EEE105
"Electronic Devices"

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Lecture 10

- Majority and Minority Carriers - Drift
- Diffusion Processes
  - Electron and hole flux
  - Electron and hole diffusion currents
  - Diffusion Coefficient
- Drift *and* Diffusion Currents
- Minority Diffusion
- Built in Fields

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

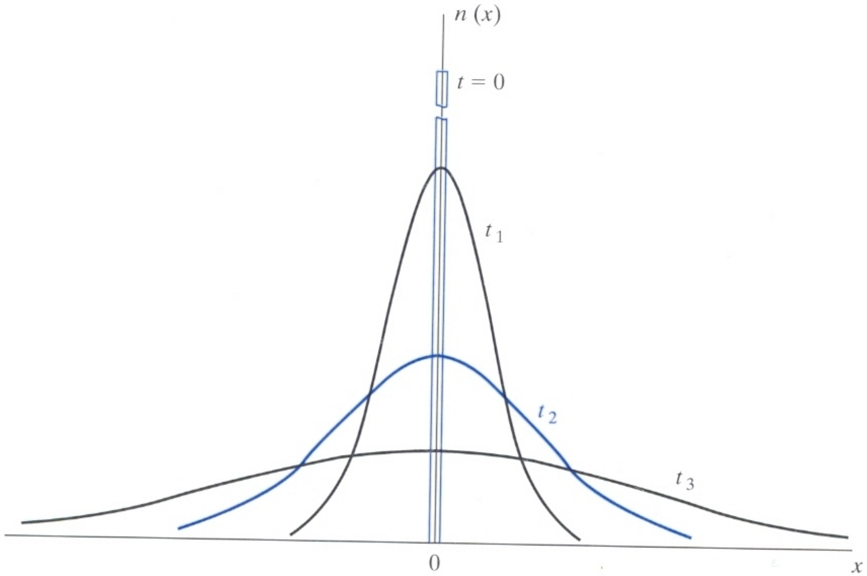
If doping is high – ignore minority carrier drift current

