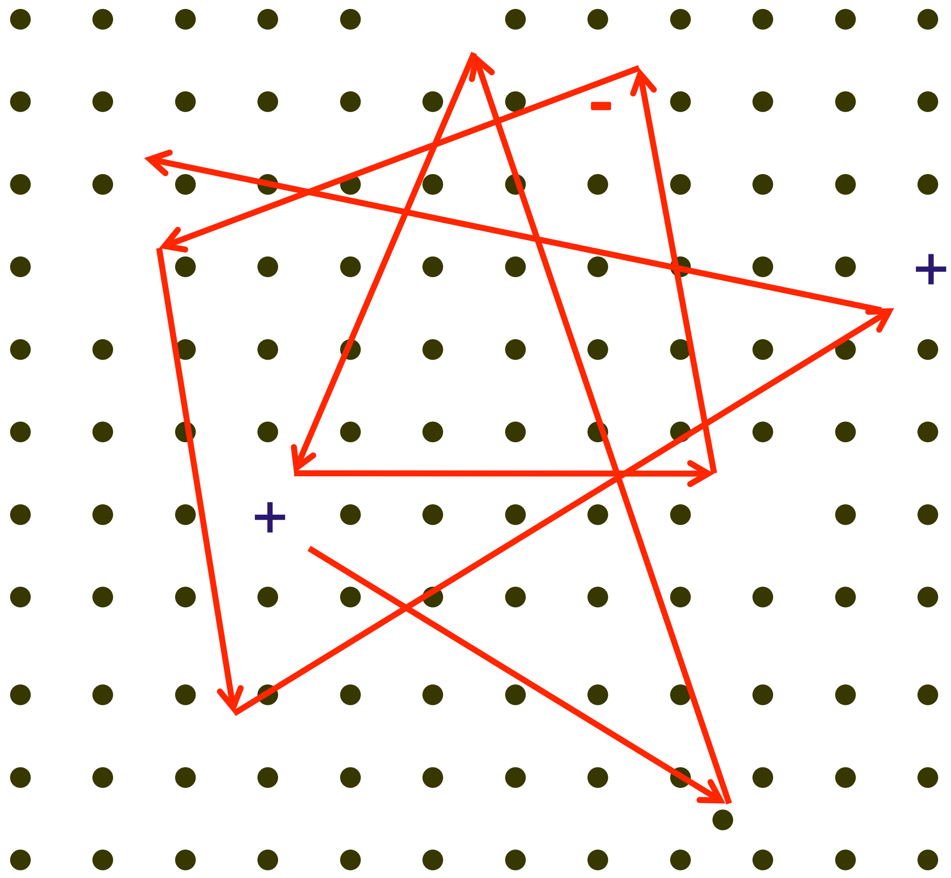
- Sudden increase in current above a critical electric field
- Limitation to dielectric – capacitor or insulator become a ~short circuit
- Reversible & non-reversible (=catastrophic)

- Breakdown E-field can be ~ 10^9 Vm^{-1}
- Ideally as high as possible

Ideal Capacitor Dielectric

- High ε_r
- Breakdown only at very high fields
- Low cost
- Manufacturability of thin films
- Reliability

Free Electron - Scattering



Imagine we can visualise the motion of electrons...

Free electrons -thermal energy– c.f. Brownian motion

Observe enough carrriers - no net movement of charge – no net current. Collisions from imperfections to crystal lattice

- Ionised impurities
- Interstitial defects
- Vacancy defects
- Phonons

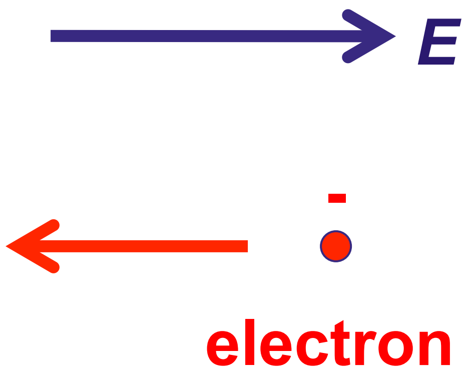
What causes a current?

