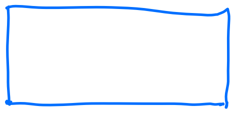
Semiconductor

intrinsic - undoped



$n = p = n_i$

For Si, $n_i = 1.5 \times 10^{10}\ cm^{-3}$

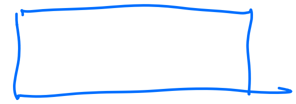
$n \times p = n_i^2$ Mass Action Law

N-type (P, As) ← Donors

$n = N_D$

$p = \frac{n_i^2}{N_D} \ll n$

P-type (B) ← Acceptor



$p = N_A$

$n = \frac{n_i^2}{N_A} \ll p$

Drift Current

$$J = \sigma E = (nq\mu_n + pq\mu_p)E$$

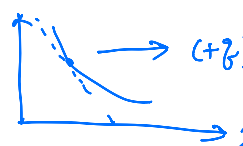
↑ mobility

$$I = \frac{V}{R} \ ; \quad R = \rho \frac{L}{A} \ : \quad \rho = \frac{1}{\sigma}$$

Diffusion Current

$$J_p = q \cdot D_p \left(-\frac{dp}{dx}\right)$$

$$J_n = (-q) D_n \left(-\frac{dn}{dx}\right) = q D_n \frac{dn}{dx}$$



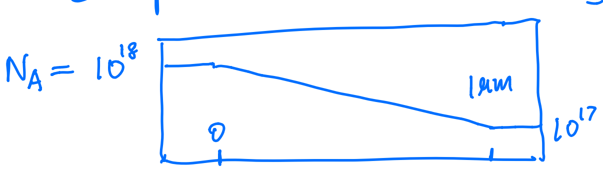
→ (+q) → J

At equilibrium

$$J_p = 0 = pq\mu_p E - qD_p \frac{dp}{dx}$$

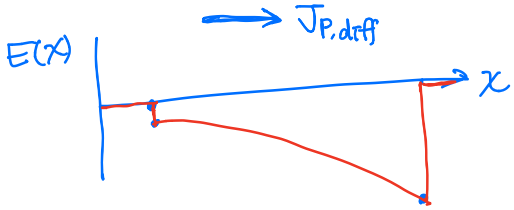
$$J_n = 0 = nq\mu_n E + qD_n \frac{dn}{dx}$$

Example: Non-uniform doping profile



hole → (+q)

→ $J_{p,diff}$



E ←

← $J_{p,drift}$

$$J_p = 0 = p(x)\cancel{q}\mu_p E - \cancel{q} D_p \frac{dp(x)}{dx}$$

$\frac{D_p}{\mu_n} = \frac{kT}{q} = V_T$ Einstein Relation

$$E(x) = V_T \cdot \frac{1}{p(x)} \frac{dp(x)}{dx}$$

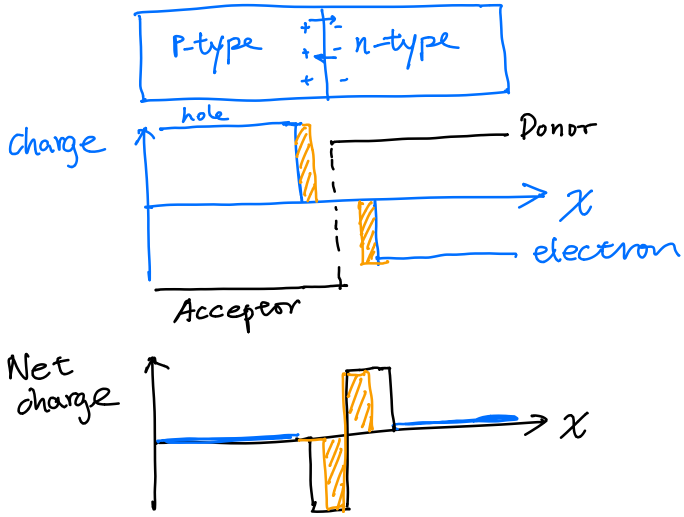
$$= \frac{V_T}{1\mu m} \cdot \frac{-(10^{18} - 10^{17})}{p(x)} \qquad \frac{V}{cm}$$

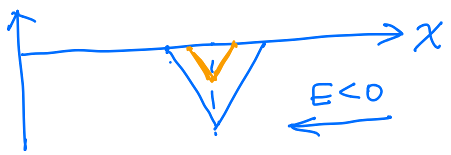
$$= 10^4 V_T \left(\frac{-9 \times 10^{17}}{p(x)}\right)$$