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

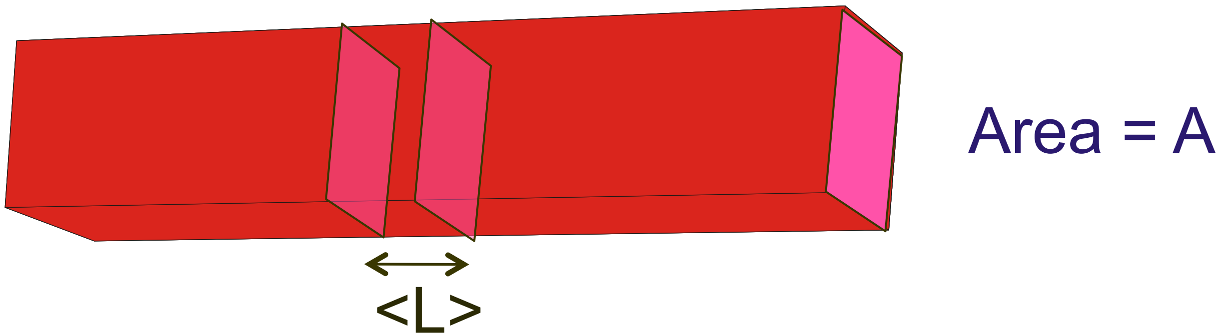
Diffusion - General



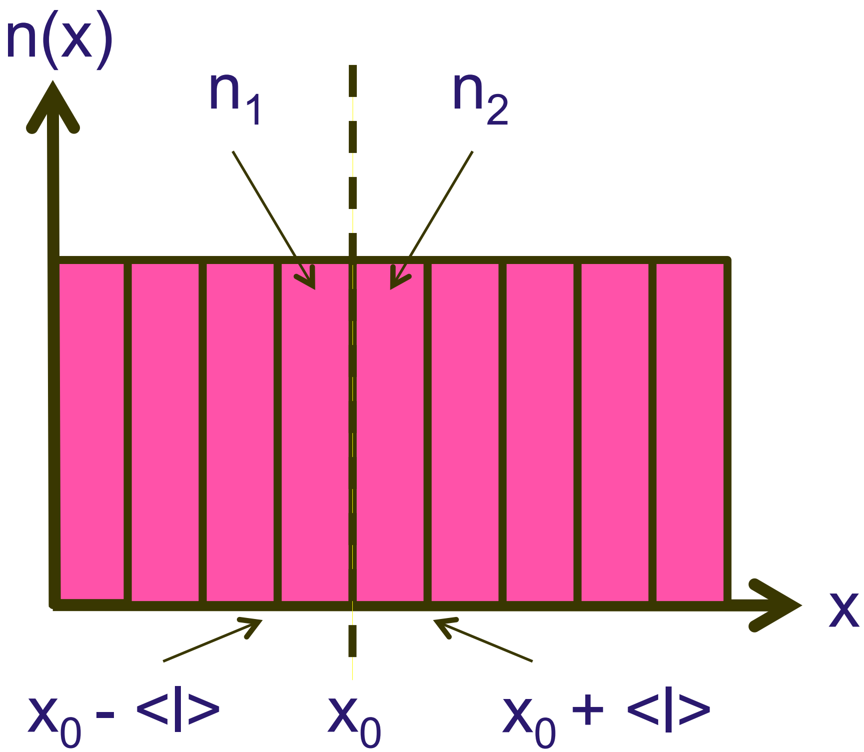
- Diffusion has been studied for a long time – salt in liquids, dust particles in air, population dynamics in biology, etc.
- Net flow (flux) of particles from high concentration to low concentration
- Acts to cancel out a non-uniform concentration distribution
- Governed by Fick’s Laws

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



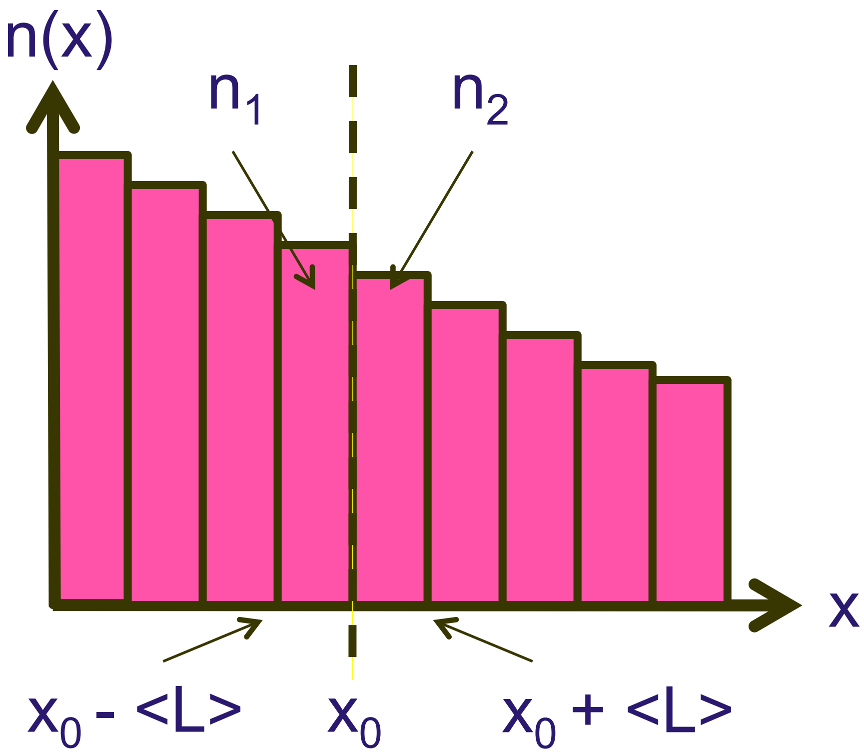
1D - Neighbouring segments of x_0

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 move from left to right as move 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

The University Of Sheffield.

