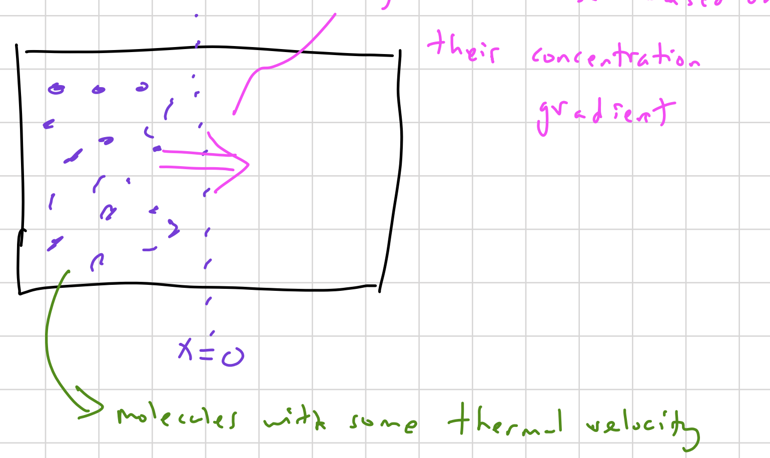
Lecture #7

Carrier Transport — Diffusion

Carrier Diffusion

Consider an example of a container of gas molecules:



→ Same theory applies to charged carriers in a semiconductor:

e^- diffusion

$$J_{n|diff} = e\, v_{th}\, l \frac{dn}{dx}$$

v_{th}: thermal velocity; l: 'mean free path'

$$\boxed{J_{n|diff} = e D_n \frac{dn}{dx}}$$

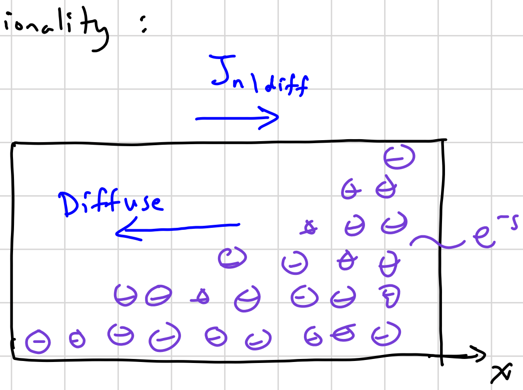
h^+ diffusion

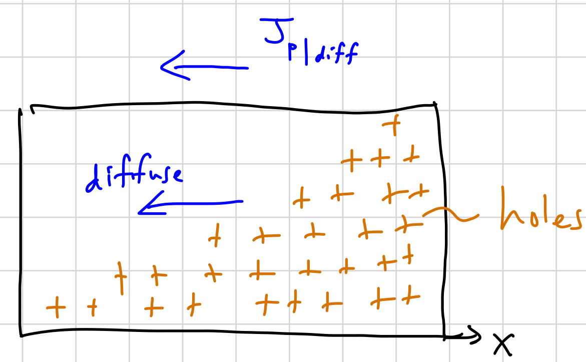
$$J_{p|diff} = -e\, v_{th}\, l \frac{dp}{dx}$$

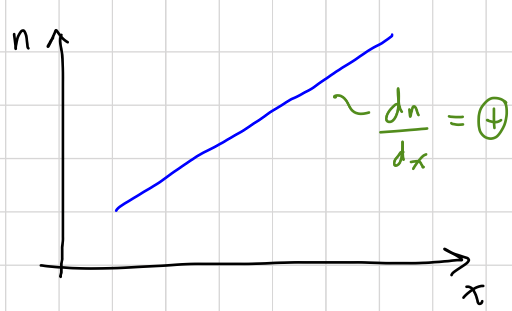
$$\boxed{J_{p|diff} = -e D_p \frac{dp}{dx}}$$

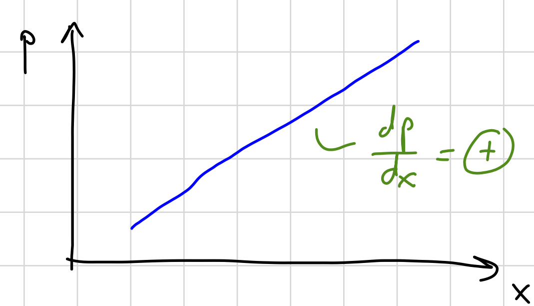
D_n, D_p: diffusion coefficient

Directionality:









Total current

Summation of drift and diffusion currents for e^- & h^+ gives J_{Total}

$$J_{total} = J_{n|drift} + J_{p|drift} + J_{n|diff} + J_{p|diff}$$

$$\boxed{J_{total} = e n \mu_n \mathcal{E} + e p \mu_p \mathcal{E} + e D_n \frac{dn}{dx} - e D_p \frac{dp}{dx}}$$

Current flow in EQ

→ In EQ the total current flow (J_{total}) = 0

→ In fact, each component must be = 0 : $J_n = 0$, $J_p = 0$ is true!

→ However, current CAN still flow in an EQ S.C. as long as

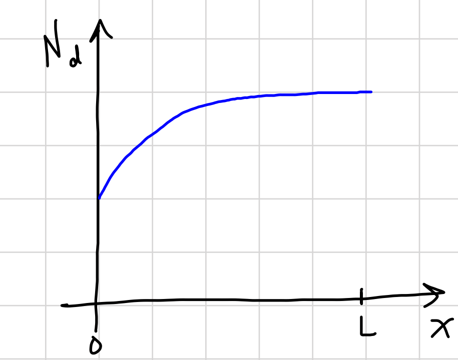
→ In EQ, $\frac{dE_F}{dx} = 0$ [E_F is flat in EQ!!]

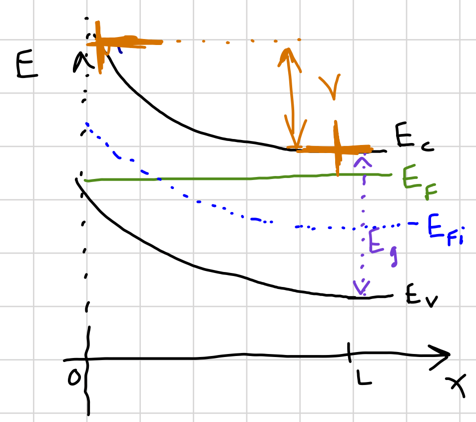
Einstein Relation

→ connecting formula between D and μ

• Assume: nondegenerate, doped s.c.; nonuniform doping; in EQ

Example:





$$J_{n|drift} + J_{n|diff} = e\,\mu_n n \mathcal{E} + e D_n \frac{dn}{dx} = 0$$

constant in x

varies in x

using: $\mathcal{E} = \frac{1}{e}\frac{dE_{Fi}}{dx}$ and $n = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right]$

$$\frac{dn}{dx} = -\frac{n_i}{kT}\exp\left[\frac{E_F - E_{Fi}}{kT}\right]\frac{dE_{Fi}}{dx}$$

$$\frac{dn}{dx} = -\frac{e}{kT} n \mathcal{E}$$

$$(e\cancel{n}\mathcal{E})\mu_n - (e\cancel{n}\mathcal{E})\frac{e}{kT}D_n = 0$$

→ The nonuniform doping concentration ensures that $\mathcal{E} \neq 0$

$$\Rightarrow \boxed{\frac{D_n}{\mu_n} = \frac{kT}{e}} \quad \text{or} \quad \boxed{\frac{D_p}{\mu_p} = \frac{kT}{e}}$$

☆ valid even under non-EQ conditions!!

