Week 13: Drift & Diffusion
Announcements

Drift & Diffusion of Carriers

- Last class we talked about qualitatively how drift and diffusion in a pn junction led to a built in voltage across the junction
- This built in voltage is what:
  – Causes a turn on voltage for diodes
  – Results in rectifying IV curve for a diode
  – Allows a solar cell to result in an output of current (rather than the solar generated electrons and holes recombining)

What causes diffusion?

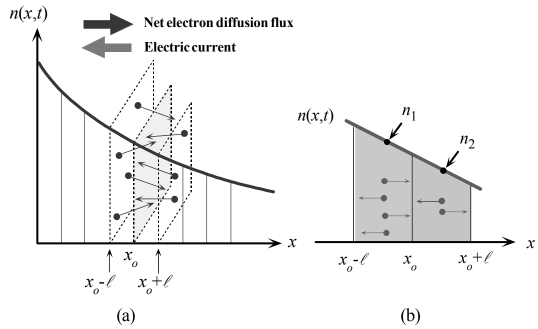

Fig. 5.29: (a) Arbitrary electron concentration $n(x,t)$ profile in a semiconductor. There is a net diffusion (flux) of electrons from higher to lower concentrations. (b) Expanded view of two adjacent sections at x_o. There are more electrons crossing x_o coming from left (x_o-ℓ) than coming from right (x_o+ℓ).

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Mathematical Look at Diffusion

$$\Gamma = \frac{\Delta N}{A \Delta t}$$

$$J = Q\Gamma$$

$$\Gamma_e = \frac{\frac{1}{2} n_1 \ell - \frac{1}{2} n_2 \ell}{\tau} = -\frac{\ell}{2\tau}\left(n_2 - n_1\right)$$

$$\left(n_2 - n_1\right) = \frac{dn}{dx}\Delta x = \frac{dn}{dx}\ell$$

$$\Gamma_e = -\frac{\ell^2}{2\tau}\frac{dn}{dx} = -D\frac{dn}{dx}$$

D for Electrons & Holes

Q=-e for electrons
+e for holes

$$J = Q\Gamma$$

$$\Gamma_e = -D_e \frac{dn}{dx} \longrightarrow$$

$$\Gamma_h = -D_h \frac{dp}{dx}$$

Einstein's Relation

- Einstein's relation relates the diffusion coefficient (D) of electron and holes to the electron and hole mobility

Photoconduction Example

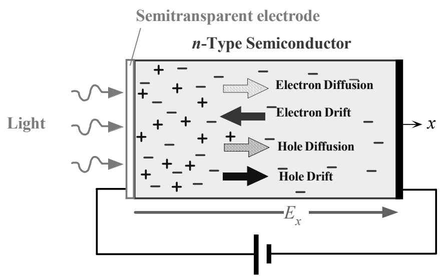

Fig. 5.31: When there is an electric field and also a concentration gradient, charge carriers move both by diffusion and drift. (E_x is the electric field.)

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Drift and Diffusion

- In photoconduction example:

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

$$J_h = ep\mu_h E_x - eD_h \frac{dp}{dx}$$

Resulting Built-in Voltage

- The built-in voltage results from the drift and diffusion terms equilibrating (canceling each other out)

$$J_e = en\mu_e E_x + eD_e \frac{dn}{dx} = -en\mu_e \frac{dV}{dx} + eD_e \frac{dn}{dx} = 0$$

$$e\frac{kT\mu_e}{e}\frac{dn}{dx} = en\mu_e \frac{dV}{dx}$$

$$\int_{V_1}^{V_2} dV = \frac{kT}{e}\int_{n_1}^{n_2}\frac{dn}{n}$$

$$V_2 - V_1 = \frac{kT}{e}\ln\left(\frac{n_2}{n_1}\right)$$

Continuity Equation

- We are also often concerned with a change in the carrier concentration with time
  - This is what results when carriers diffuse or drift away
- The continuity equation quantifies the change in carriers with time as a function of location
- Steady state continuity equation is when the total amount of carriers is conserved (none is being added or subtracted)

Continuity Equation for Holes

$$\frac{\partial p_n}{\partial t} = -\frac{1}{e}\left(\frac{\partial J_h}{\partial x}\right) - \frac{p_n - p_{no}}{\tau_h} + G_{\mathrm{ph}}$$

e = electronic charge (1.60218 x 10^{-19} C), J_h = hole current due to drift and diffusion, x = position, p_n = hole concentration in an *n*-type semiconductor, p_{no} = equilibrium minority carrier (hole concentration in an *n*-type semiconductor) concentration, τ_h = hole recombination time (lifetime), G_{ph} = photogeneration rate at x at time t, t = time

Continuity Equation with Uniform Photogeneration

$$\frac{\partial \Delta p_n}{\partial t} = -\frac{\Delta p_n}{\tau_h} + G_{\mathrm{ph}}$$

$\Delta p_n = p_n - p_{no}$ is the excess hole concentration, t = time, τ_h = hole recombination time (lifetime), G_{ph} = photogeneration rate at x at time t

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Steady State Decay in Minority Carrier Lifetime

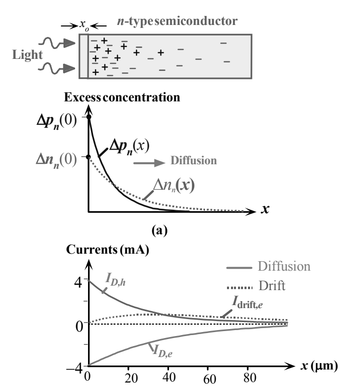

Fig. 5.34: (a) Steady state excess carrier concentration profiles in an *n*-type semiconductor that is continuously illuminated at one end. (b) Majority and minority carrier current components in open circuit. Total current is zero.

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Steady State Decay in Minority Carrier Lifetime

$$\frac{\partial p_n}{\partial t} = -\frac{1}{e}\left(\frac{\partial J_h}{\partial x}\right) = -\frac{p_n - p_{no}}{\tau_h}$$

$$\Delta p_n(x) = \Delta p_n(x=0)\exp\left(-\frac{x}{L_h}\right)$$

$$L_h = \sqrt{D_h \tau_h}$$