Three causes of net flow of current

- An electric potential gradient dV/dx (i.e. an E-field)
- An electron density gradient dn/dx
- A temperature gradient dT/dx

Application of E-field

Force = - e E



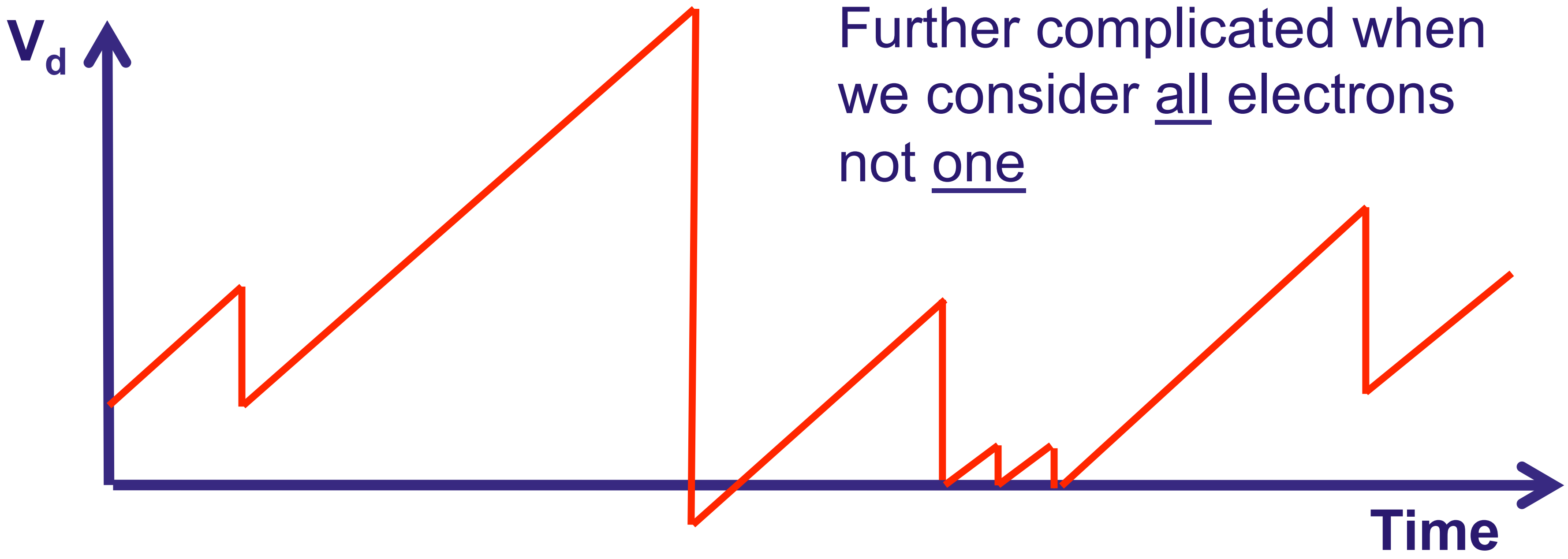
Electron acceleration?

- In vacuum we use Newton's laws $F = m_e A$
- In semiconductor just apply effective mass $F = m^* A$

- n.b. you need to be careful in using m* - some authors assume you know $m^* = m^* m_e$ (just like I do)

Drift Velocity

- Electron gains velocity as it is accelerated in E-field
- Electron can loose velocity when they are scattered



Further complicated when we consider all electrons not one

Derivation

- Solid with free electron concentration, *n* m^{-3}
- E-field applied, electrons will accelerate $a = \frac{-qE}{m^*}$
- Acceleration so velocity and momentum are changing. Rate of change of momentum with time for each electron

$$\frac{dp_e}{dt} = \frac{d\left(m^* v_d\right)}{dt} = m^* \frac{dv_d}{dt} = m^* a = F = -qE$$

- Rate of change of momentum, p, of all n electrons

$$\left(\frac{dp}{dt}\right)_{drift} = -qEn$$

Derivation (2)

- Electrons will accelerate until scattered
- Chance (or probability) that a particular electron will be scattered in unit time is a number between 0 and 1. For a large number of electrons this fraction will be scattered.

