Lecture 7

- 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 (Doped) Semiconductor

- Extrinsic semiconductors have so-called majority carriers coming from the doping and minority charge carriers from the thermal generation

- N-type semiconductor: Electrons are majority carriers and holes are minority carriers

- P-type semiconductor: Holes are majority carriers and electrons are minority carriers

- The minority carriers are generally much smaller in number compared to majority carriers

Extrinsic Semiconductor

Let's look at the example of p-type doping in Silicon doped with say, $10^{21}m^{-3}$ atoms of Boron.

- Majority hole concentration is $p = 10^{21}$ m^{-3} (at room temp we get all the holes from the acceptors)
- Minority electron concentration $n \sim n_i = 10^{16}$ m^{-3} thermally generated (see formula for n_i)
- Looking at conductivity:

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

With $\mu_e = 0.12$ $m^2v^{-1}s^{-1}$, $\mu_h = 0.05$ $m^2v^{-1}s^{-1}$, the hole component of conductivity (second term in above) is $>10^4$ times the electron conductivity ($\mu_h < \mu_e$ *but* $p >> n$)

Hence at typical doping levels we can ignore the minority carrier contribution to conductivity and drift current

Sources of Current

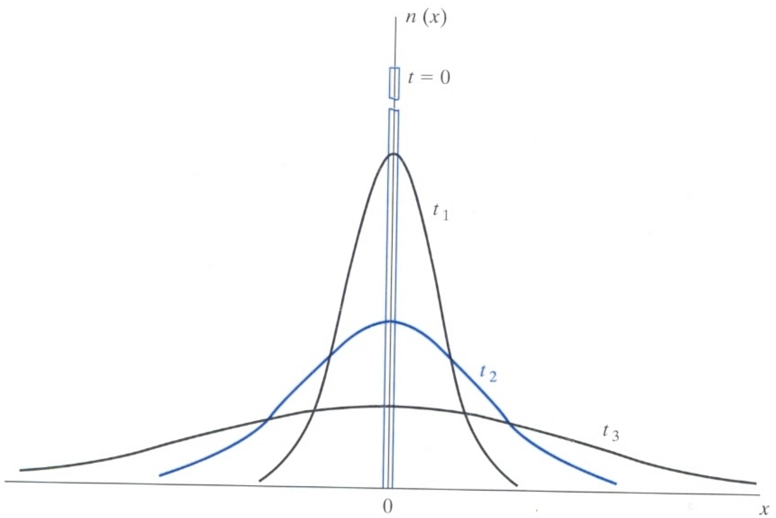
We mentioned three causes of net flow of current