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

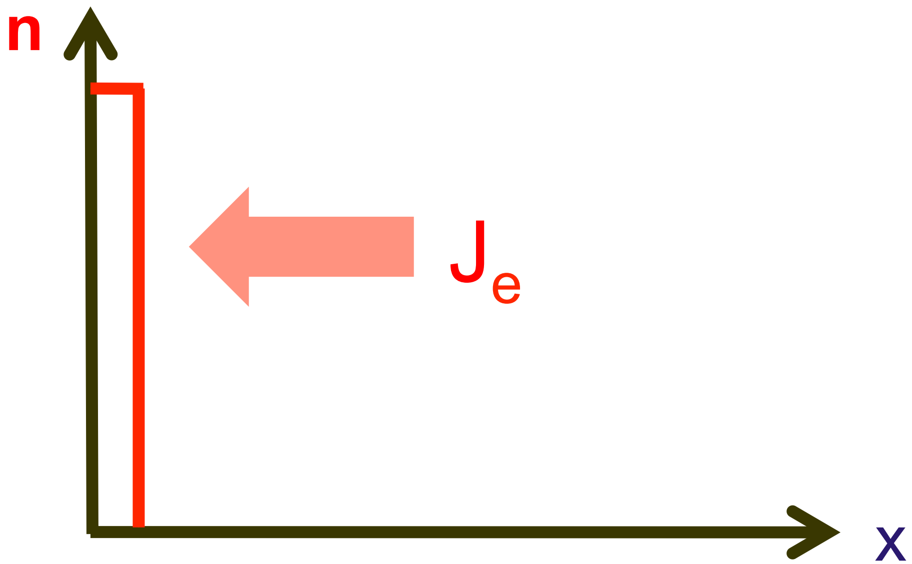
$$D_{e,h} = \frac{k_B T \mu_{e,h}}{q}$$

"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

Minority Carrier Diffusion Length

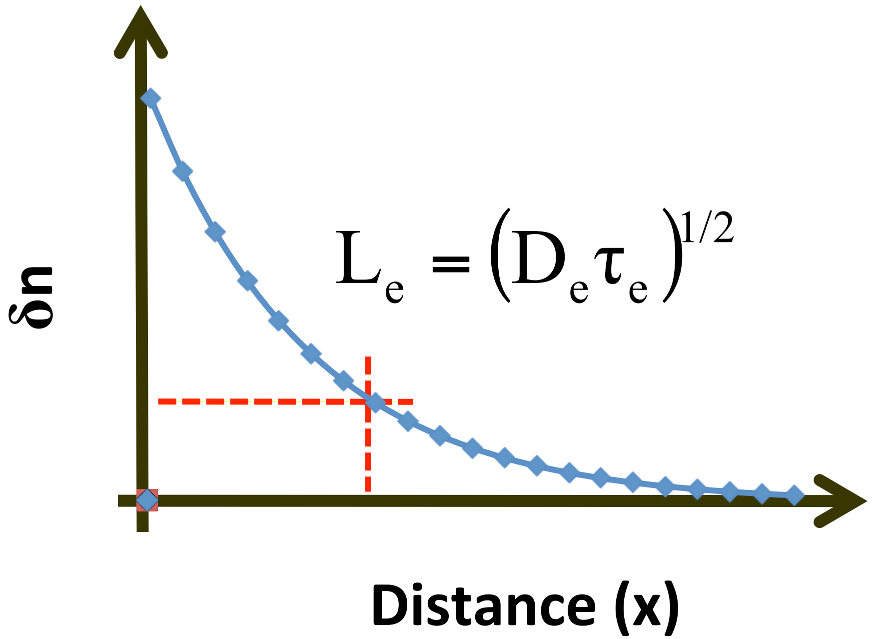


Introduce excess electrons to p-type block of semiconductor

Carrier concentration gradient brings about carrier diffusion and diffusion current J_e