$$\text{Number scattered per unit time} = \frac{n}{\tau}$$

- Where τ is a time constant (= average time between scattering events)
- Assume that on average each scattering event causes the electron to loose all momentum (momentum at this instant = m^*v_d)
- Total change in momentum due to scattering events is;

$$\left(\frac{dp}{dt}\right)_{\text{scatter}} = \frac{\text{number scattering events}}{\text{time}} \times \text{momentum change}$$

Derivation (3)

- Where v_d is the average drift velocity of the electron population
- At equilibrium the total momentum change of the population is zero

$$\left(\frac{dp}{dt}\right)_{drift} + \left(\frac{dp}{dt}\right)_{scatter} = 0$$

- Hence

$$-qEn - \frac{n}{\tau} m^* \langle v_d \rangle = 0 \qquad \text{and} \qquad \langle v_d \rangle = -\frac{qE\tau}{m^*}$$

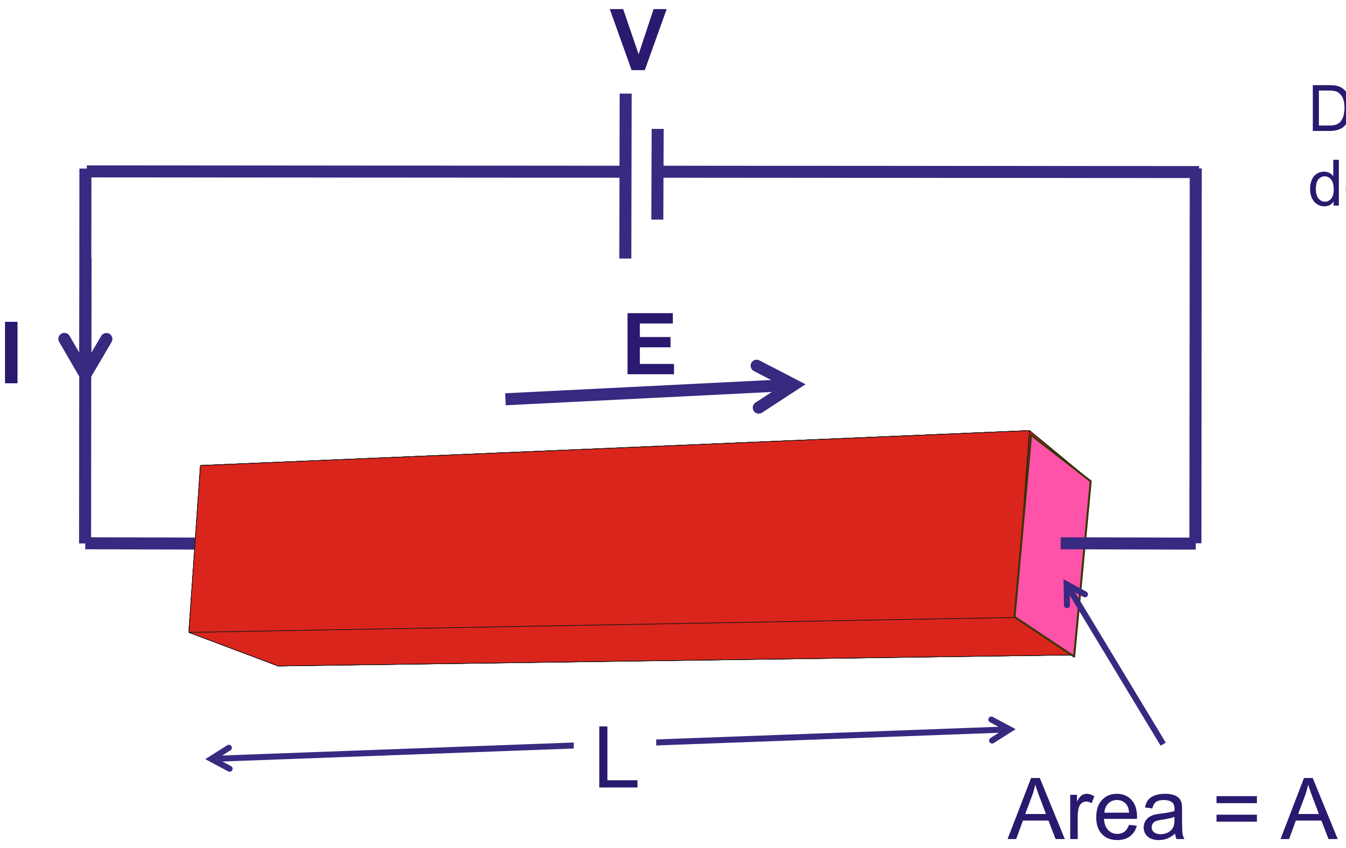
- n.b. Some text books derivations assume regular scattering events and obtain the approximate result in slide 8. This derivation is better.

