ECE 340: Semiconductor Electronics

Chapter 1 to 4 review

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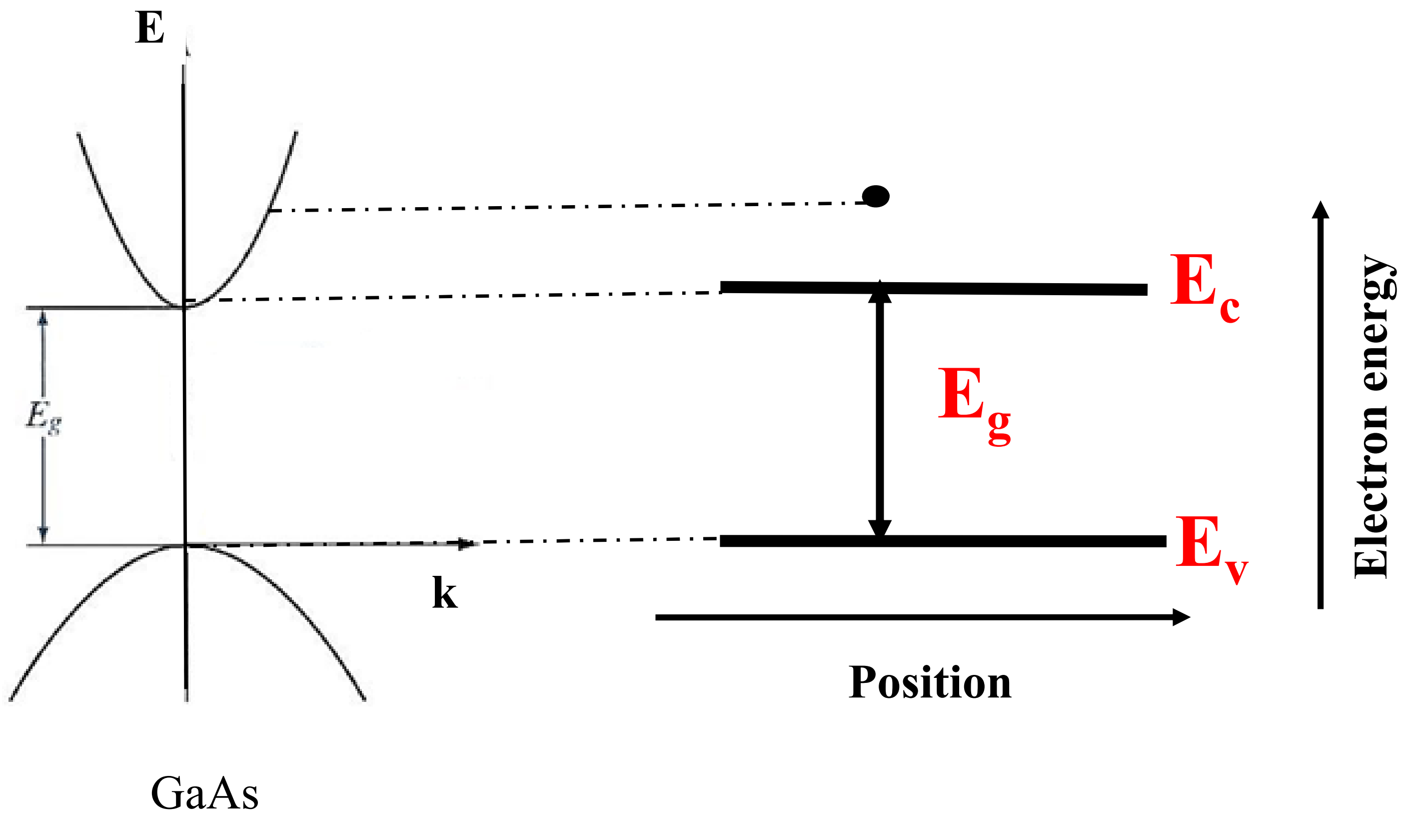
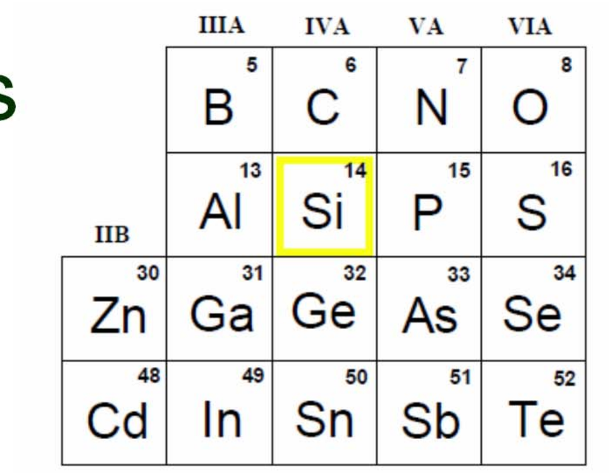
Outline

