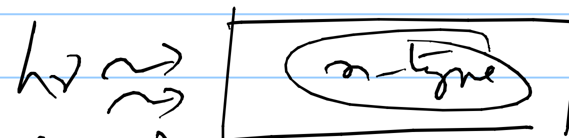
Continuity Eq.

To understand the situations of excess carriers

$$\frac{dp(t)}{dt} = \underline{\underline{G_{th}}} - \underline{\underline{R}} + g_{op} \quad /cm^3\text{-sec.}$$

$$p(t) = p_0 + \delta p(t)$$



$$\frac{d\delta p(t)}{dt} = \alpha_r n_i^2 - \alpha_r (n_0+\delta n(t))(p_0+\delta p(t))$$

$t = t_1$ <u>switch off the</u> <u>light source.</u>

$$= \cancel{\alpha_r n_i^2} - \cancel{\alpha_r n_i^2} - \alpha_r (n_0+p_0)\delta p(t) - \alpha_r \delta p^2(t)$$

Transient

$$\frac{d\delta p(t)}{dt} = -\alpha_r (n_0+p_0)\delta p(t)$$

if $\delta p(t) = \delta n(t) \ll n_0$ <u>low level generation</u>

$$\frac{d}{dt}\delta p(t) = -\frac{\delta p(t)}{\tau_p}$$

τ_p = Recombination lifetime of hole within the n-type semiconductor

= Recombination minority carrier (hole) life-time

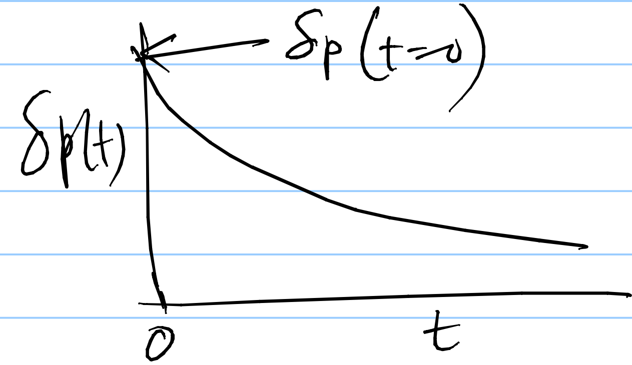
τ_n = Recombination life time of electron

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

(n-type semiconductor)

$\underline{\underline{n_0}} \gg p_0$

$$\delta p(t) = \delta p(t=0)\, e^{-t/\tau_p}.$$



$$\delta p(t) = \delta p(t=t_1)\, e^{-(t-t_1)/\tau_p}$$

Steady State problem

light source is continuously ON

$$\frac{d}{dt}p(t) = 0 = G_{th} - R + g_{op}$$

$$\underbrace{-\alpha_r(n_0+p_0)\delta p}_{} + g_{op} = 0$$

assuming generation is low level.

$$\Rightarrow \frac{\delta p}{\tau_p} = g_{op} \Rightarrow \delta p = g_{op}\tau_p.$$

$$\delta n = g_{op}\tau_n.$$

$$(n_0, p_0) \Rightarrow \sigma = n_0 q\mu_n + p_0 q\mu_p$$

$$(n_0+\delta n, p_0+\delta p) \Rightarrow \sigma = (n_0+\delta n)q\mu_n + (p_0+\delta p)q\mu_p = \sigma + \Delta\sigma$$