$x = 0$, $p = 10^{18}$ $E = -0.9 \times 10^4 V_T$

$x = 1\mu m$ $p = 10^{17}$ $E = -9 \times 10^4 V_T$

P-n Junction





$E = -\int \frac{\rho}{\epsilon} dx$

Gauss Law

$\rightarrow J_{p,diff}$

$\leftarrow J_{p,drift}$

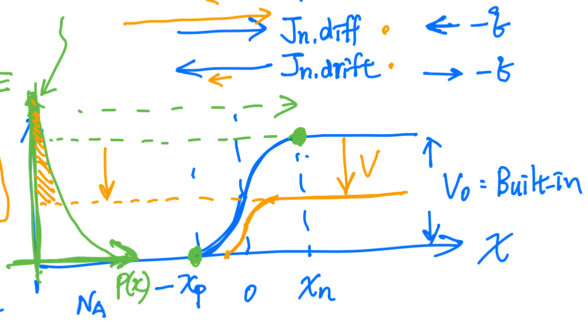
$\rightarrow J_{n,diff} \quad \leftarrow -q$

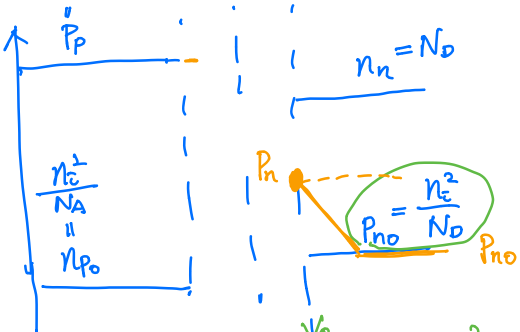
$\leftarrow J_{n,drift} \quad \rightarrow -q$

$p = c \cdot e^{-\frac{V}{V_T}}$

Boltzmann

$\boxed{\phi = -\int E dx}$



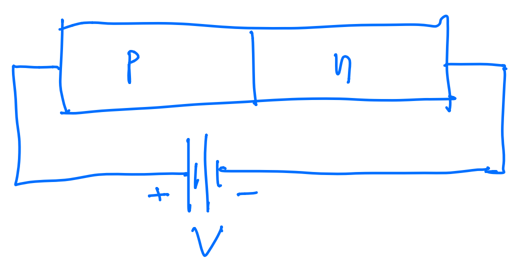


$P_p = N_A$, $P_{no} = P_p \cdot e^{-\frac{V_0}{V_T}} = \cancel{N_A} \cdot \frac{n_i^2}{N_D \cdot \cancel{N_A}}$

$= \frac{n_i^2}{N_D}$

$V_0 = V_T \cdot \ln \frac{N_A \cdot N_D}{n_i^2}$

Forward Bias



Depletion width narrows

E_{max} reduces

Net current $\longrightarrow J_p > 0$, $J_n > 0$

V: applied voltage
Lower potential barrier by V

minority carrier at $x = x_p$ under forward

$\Delta P_n = P_{no} e^{\frac{V}{V_T}} - P_{no}$

$= P_{no}(e^{\frac{V}{V_T}} - 1)$

$\Delta P_n(x) = \Delta P_n(x = x_n)\, e^{-\frac{x - x_p}{L_p}}$

↳ Exponentially decrease with L_p: diffusion length

In depletion region
both $J_{p,diff}$, $J_{p,drift}$
$J_{n,diff}$, $J_{n,drift}$
Instead, we estimate current
at $x = x_n$. charge neutral region
$E = 0$
only diffusion current

$$J_{p,diff} = -q \cdot D_p \cdot \frac{dP(x)}{dx}$$
$$= -q D_p \frac{d\, \Delta P_n(x)}{dx}$$
$$= -q D_p \left(-\frac{1}{L_p} \Delta P_n(x = x_n)\right)$$
$$= \frac{q D_p}{L_p} \cdot P_{n0} \left(e^{\frac{V}{V_T}} - 1\right)$$
$$= \frac{q D_p}{L_p} \cdot \frac{n_i^2}{N_D} \left(e^{\frac{V}{V_T}} - 1\right)$$

Similarly

$$J_{n,diff} = \frac{q D_n}{L_n} \frac{n_i^2}{N_A} \left(e^{\frac{V}{V_T}} - 1\right)$$

$$J_{total} = J_{p,diff} + J_{n,diff} = \underbrace{\left[\frac{q D_p}{L_p} \frac{n_i^2}{N_D} + \frac{q D_n}{L_n} \cdot \frac{n_i^2}{N_A}\right]}_{J_s} \left(e^{\frac{V}{V_T}} - 1\right)$$

$$I = J_{total} \times Area = I_s \left(e^{\frac{V}{V_T}} - 1\right)$$

$$\Delta P_n(x) = \Delta P_n(x = x_n)\, e^{-\frac{x - x_n}{L_p}}$$

$$\frac{d(e^{ax})}{dx} = a \cdot e^{ax}$$

$$\left.\frac{d\, \Delta P_n(x)}{dx}\right|_{x = x_n} = \left.\Delta P_n(x = x_n) \left(-\frac{1}{L_p}\right) e^{-\frac{x - x_n}{L_p}}\right|_{x = x_n}$$

$$= \frac{-\Delta P_n(x = x_n)}{L_p}$$