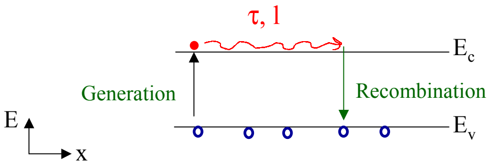
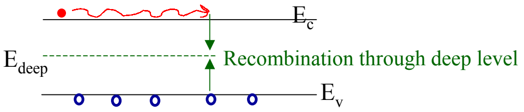
Minority Carrier Lifetimes, τ

- Minority carriers (e.g. electrons (minority carrier) in p-type material with majority holes
  - τ is the time to recombination: recombination time
  - means for system to return to equilibrium after perturbation, e.g. by illumination



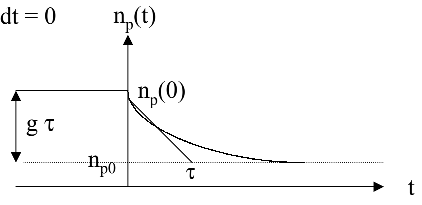
- Deep levels in semiconductors act as carrier traps and/or enhanced recombination sites



Generation and Recombination

- Generation
  - photon-induced or thermally induced, G=#carriers/vol.-sec
  - e.g. $g = P/h\nu$
  - G_o is the *equilibrium* generation rate
- Recombination
  - R=# carriers/vol.-sec
  - R_o is the equilibrium recombination rate, balanced by G_o
- Net change in carrier density:
  - $dn/dt = G - R = G - (n - n_0) / \tau = G - \Delta n / \tau$
  - Under steady state illumination: $dn/dt = 0$
  - $n_p(0) = n_{p0} + G\,\tau$

  After turning off illumination:
  - $\boxed{n_p(0) = n_{p0} + G\,\tau\, e^{-t/\tau}}$



Key Processes: Drift and Diffusion

Electric Field: Drift

$$I_h = epv_d A;\ \ J_h = ep\mu_h E$$
$$I_e = env_d A;\ \ J_e = en\mu_e E$$

Concentration Gradient: Diffusion

$$J_h = -eD_h \nabla p$$
$$J_e = eD_e \nabla n$$

$$J_{hTOT} = ep\mu_h E - eD_h \nabla p$$
$$J_{eTOT} = en\mu_e E + eD_e \nabla n$$

Electrochemical Potential

$\eta_j = \mu_j + z_j q\varphi$ Electrochemical Potential ⇒E_F

$\mu_j = \mu_j^0 + kT \ln c_j$ Chemical Potential

$\varphi =$ Electrostatic Potential

$$j_j = \left(\frac{-\sigma_j}{z_j q}\right)\frac{\partial \eta_j}{\partial x}$$
$$= \sigma_j \frac{\partial \varphi}{\partial x} - z_j q D_j \frac{\partial c_j}{\partial x}$$

Note: $\frac{\partial \eta_j}{\partial x} = 0$ Under equilibrium conditions

Continuity Equations

- For a given volume, change in carrier concentration in time is related to J

$$\frac{\partial n}{\partial t} = \left.\frac{\partial n}{\partial t}\right|_{drift} + \left.\frac{\partial n}{\partial t}\right|_{diff} - \left.\frac{\partial n}{\partial t}\right|_{R} + \left.\frac{\partial n}{\partial t}\right|_{G}$$

$$\frac{\partial n}{\partial t} = \frac{1}{e}\nabla \cdot J_{TOT} - \left.\frac{\partial n}{\partial t}\right|_{R} + \left.\frac{\partial n}{\partial t}\right|_{G}$$

$$\frac{\partial p}{\partial t} = -\frac{1}{e}\nabla \cdot J_{TOT} - \left.\frac{\partial p}{\partial t}\right|_{R} + \left.\frac{\partial p}{\partial t}\right|_{G}$$

1-D,

$$\frac{\partial n}{\partial t} = n\mu_e \frac{\partial E}{\partial x} + D_e \frac{\partial^2 n}{\partial x^2} - R + G$$

$$\frac{\partial p}{\partial t} = -p\mu_h \frac{\partial E}{\partial x} + D_h \frac{\partial^2 p}{\partial x^2} - R + G$$