$$\Delta\sigma = \delta n\, q\mu_n + \delta p\, q\mu_p$$

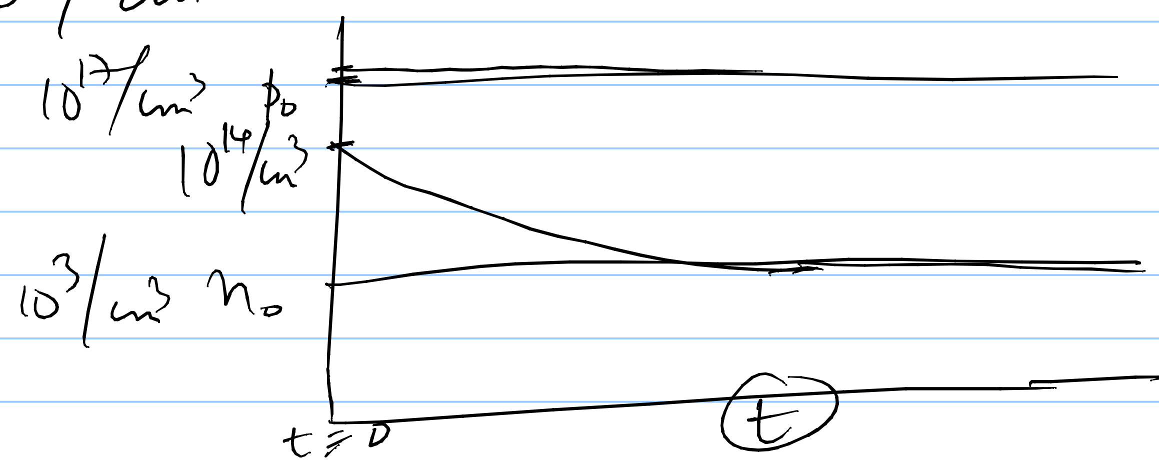
$$\Delta\sigma = g_{op}\, q\, (\mu_n \tau_n + \mu_p \tau_p)$$

photo-conductivity (Extra or increase in conductivity of the material due to photo generation)

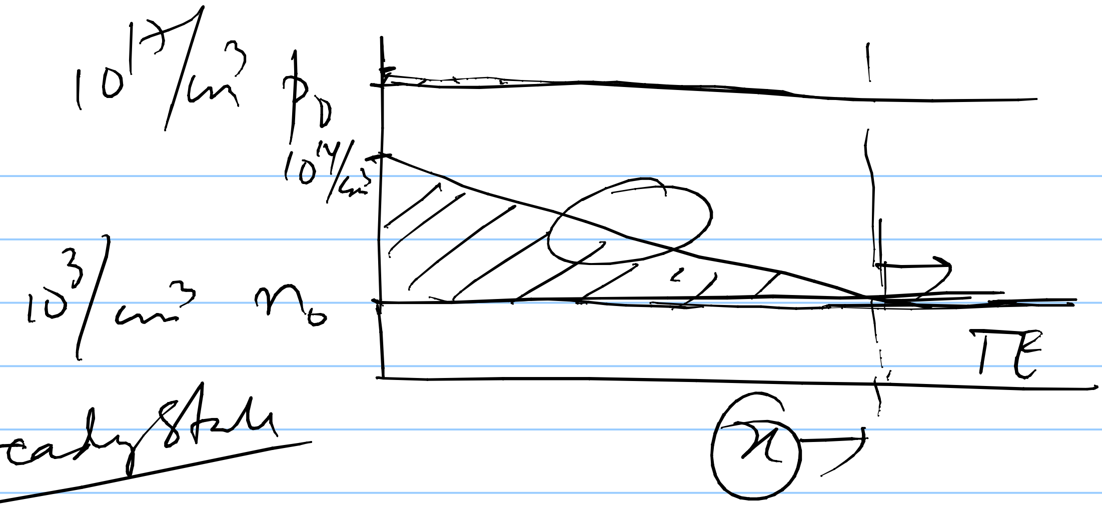
$p_0 = 10^{17}/cm^3$

$n_0 = 10^{3}/cm^3$

$\delta p = \delta n = 10^{14}/cm^3$



Transient



Steady State

Continuity Eqn.

E-M Theory Knowledge.

$$\nabla\cdot(\nabla\times H) = \nabla\cdot J + \nabla\cdot\frac{dD}{dt}$$

$$D = \epsilon\,\mathcal{E}.$$

$$\nabla\cdot D = \rho$$

$$0 = \nabla\cdot J + \frac{d}{dt}(\nabla\cdot D)$$

Continuity Eqn $\boxed{\frac{d}{dt}\rho = -\nabla\cdot J.}$ $\Rightarrow$ $\frac{dp}{dt} = -\frac{1}{\mathcal{E}}\nabla\cdot J_p$

$$\begin{cases} \dfrac{d}{dt} p = \underline{\underline{G - R}} \\ \dfrac{d}{dt} p = -\dfrac{1}{q} \nabla \cdot J_p \end{cases}$$

$$p = p_0 + \delta p$$

$$\frac{d}{dt} p(x,t) = -\frac{1}{q} \nabla \cdot J_p(x,t) + (\underline{\underline{G - R}})$$

$$\frac{\partial}{\partial t} \delta p(x,t) = -\frac{1}{q} \nabla \cdot J_p(x,t) - \frac{\delta p(x,t)}{\tau_p}$$

