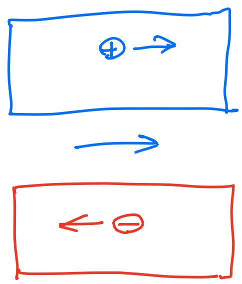
Recap of semiconductor

undoped. $n = p = n_i = 1.5 \times 10^{10}\ \frac{1}{cm^3}$

N-type: (As, P) $n = N_D$. $p = \frac{n_i^2}{N_D}$ small

P-type: (B) $p = N_A$ $n = \frac{n_i^2}{N_A}$ small

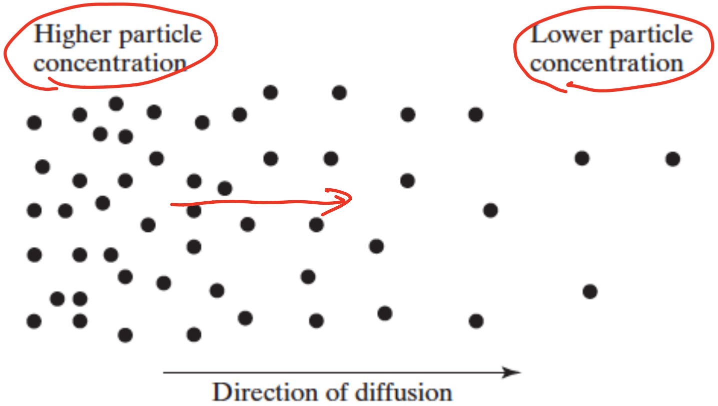


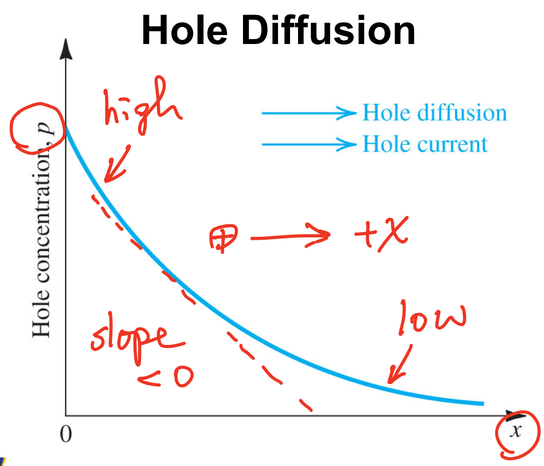
Drift current

$$J_p = p \cdot q\, v_p = \underbrace{p q \mu_p}_{\sigma} \cdot E$$

$$J_n = n(-q) \cdot (-\mu_n E) = \underbrace{n q \mu_n}_{\sigma} E$$

Current in Semiconductor (2): Diffusion Current - Holes





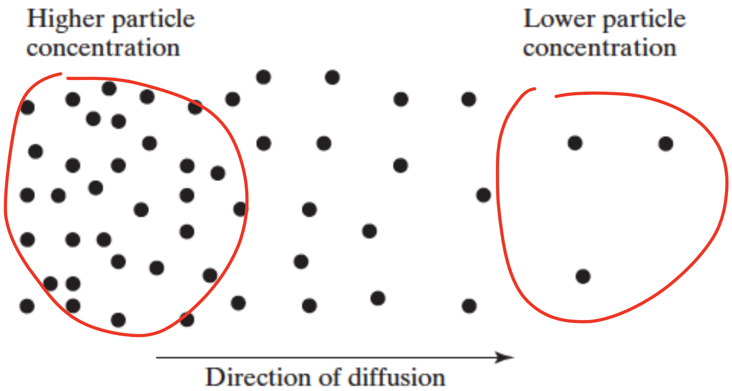
- If hole distribution is non-uniform, holes will move from high to low concentration areas
- **Flux** ∝ **- [conc. gradient]** $-\frac{dp(x)}{dx}$
- Current flows since holes carry charge:

$$\left[\frac{A}{cm^2}\right] \qquad J_{p-diff} = qD_p\underbrace{\left(-\frac{dp(x)}{dx}\right)}$$