Mobility, μ

- Drift velocity given by $\langle v_d \rangle = -\frac{q\tau E}{m^*}$
- Important parameter is average time between scattering events, τ
- Governed by impurity concentration, phonons, defects
- Effective mass also important – can simplify to one (easily measureable) material parameter the mobility, μ, to give;

$$\langle v_d \rangle = -\mu E \qquad \text{Where} \qquad \mu = \frac{q\tau}{m^*}$$

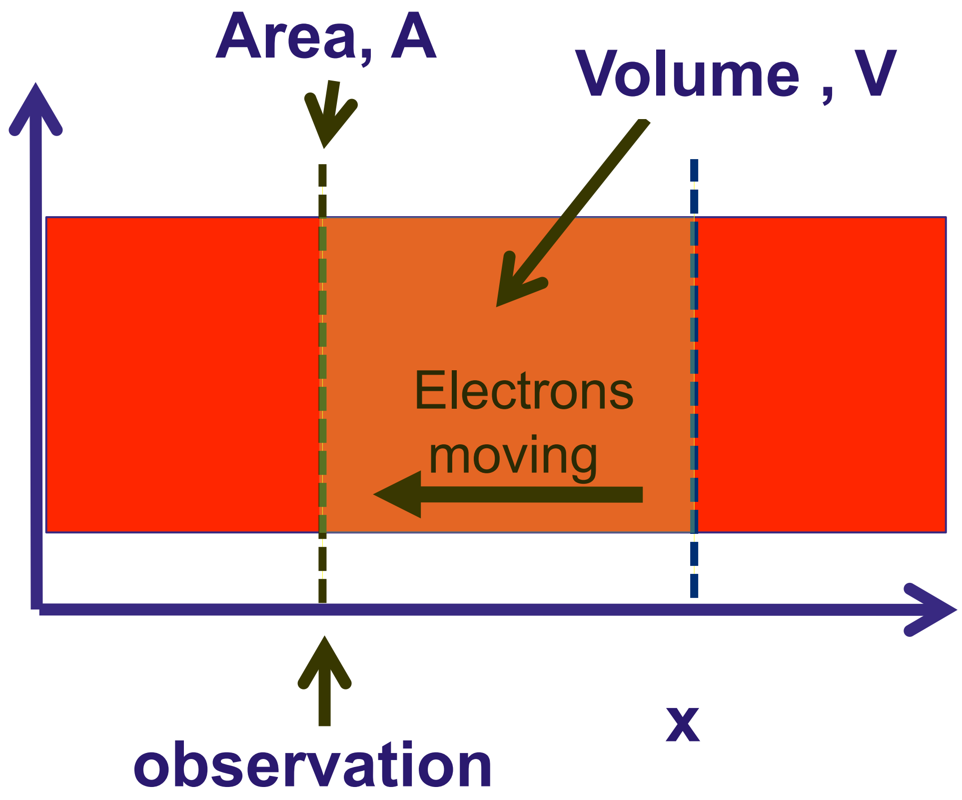
Solid with Free Electrons



Define a current density, J,

$$J = \frac{I}{A}$$

Longitudinal Slice



Have average velocity , v_d of electrons and density of electrons n

In time t, all electrons in shaded region will move past observation point

$\rightarrow \qquad x = v_d\, t$

Number of electrons in this volume is

$n\,V = n\,A\,x = n\,A\,v_d\,t$

Continued

- Charge on electron =-q ($q=1.6\times10^{19}$ C) so in unit time (a second) the amount of charge flowing past our observation point is the current $I = - n A q v_d$

The current density is given by; $J=I/A=-n q v_d$

n.b.