Minority Carrier Diffusion Equations

- In many devices, carrier action outside E-field controls properties--> minority carrier devices
- Only diffusion in these regions

$$\frac{\partial n}{\partial t} = D_e \frac{\partial^2 n}{\partial x^2} - R + G$$

$$\frac{\partial p}{\partial t} = D_h \frac{\partial^2 p}{\partial x^2} - R + G$$

in n-type, $R = -\dfrac{\Delta p}{\tau_h}$

in p-type, $R = -\dfrac{\Delta n}{\tau_e}$

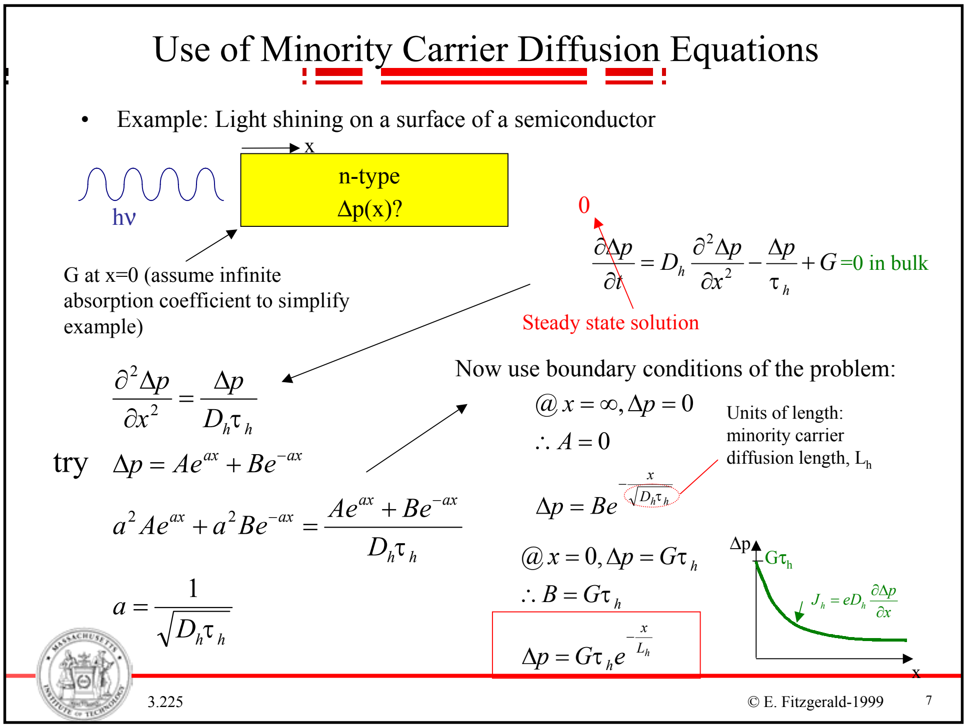
Assuming low-level injection,

$$\frac{\partial n}{\partial t} = \frac{\partial n_o}{\partial t} + \frac{\partial \Delta n}{\partial t} \approx \frac{\partial \Delta n}{\partial t}$$

therefore

$$\frac{\partial \Delta n}{\partial t} = D_e \frac{\partial^2 \Delta n}{\partial x^2} - \frac{\Delta n}{\tau_e} + \text{G in p-type material}$$

$$\frac{\partial \Delta p}{\partial t} = D_h \frac{\partial^2 \Delta p}{\partial x^2} - \frac{\Delta p}{\tau_h} + G \text{ in n-type material}$$



Use of Minority Carrier Diffusion Equations

- Example: Light shining on a surface of a semiconductor

x

hν

n-type

Δp(x)?

G at x=0 (assume infinite absorption coefficient to simplify example)

0

$$\frac{\partial \Delta p}{\partial t} = D_h \frac{\partial^2 \Delta p}{\partial x^2} - \frac{\Delta p}{\tau_h} + G = 0 \text{ in bulk}$$

Steady state solution

$$\frac{\partial^2 \Delta p}{\partial x^2} = \frac{\Delta p}{D_h \tau_h}$$

try $\Delta p = Ae^{ax} + Be^{-ax}$

$$a^2 Ae^{ax} + a^2 Be^{-ax} = \frac{Ae^{ax} + Be^{-ax}}{D_h \tau_h}$$

$$a = \frac{1}{\sqrt{D_h \tau_h}}$$

Now use boundary conditions of the problem:

$$@\, x = \infty, \Delta p = 0$$

$$\therefore A = 0$$

$$\Delta p = Be^{-\frac{x}{\sqrt{D_h \tau_h}}}$$

Units of length: minority carrier diffusion length, L_h

$$@\, x = 0, \Delta p = G\tau_h$$

$$\therefore B = G\tau_h$$

$$\boxed{\Delta p = G\tau_h e^{-\frac{x}{L_h}}}$$

Δp

$G\tau_h$

$J_h = eD_h \frac{\partial \Delta p}{\partial x}$

x

Semiconductor Electronics

- Single crystalline - largely Si
  some III - V compounds
- Dominated by many nearly identical, highly engineered junctions