Continuity Eqn for hole

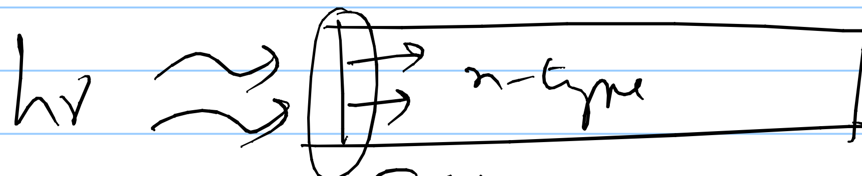
$$\boxed{\frac{\partial}{\partial t} \delta p(x,t) = -\frac{1}{q} \frac{\partial}{\partial x} J_p(x,t) - \frac{\delta p(x,t)}{\tau_p}}$$

Continuity Eqn for electron

$$\boxed{\frac{\partial}{\partial t} \delta n(x,t) = -\frac{1}{(-q)} \frac{\partial}{\partial x} J_n(x,t) - \frac{\delta n(x,t)}{\tau_n}}$$

Steady State Situation

$$0 = \frac{\partial}{\partial t}\delta p(x,t) = -\frac{1}{q}\frac{\partial J_p(x,t)}{\partial x} - \frac{\delta p(x,t)}{\tau_p}$$



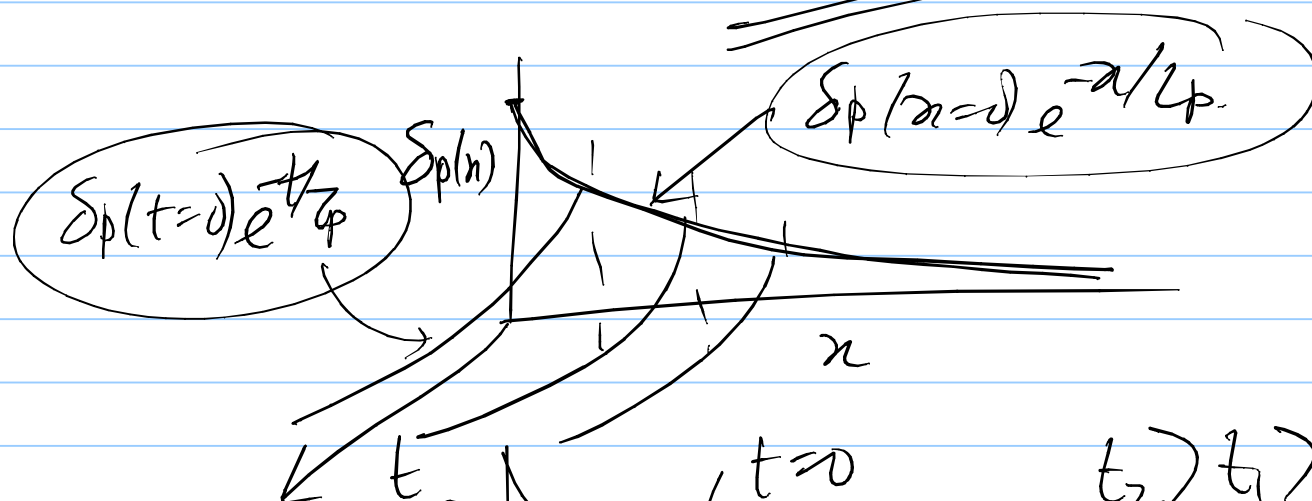
$$J_{p\,diff} = -q D_p \frac{d\,\delta p(x)}{dx}$$

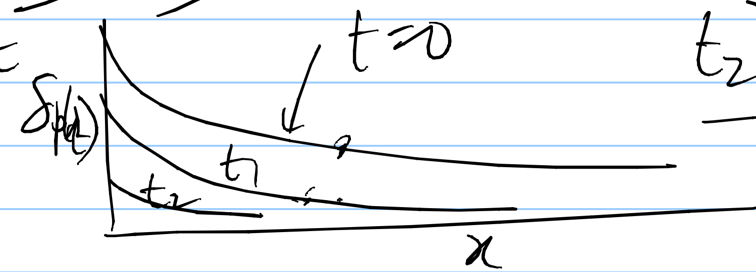
$$D_p \frac{d^2}{dx^2}\delta p(x) = \frac{\delta p(x)}{\tau_p} \Rightarrow \frac{d^2\,\delta p(x)}{dx^2} = \frac{\delta p(x)}{D_p \tau_p} = \frac{\delta p(x)}{L_p^2}$$