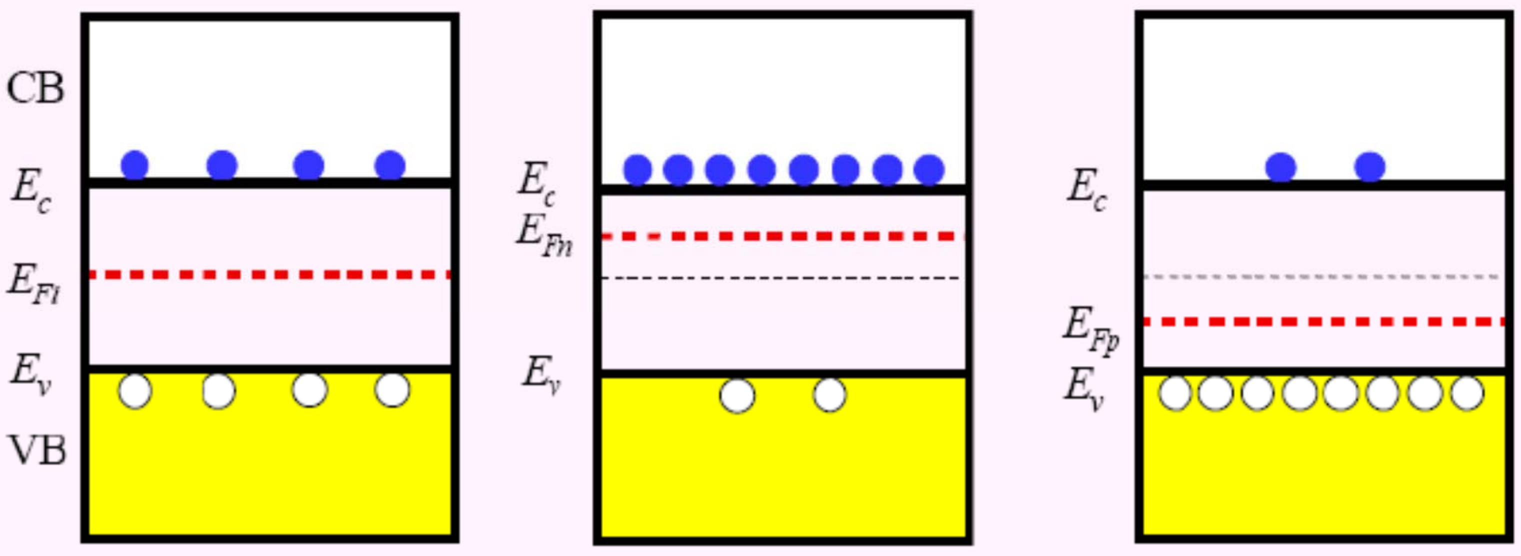
- Crystal properties and growth of semiconductors
- Atoms and electrons
- Energy bands and charge carriers in semiconductors
- Excess carriers in semiconductors