J and I in opposite direction to electron flow as expected

Sometimes drift velocity written as v or v_d

Sometimes charge on electron written as e or q

Often we use centimetres instead of metres .... be careful!

Eliminate V_d

- The previous equation is only useful if we now the drift velocity, which we have derived $v_d = -\mu E$

- Which gives $J = n\, q\, \mu\, E$
- So the current density in our solid depends upon
  - Carrier concentration - how many carriers
  - E-field – magnitude dv/dx
  - Mobility - how easy the carriers can move
  - (The charge on an electron not negotiable!)

Ohm's Law

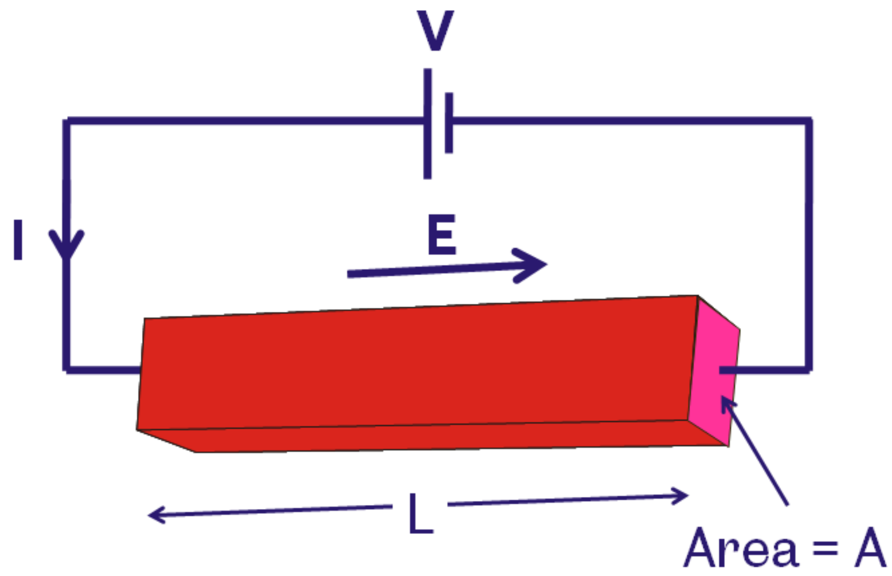
$J = n\,q\,\mu\,E$ Can be simplified to $J = \sigma E$

Where the conductivity $\sigma = nq\mu$

Conductivity is inverse of resistivity $\rho = \dfrac{1}{\sigma}$

This is the general form of ohm's law

Ohm's Law (2)