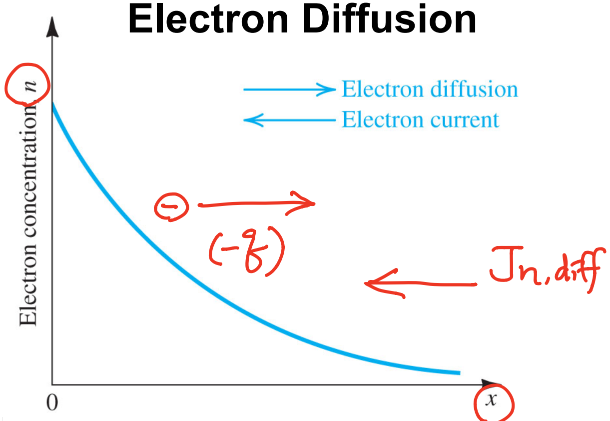
D_p: hole diffusion coef. [cm²/s]

- Note: since hole carries positive charge, hole diffusion and hole current are in the same direction

Current in Semiconductor (2): Diffusion Current - Electrons



Electron Diffusion



- **Similarly, electron diffusion also causes current to flow, but in opposite direction since electron carries negative charge**

$$J_{n-diff} = (-q)D_n\left(-\frac{dn(x)}{dx}\right)$$
$$= qD_n\frac{dn(x)}{dx}$$

D_n: electron diffusion coef. [cm²/s]

J_{n-diff} : [A/cm²]

$\mu_n \simeq 3\mu_p$

- **In Si,**
  - **D_n = 35 cm²/s**
  - **D_p = 12 cm²/s**

$D_n \simeq 3 D_p$

Einstein Relationship

$$\frac{D_n}{\mu_n} = \frac{D_n}{\mu_n} = V_T = \frac{kT}{q}$$

$\hookrightarrow = 26\,mV$ at $T = 300K$

V_T : Thermal voltage

At room temperature, $V_T = 26$ mV

Proof: Total electron current:

$$J_n = J_{n-drift} + J_{n-diff} = qn(x)\mu_n E + qD_n \frac{dn(x)}{dx}$$

$$E = -\frac{d\phi}{dx}, \quad \phi: \text{ potential}$$

$$n(x) = n_0 e^{-\frac{(-q\phi)}{kT}} = n_0 e^{\frac{\phi}{V_T}} : \text{ Boltzmann distribution}$$

In equilibrium, no net current flow

$$\Rightarrow \quad qn(x)\mu_n E + qD_n \frac{dn(x)}{dx} = 0$$

$$n(x)\mu_n E + D_n \frac{dn(x)}{d\phi}\frac{d\phi}{dx} = 0$$

$$n(x)\mu_n E + D_n \left(\frac{1}{V_T} n(x)\right)(-E) = 0$$

$$\frac{D_n}{\mu_n} = V_T$$

Assume $n(x)$

$$J_n = \cancel{q} n(x)\mu_n \cdot E + \cancel{q} D_n \frac{dn(x)}{dx} = 0$$

$\uparrow$ equilibrium

$$E = -\frac{d\phi}{dx}, \quad \phi = \text{potential}$$

$$n = n_0 e^{-\frac{(-q)\phi}{k_B T}} = \boxed{n_0 e^{\frac{q\phi}{k_B T}}}$$

$\uparrow$ Boltzmann's dist

$$n(x)\mu_n\left(-\cancel{\frac{d\phi}{dx}}\right) + D_n \underbrace{\left(\frac{dn}{d\phi}\right)}_{\frac{q}{k_B T} \cdot n_0 e^{\frac{q\phi}{k_B T}}}\left(\cancel{\frac{d\phi}{dx}}\right) = 0$$

$$\frac{q}{k_B T} \cdot \underbrace{n_0 e^{\frac{q\phi}{k_B T}}}_{=}$$

BSAC

$$\overbrace{\frac{q\cdot n}{k_B T}}^{n}$$

$$-\cancel{n(x)}\cdot\mu_n + D_n\,\cancel{n(x)}\,\frac{q}{k_B T} = 0$$

$$D_n \frac{q}{k_B T} = \mu_n$$

$$v_n = \mu_n \cdot E$$

$$\left[\frac{cm}{s}\right] \quad \left[\frac{V}{cm}\right]$$

$$\frac{D_n}{\mu_n} = \frac{k_B T}{q} = V_T$$

$$\frac{\left[\frac{cm^2}{s}\right]}{\left[\frac{cm}{s}\right]/\left[\frac{V}{cm}\right]} = [V]$$

$$= \frac{\cancel{\left[\frac{cm^2}{s}\right]}[V]}{\cancel{\left[\frac{cm^2}{s}\right]}} = [V]$$