  - DRAMS (today) ≈ 10^9 transistors
  - Microprocessors (2002) ≈ 10^8 transistors
  - Total ≈ 10^{18} yr ≈ 10^6/person/day

Junction Fabrication Processes

CMOS Devices

The p-n Junction (The Diode)

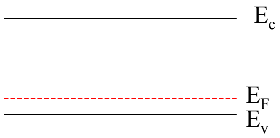
- Note that dopants move the fermi energy from mid-gap towards either the valence band edge (p-type) or the conduction band edge (n-type).

<u>p-type material in equilibrium</u>

$p \sim N_a$

$n \sim n_i^2/N_a$

$$E_F = -k_b T \ln\left(\frac{N_a}{N_V}\right)$$

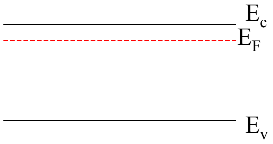


<u>n-type material in equilibrium</u>

$n \sim N_d$

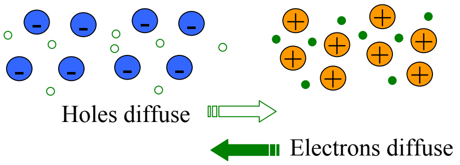
$p \sim n_i^2/N_d$

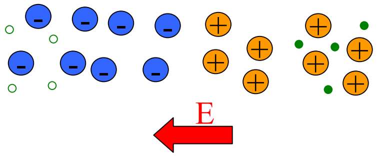
$$E_F = E_g + k_b T \ln\left(\frac{N_d}{N_C}\right)$$



What happens when you join these together?

Drift and Diffusion

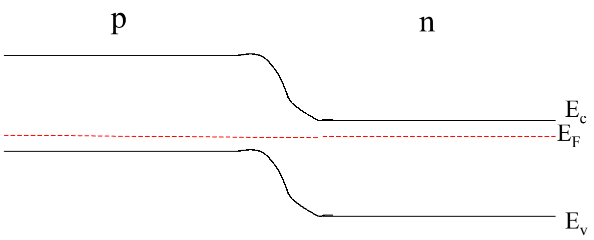




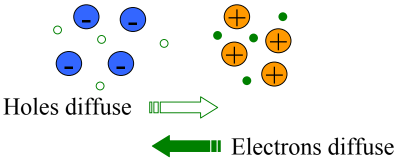
An electric field forms due to the fixed nuclei in the lattice from the dopants

Therefore, a steady-state balance is achieved where diffusive flux of the carriers is balanced by the drift flux

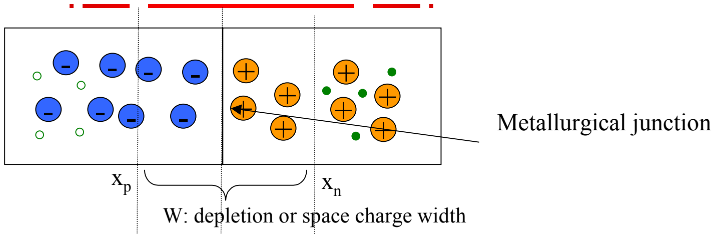
Joining p and n

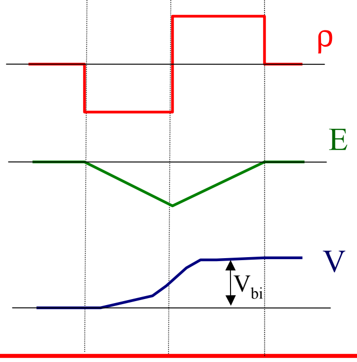


Carriers flow under driving force of diffusion until E_F is flat



Space Charge, Electric Field and Potential





$$N_d x_n = N_a x_p$$

$$E = \int \frac{\rho(x)}{\varepsilon} dx$$

$$x_p = \sqrt{\frac{2\varepsilon_r\varepsilon_o V_{bi}}{e}\frac{N_d}{N_a(N_d+N_a)}}$$

$$x_n = \sqrt{\frac{2\varepsilon_r\varepsilon_o V_{bi}}{e}\frac{N_a}{N_d(N_d+N_a)}}$$

$$V = \int E(x)dx$$

$$W = \sqrt{\frac{2\varepsilon_r\varepsilon_o V_{bi}}{e}\frac{N_a+N_d}{N_dN_a}}$$