Let's leave the supply of electrons on and look at the steady-state situation

Minority Carrier Diffusion Length



$$L_e = \left(D_e \tau_e\right)^{1/2}$$

$$\partial n(x) = \partial n_0 \exp\left(-\frac{x}{L_e}\right)$$

L_e is minority carrier diffusion length for electrons (replace subscripts for holes)

Drift and Diffusion

- E-field *and* carrier concentration gradient

$$\mathrm{J}_{\mathrm{e}}^{\mathrm{total}}(x) = \mathrm{J}_{\mathrm{e}}^{\mathrm{drift}} + \mathrm{J}_{\mathrm{e}}^{\mathrm{diffusion}} = q\mu_e E_x n + \mathrm{qD}_{\mathrm{e}} \frac{\mathrm{dn}}{\mathrm{dx}}$$

$$\mathrm{J}_{\mathrm{h}}^{\mathrm{total}}(x) = \mathrm{J}_{\mathrm{h}}^{\mathrm{drift}} + \mathrm{J}_{\mathrm{h}}^{\mathrm{diffusion}} = q\mu_h E_x p - \mathrm{qD}_{\mathrm{h}} \frac{\mathrm{dp}}{\mathrm{dx}}$$

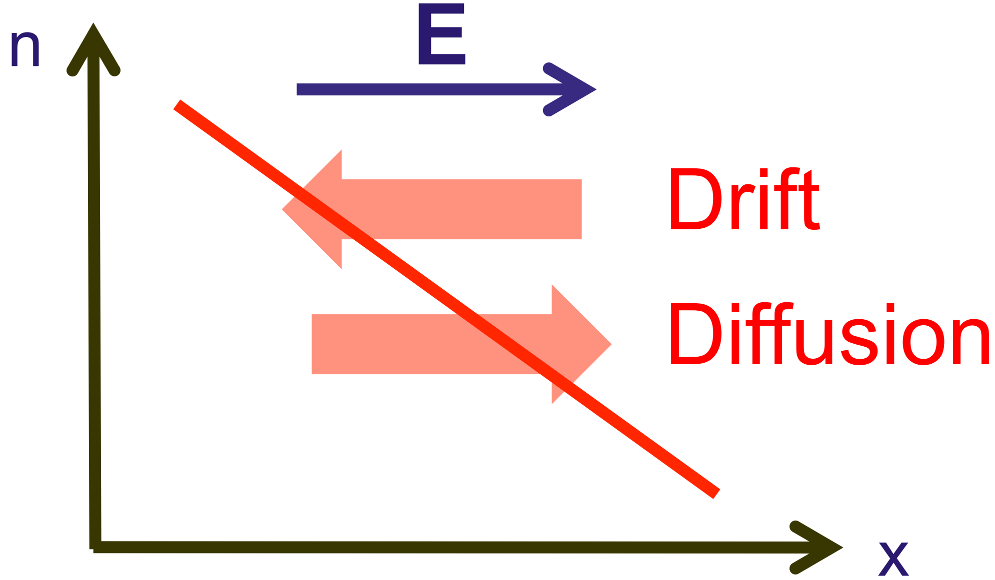
Minority Diffusion

- 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

- Minority carriers may have insignificant drift currents compared to majority carriers
- In addition to drifting in an E-field, a net motion of charge carriers can be obtained if the charge carrier density is non-uniform
- A net motion (flux) of charge carriers leads to a diffusion current
- The diffusion current at any point in a material is proportional to the concentration gradient of charge carriers
- Minority carriers can therefore have significant diffusion currents

Summary (2)

- With a carrier concentration gradient, drift and diffusion currents may be in opposite senses
- Excess minority carriers with a spatial variation have a characteristic diffusion length – governed by minority carrier lifetime and diffusion coefficient
- Under equilibrium (no applied voltage, no current, no temperature gradient, in the dark...) carrier concentration gradients, e.g. Via doping, can realise internal electric fields