$$J = \frac{I}{A} \qquad E = \frac{V}{L} \qquad J = \sigma E$$

$$\frac{I}{A} = \frac{\sigma V}{L}$$

$$I = \frac{\sigma A V}{L}$$

(Ohm's law) is true if $R = \dfrac{L}{\sigma A}$

Extrinsic Semiconductor -Drift

Extrinsic Si
– p-doped with B to give

$p = 10^{21}\ m^{-3}$
$n \sim n_i = 10^{16}\ m^{-3}$

$\mu_e = 0.12\ m^2v^{-1}s^{-1}$
$\mu_h = 0.05\ m^2v^{-1}s^{-1}$

$$\sigma = nq\mu_e + pq\mu_h$$

Hole drift current >10^4 x electron drift current

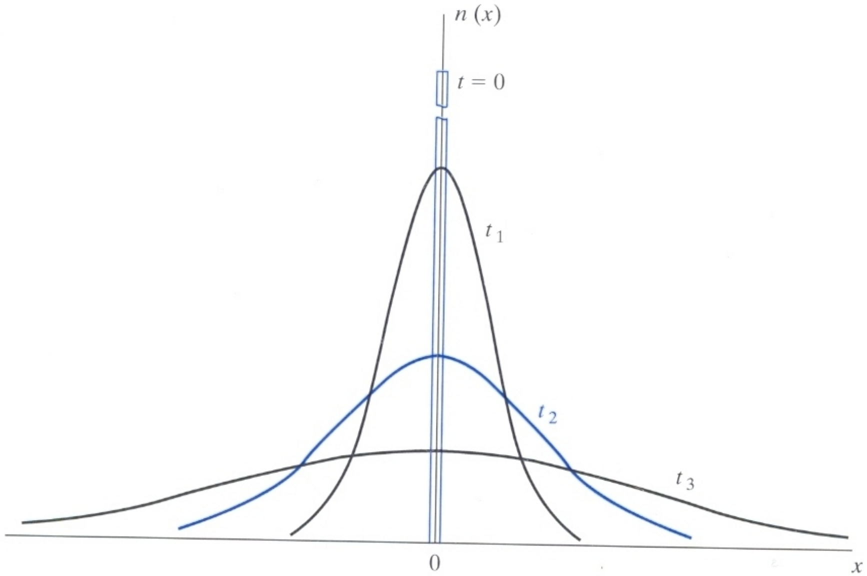
If doping is high – ignore minority carrier drift current

Sources of Current

Three causes of net flow of current

- An electric potential gradient dV/dx (i.e. an E-field)
- An electron density gradient dn/dx
- A temperature gradient dT/dx

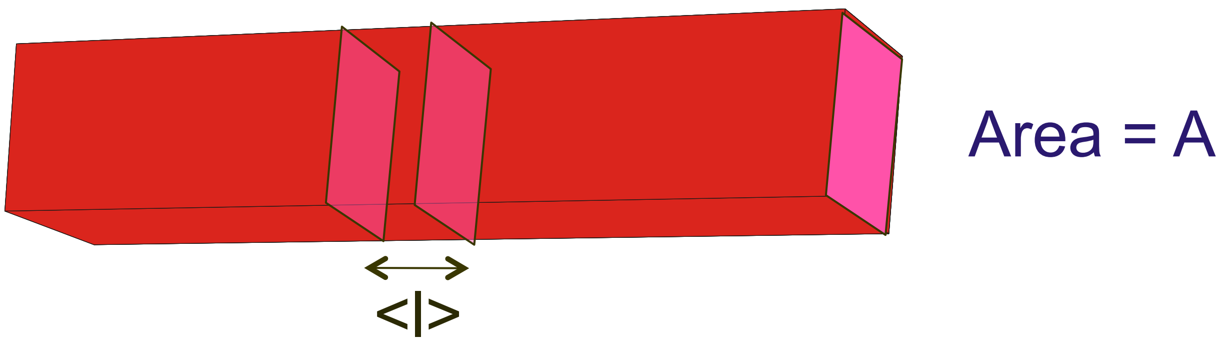
Diffusion - General



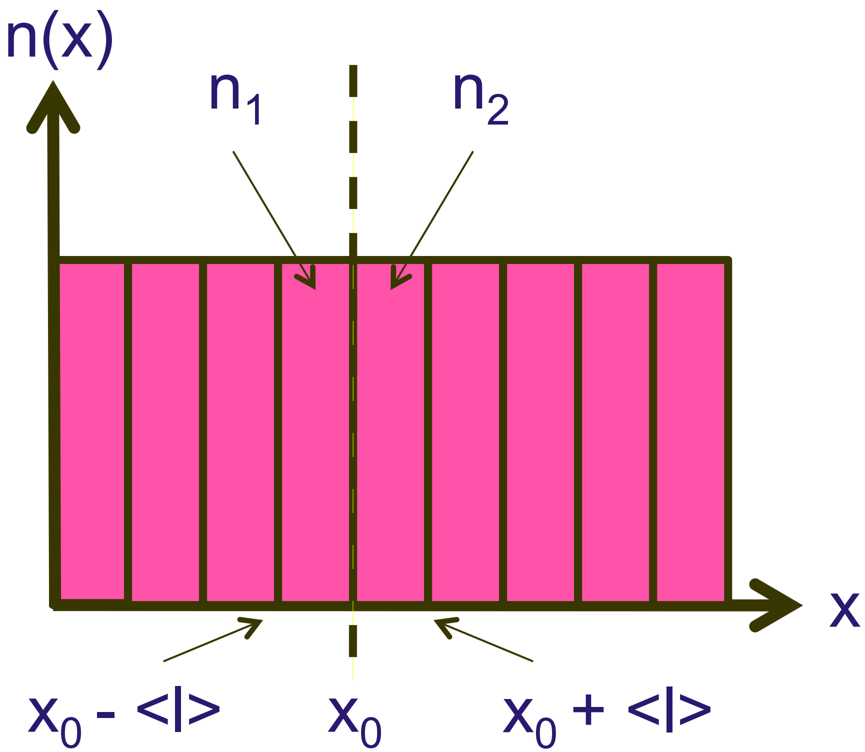
- Diffusion has been studied for a long time – salt in liquids, dust particles in air, population dynamics in biology, etc.
- Net flow (flux) of particles from high concentration to low concentration
- Acts to cancel out a non-uniform concentration distribution
- Governed by Fick's Laws