1. An electric potential gradient dV/dx (i.e. an E-field)

2. An electron density gradient dn/dx

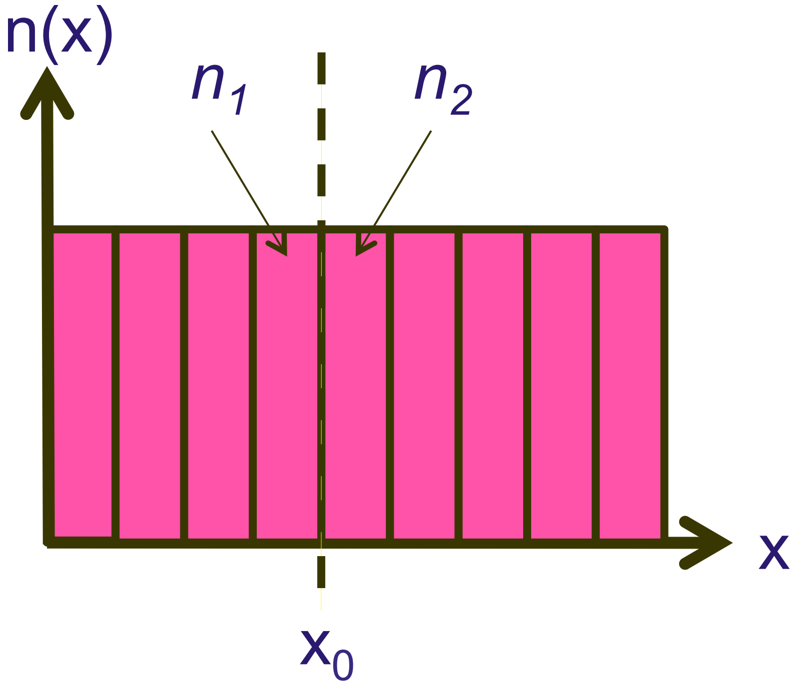
3. A temperature gradient dT/dx

Diffusion - General



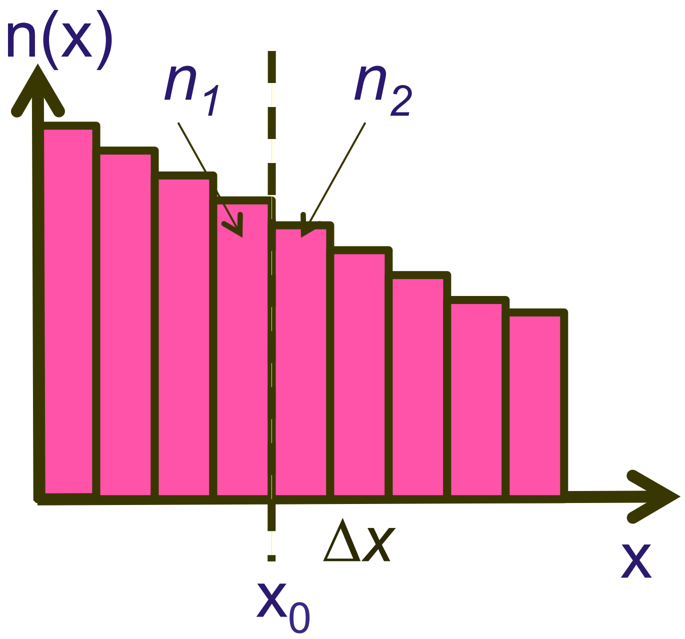
- Diffusion has been studied for a long time – salt in liquids, dust particles in air, population dynamics in biology, etc.
- Net flow (flux) of particles occurs from high concentration to low concentration
- Acts to cancel out a non-uniform concentration distribution
- Governed by **Fick's Law**

Uniform Carrier Distribution



- Concentrations n_1 and n_2 equal
- Individual carriers move in any direction
- Hence in one dimension half of all carriers move in +ve direction, half in –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



- This time $n_1 > n_2$
- Carrier flux, ϕ, passing x_0 from left to right

$$\varphi(x) \propto \frac{n_1 - n_2}{\Delta x}$$

If Δx small $\quad \varphi(x) = -D_e \frac{dn}{dx}$

Diffusion Coefficient

- This is Fick's Law
- -ve sign because net motion is in direction of decreasing n, i.e.

$$-\frac{dn}{dx}$$

Electrons and Holes

- In a semiconductor, we 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 (-e for electrons, +e for holes)

$$J_e = eD_e \frac{dn}{dx} \qquad J_h = -eD_h \frac{dp}{dx}$$

- Note: the sign of the carrier concentration gradient is important, i.e. $-\frac{dn}{dx}$ for a decreasing concentration with increasing x

Diffusion Coefficient, *D*

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

This is the Einstein relationship

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

- *D* increases when T increases – more thermal energy (the driving force for diffusion)

- *D* increases as the mobility increases – easier to move through lattice

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Drift *and* Diffusion together

We will often find carriers driven by both an ***E***-field *and* carrier concentration gradient

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

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

i.e. we must add the two contributions, paying attention to the sign of the conventional current

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Minority Diffusion

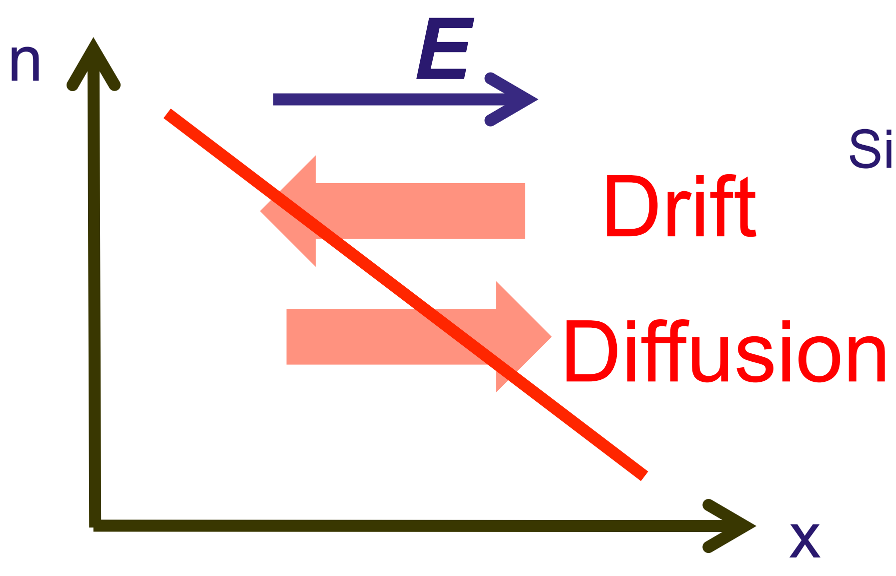
- Since drift current (due to an ***E***-field) is proportional to carrier concentration, we know that minority carriers (small compared to majority carries) seldom provide much drift current and may often be ignored with little error

- Since diffusion current is proportional to the ***gradient*** of the carrier concentration, minority carrier diffusion currents can therefore be large, even if the concentrations are small

Drift versus Diffusion

- Consider case where there is a concentration gradient *and* an ***E***-field in n-type

$$J_e = e\mu_e E_x n + eD_e \frac{dn}{dx}$$



Since the two current components are in opposite directions, there is a case when they exactly balance and $J_e=0$

That is when:

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

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Carrier Concentration Gradients at Equilibrium

- Imagine a sample with a doping concentration gradient – e.g. vary doping in one direction
- At *equilibrium* (no voltage and constant temperature) there must be no net flow of current
- There must be an ***internal*** field induced to balance the tendency of the carriers to diffuse
- Varying doping concentrations results in ***"built-in" E***-fields and potentials (i.e. not arising from external applied voltage)

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 have significant diffusion currents

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Summary (2)

- With a carrier concentration gradient, drift and diffusion currents may be in opposite senses
- Under equilibrium (no applied voltage, no current, no temperature gradient, in the dark...) carrier concentration gradients, e.g. from doping, can produce internal electric fields

Past notes and problems

- *http://hercules.shef.ac.uk/eee/teach/resources/first.html*

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