Energy band: E-K vs. E-X



Intrinsic and extrinsic materials



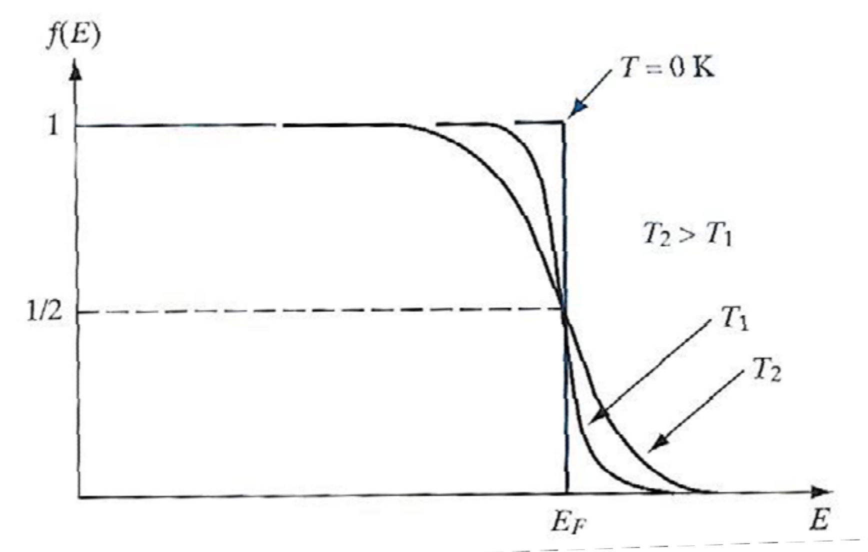


(a) intrinsic (b) *n*-type (c) *p*-type

$\boldsymbol{n = p = n_i}$ $n_0 > p_0$ $p_0 > n_0$

Fermi-Dirac distribution and carrier concentration

$$f(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$



$$\boxed{n_0 = n_i e^{(E_F - E_i)/kT}}$$

$$\boxed{p_0 = n_i e^{(E_i - E_F)/kT}}$$

$$\boxed{n_0 p_0 = n_i^2}$$

Space Charge Neutrality

- If there 2 or more different dopants, charge neutrality in the material:

$$p_0 + N_d^+ = n_0 + N_a^-$$

- If all the impurities are ionized ($N_d^+ = N_d, N_a^- = N_a$):

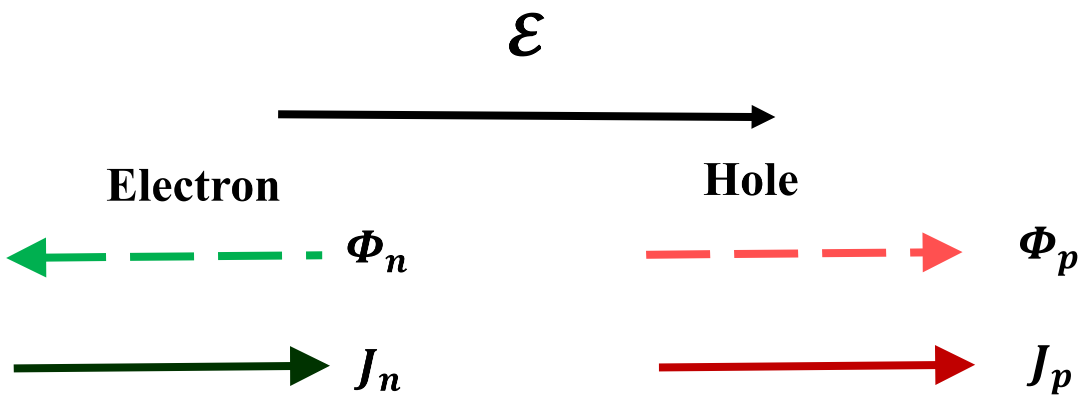
$$p_0 + N_d = n_0 + N_a$$

- If $|N_d - N_a|$ *is comparable with* n_i,

$$\boxed{n_o = \frac{N_d - N_a}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}}$$

$$\boxed{p_o = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2}}$$

Drift current



Conductivity:

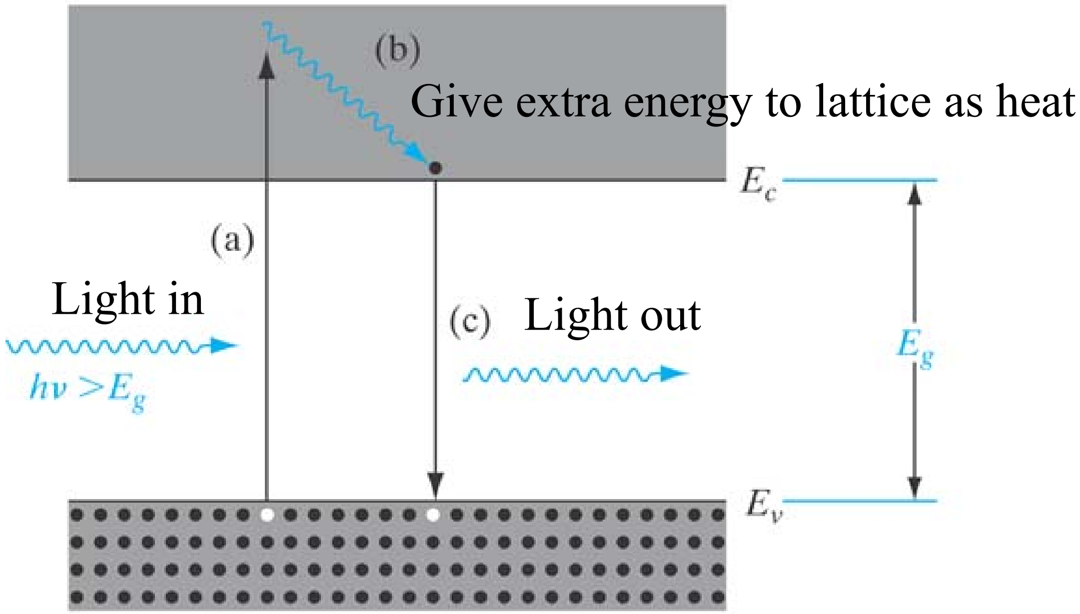
$$\boxed{\sigma = q(n\mu_n + p\mu_p)}$$

Resistivity: $\rho = \dfrac{1}{\sigma}$

Resistance $R = \rho \dfrac{L}{wt}$

mobility $\mu = \dfrac{q\tau_c}{m^*}$

Light absorption and photoluminescence



If $h\nu < E_g$ **no light absorption**

If $h\nu \geq E_g$ $I_t = I_0 e^{-\alpha l}$

Incident photon flux $\boldsymbol{\Phi = \frac{P_{op}}{h\nu}}$

Steady state light illumination

- The excess electron-hole pair concentration:

$$\boxed{\Delta n = \Delta p = g_{op}\tau_n}$$

- Quasi-Fermi Level

$$\boxed{n = n_i e^{(F_n - E_i)/kT}}$$

$$\boxed{p = p_i e^{(E_i - F_p)/kT}}$$

- Photoconductivity:

$$\Delta\sigma = q g_{op}(\tau_n \mu_n + \tau_p \mu_p)$$

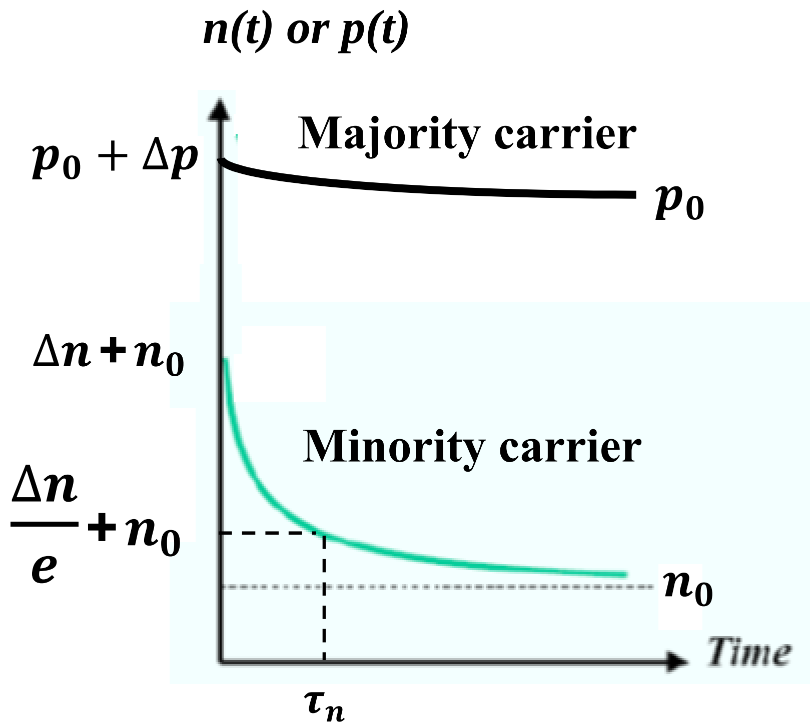
Light is turned off at t=0 :

- Electron and hole concentration as a function of time

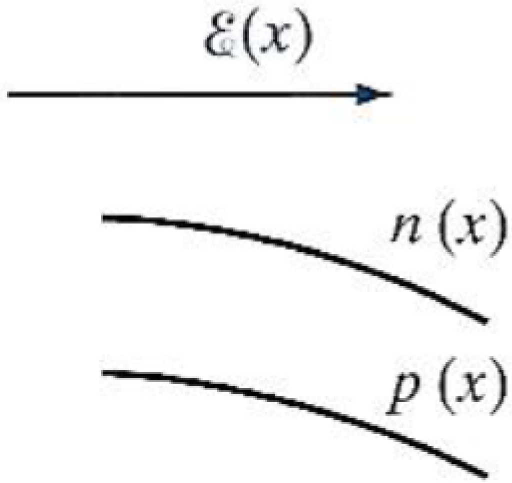
$$\boxed{n(t) = n_0 + \Delta n e^{-t/\tau_n}}$$