Mean free Path

- For a carrier population we have a mean velocity, and a mean scattering time.
- There is a mean distance the carrier travels before scattering (Distance = Velocity x time). Termed the mean free path = <l>
- Imagine a bar or rod we split into segments <l> wide



Uniform Carrier Distribution



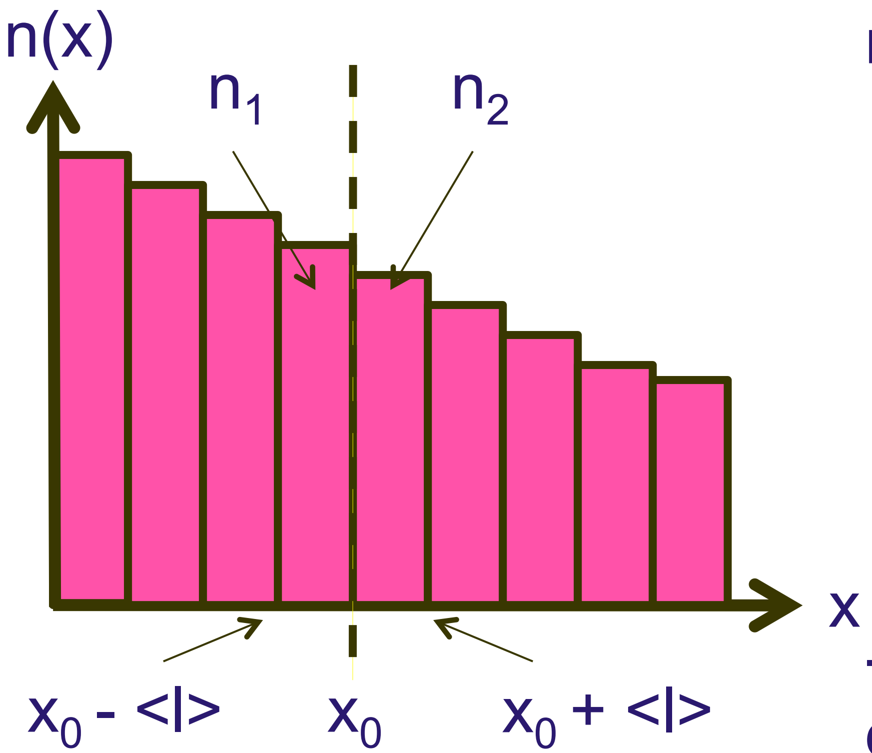
1D - Neighbouring segments of x_0

Concentrations n_1 and n_2

Half of all carriers moving +ve direction, half –ve direction

No net flow of charge – no current
- As many carriers from left to right as from right to left through x_0