$L_p \Rightarrow$ Diffusion length of hole in n-region. cm^2/sec sec

$$\frac{d^2}{dx^2}\delta p(x) = \frac{\delta p(x)}{L_p^2}$$

$$\Rightarrow \quad \delta p(x) = \delta p(x=0)\, e^{-x/L_p}$$





$t_2 > t_1 > 0$

$\mu_p = 500\ cm^2/V\text{-}sec$, $\tau_p = 1\ \mu sec$.

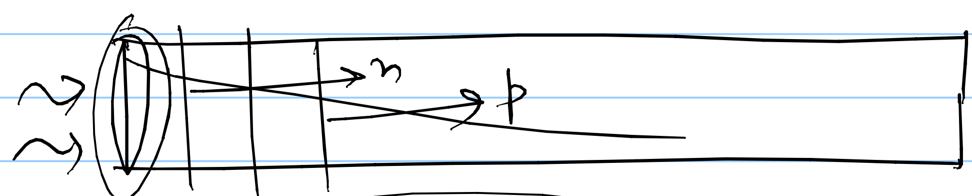
$\downarrow$

$$D_p = V_T\, \mu_p \cong 0.0259 \times 500$$

$$\simeq 10\ cm^2/sec$$

$$D_p \tau_p = L_p^2 = 10 \times 10^{-6}\ cm^2$$

$$L_p \simeq 10^{-3}\ cm$$



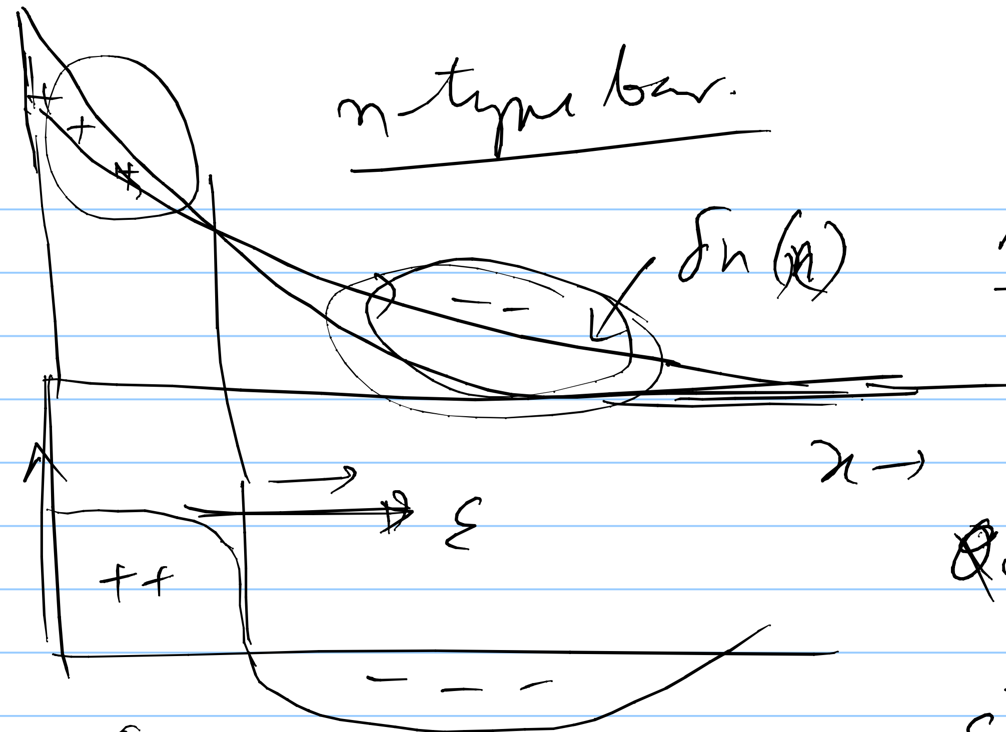
x $J(x) = 0$ $J_p(x) \longrightarrow$

This is a Non-equilibrium situation $J_n(x) \longleftarrow$

$J_p(x) \neq 0$, $J_n(x) \neq 0$.