$$\boxed{p(t) = p_0 + \Delta p e^{-t/\tau_p}}$$

$$\tau_n = \frac{1}{\alpha_r(n_0 + p_0)} \approx \frac{1}{\alpha_r p_0}$$



Drift and diffusion directions for electrons and holes



	Electron	Hole
Diffusion	$\dashrightarrow$ $\boldsymbol{\Phi_n(diff.)}$	$\dashrightarrow$ $\boldsymbol{\Phi_p(diff.)}$
	$\longleftarrow$ $\boldsymbol{J_n(diff.)}$	$\longrightarrow$ $\boldsymbol{J_p(diff.)}$
Drift	$\dashleftarrow$ $\boldsymbol{\Phi_n(drift.)}$	$\dashrightarrow$ $\boldsymbol{\Phi_p(drift.)}$
	$\longrightarrow$ $\boldsymbol{J_n(drift.)}$	$\longrightarrow$ $\boldsymbol{J_p(drift.)}$

Diffusion and drift current density

- The electron and hole current density:

$$\boxed{J_n(x) = q\mu_n n(x)\mathcal{E}(x) + qD_n \frac{dn(x)}{dx}}$$

drift **diffusion**

$$\boxed{J_p(x) = q\mu_p p(x)\mathcal{E}(x) - qD_p \frac{dp(x)}{dx}}$$

- The total current density:

$$\boxed{J(x) = J_n(x) + J_p(x)}$$

- **Einstein relation**

$$\boxed{\frac{D}{\mu} = \frac{kT}{q}}$$

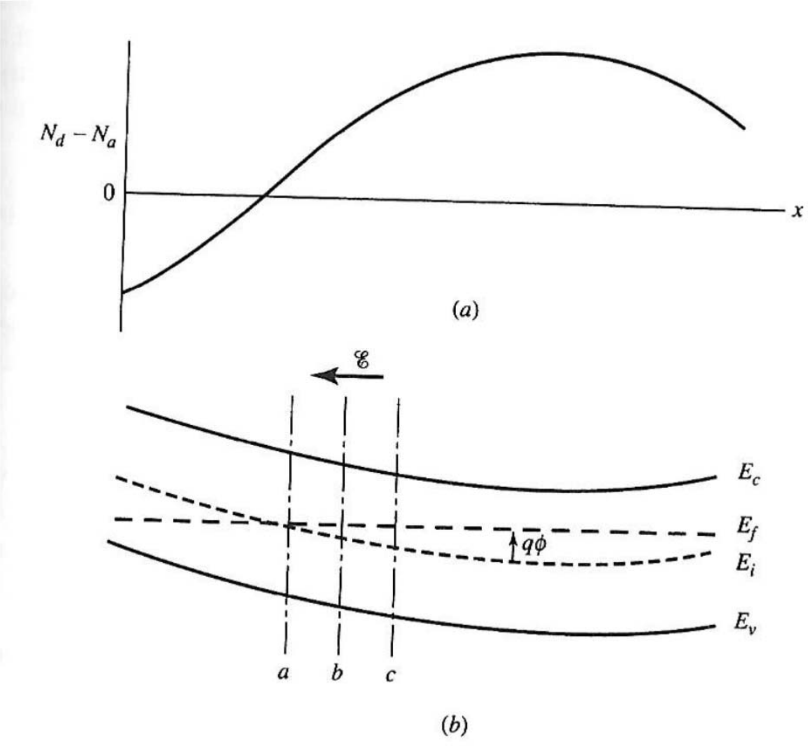
Built-in field

- Non-uniform doping result in carrier diffusion, which generate built-in field.
- At equilibrium, drift current balances diffusion current.

$$\begin{cases} J_n(x) = q\mu_n n(x)\mathcal{E}(x) + qD_n \dfrac{dn(x)}{dx} = 0 \\ \dfrac{D}{\mu} = \dfrac{kT}{q} \end{cases}$$

$$\Rightarrow \boxed{\mathcal{E} = -\frac{kT}{q}\frac{1}{n}\frac{dn}{dx}}$$

Similarly: $\boxed{\mathcal{E} = \frac{kT}{q}\frac{1}{p}\frac{dp}{dx}}$



Continuity equation for holes and electrons

$$\frac{\partial \delta p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} - \frac{\delta p}{\tau_p}$$ **continuity equation for holes**

$$\frac{\partial \delta n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} - \frac{\delta n}{\tau_n}$$ **continuity equation for electrons**

Carrier concentration changing rate

Carrier flow in-out rate

Thermal Generation Recombination rate

Diffusion current

- If carrier inject from one end, excess carrier concentration:

$$\delta p(x) = \Delta p e^{-x/L_p}$$

L_p is the average distance a hole diffuses before recombining

- **Diffusion current:**

$$J_p(x) = q\frac{D_p}{L_p}\delta p(x)$$