Carrier Distribution Gradient



Carrier flux passing x_0 from left to right (see e.g. Streetman)

$$\varphi(x) = -D\frac{dn}{dx}$$

Concentration

Distance

Flux

Diffusion Coefficient

-ve sign as net motion is in direction of decreasing n

Electrons and Holes

- Must consider electrons and holes – electron and hole fluxes per unit area

$$\varphi_e(x) = -D_e \frac{dn}{dx} \qquad \varphi_h(x) = -D_h \frac{dp}{dx}$$

- Diffusion Current is carrier flux times charge (-q for elecrons, +q for holes)

$$J_e = qD_e \frac{dn}{dx} \qquad J_h = -qD_h \frac{dp}{dx}$$

Diffusion Coefficient

$$D_{e,h} = \frac{k_B T \mu_{e,h}}{q}$$

"Einstein relationship"

Diffusion Coefficient or Diffusivity, D is measure of how easily carriers diffuse

•D increases when T increases – more thermal energy

•D increases when mobility increases – less inhibition to motion

Drift and Diffusion

- E-field *and* carrier concentration gradient

$$J_e^{total}(x) = J_e^{drift} + J_e^{diffusion} = q\mu_e E_x n + qD_e \frac{dn}{dx}$$

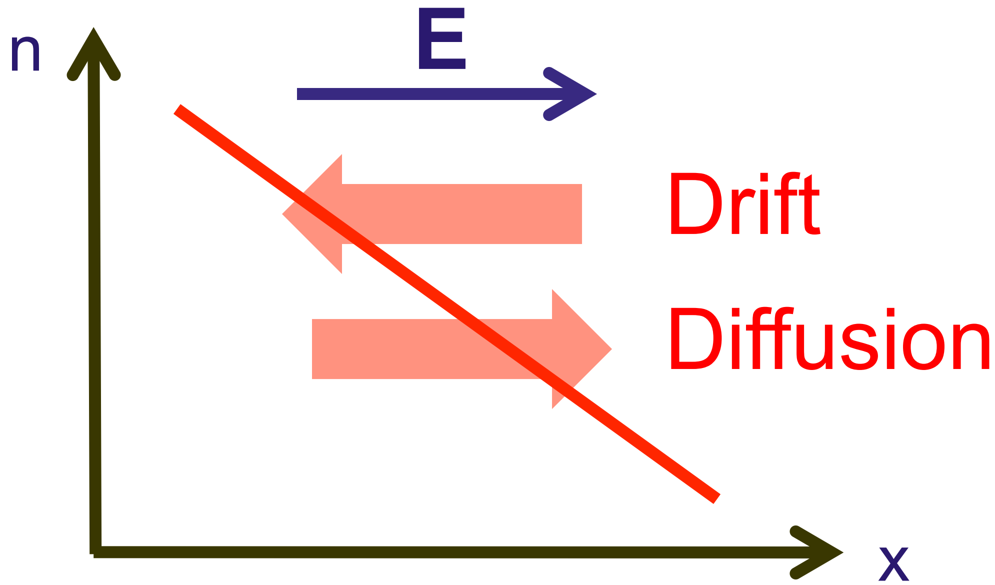
$$J_h^{total}(x) = J_h^{drift} + J_h^{diffusion} = q\mu_h E_x p - qD_h \frac{dp}{dx}$$

Minority Diffusion

- As drift current is proportional to carrier concentration, we know that minority carriers seldom provide much drift current and may often be ignored with little error
- As diffusion current is proportional to the *gradient* of carrier concentration, minority carrier diffusion currents can therefore be large

Drift Vs. Diffusion

- Consider case where there is a composition gradient *and* an E-field



$$J_e = q\mu_e E_x n + qD_e \frac{dn}{dx}$$

There is a case when J=0

$$E_x = -\frac{D_e}{n\mu_e}\frac{dn}{dx}$$

Carrier Concentration Gradients At Equilibrium

- Imagine a sample with carrier concentration – e.g. Vary doping in one direction
- At equilibrium there must be no net flow of current
- There is an *internal* field induced to ensure this is the case
- Varying doping concentrations results in built-in E-fields and potentials

Summary

- Discussed polarisation and capacitance
- Explored how a free electron is scattered within the crystal
- Discussed by drift and diffusion currents
  - Drift – E-field driven
  - Diffusion – carrier concentration gradient driven
- Combination of Diffusion and Drift – give rise to internal E-Fields