whether n-type or p-type

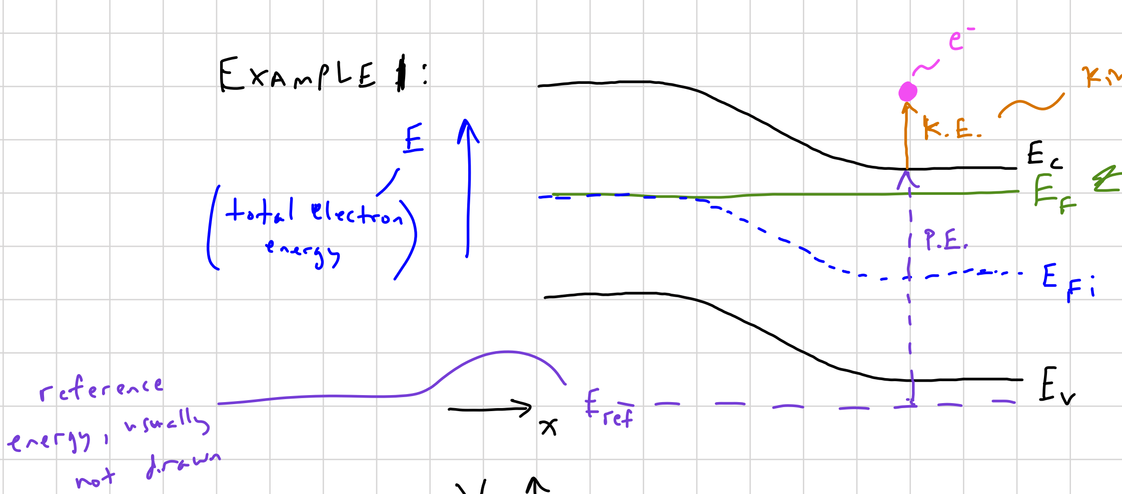
electric potential (volts) is simply: ϕ or $V = (+)\frac{1}{e}(E_F - E_{Fi}) = -\frac{1}{e}(E_c - E_{ref})$

and, since $\mathcal{E} = -\frac{d\phi}{dx}$: $\quad \mathcal{E} = \frac{1}{e}\frac{dE_{Fi}}{dx} = \frac{1}{e}\frac{dE_c}{dx} = \frac{1}{e}\frac{dE_v}{dx}$

Band Diagrams

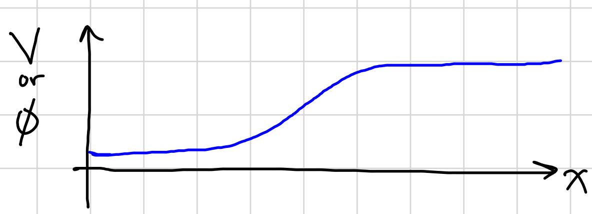
A great deal of information can all be summarized in an energy band diagram:

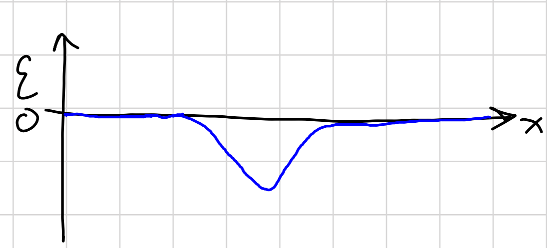
EXAMPLE 1:



In EQ?

YES!

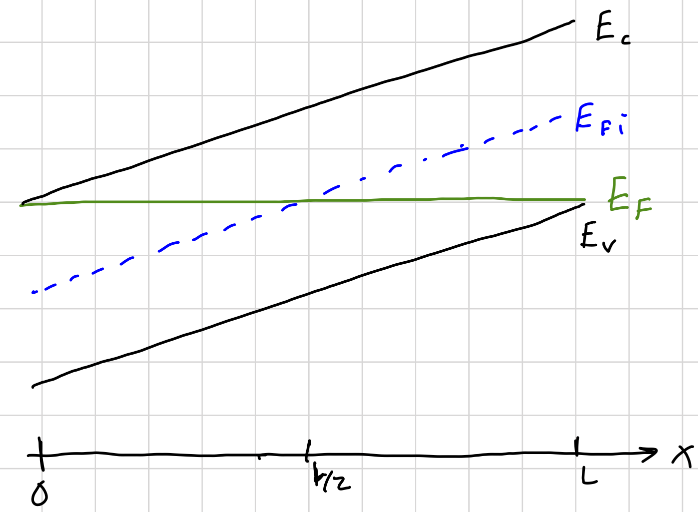


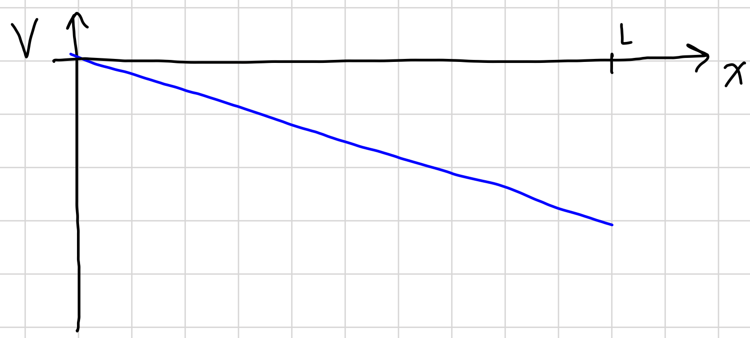


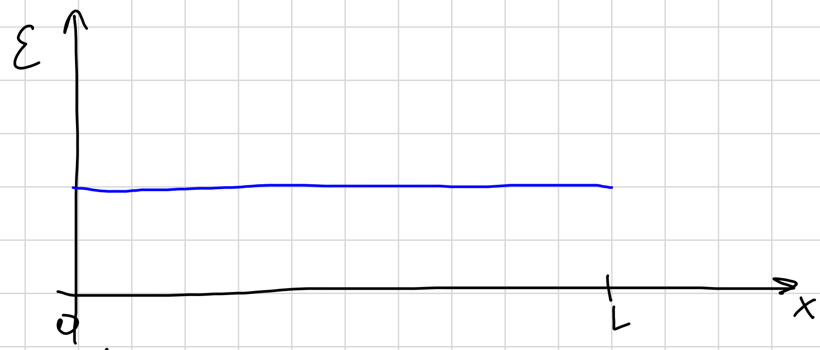
$$\mathcal{E} = \frac{1}{e}\frac{dE_c}{dx}$$

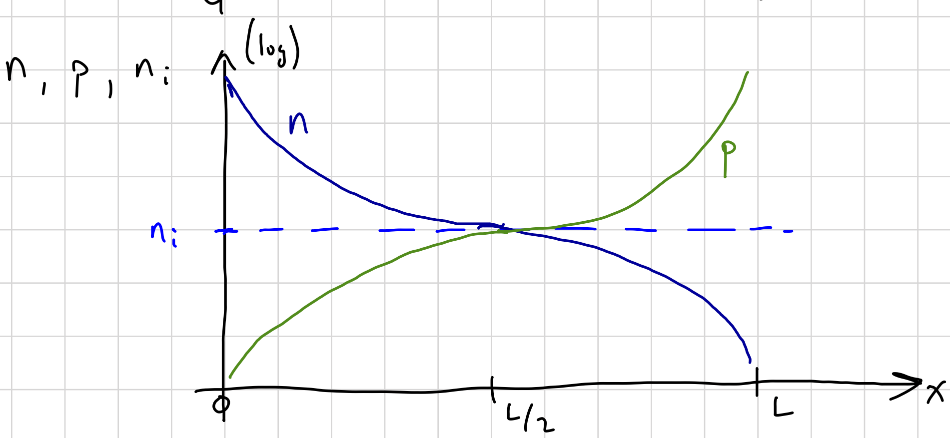
EXAMPLE 2:

Given:







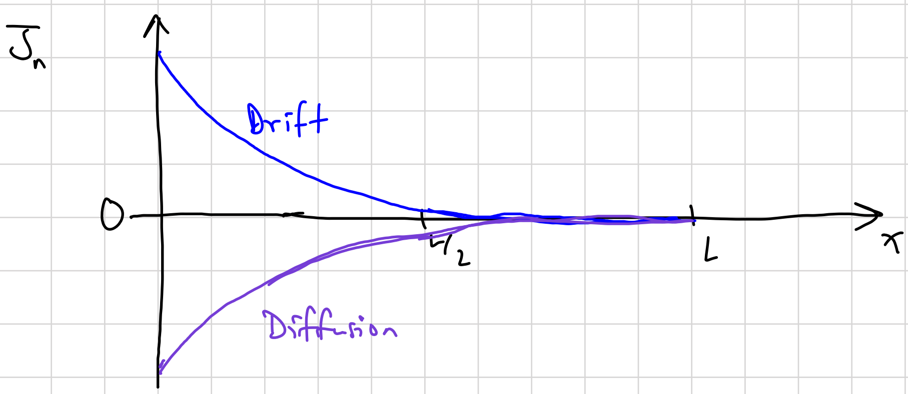


$E_F - E_{Fi}$ vs. x

$$n = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right]$$

$$p = n_i \exp\left[\frac{E_{Fi} - E_F}{kT}\right]$$

$$n_i^2 = n_0 p_0$$



$$J_n\big|_{drift} = e \mu_n n \mathcal{E}$$ (product of $\mathcal{E}$ vs. x and n vs. x)

$$J_n\big|_{diff} = -J_n\big|_{drift}$$ in EQ