$\delta p(x)$

$\delta n(x)$



n-type bar.

$\mu_n > \mu_p$

Quasi-neutral situation

$\mathcal{E} \simeq 0$ but $\mathcal{E} \neq 0$

n_0^2 is high

$$J_{n,drift} = (n_0 + \delta n)\, q \mu_n \mathcal{E} \neq 0$$

$$J_{p,drift} = (p_0 + \delta p)\, q \mu_p \mathcal{E} \simeq 0 \qquad \delta p << n_0 \qquad p_0 \text{ is small}$$

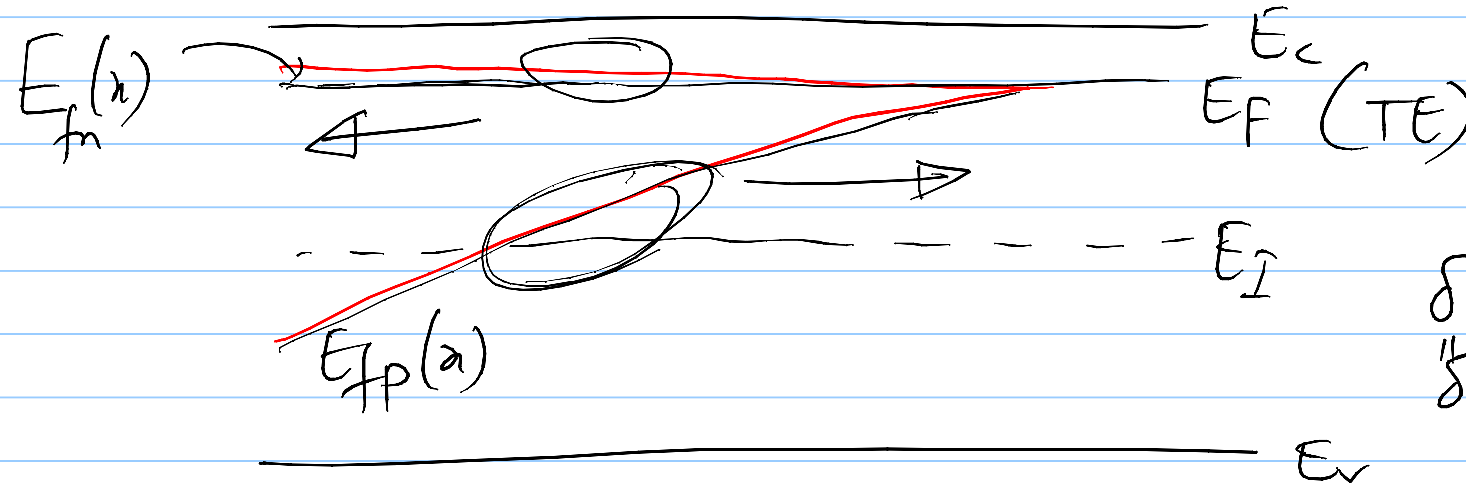
J_p, diffusion $\longrightarrow$

J_n, diffusion $\longleftarrow$

J_n, drift $\longrightarrow$

$$|J_{p,diff}(x)| = |J_{n,diff}(x)| + |J_{n,drift}(x)|$$

$\longrightarrow J(x) = 0 \longleftarrow$



$\delta n << n_0$

$\delta p >> p_0$

$$J_p(x) = \sigma_p \frac{d}{dx}\left(E_{fp}(x)/q\right) \neq 0$$

$$J_n(x) = \sigma_n \frac{d}{dx}\left(E_{fn}(x)/q\right) \neq 0$$

$$J(x) = J_p(x) + J_n(x) = 0$$

$\delta p = \delta n = 10^{14}/cm^3$

$n_0 = 10^{17}/cm^3$

$p_0 = 10^3/cm^3$

$$J_p = p q \mu_p \mathcal{E} - q D_p \frac{dp}{dx}$$

$$= p q \mu_p \frac{d}{dx}(E_I/q) - \frac{q D_p}{kT} p \frac{d}{dx}(E_I - E_{fp}) \qquad \mathcal{E} = -\frac{dV}{dx}$$

$$= p \cancel{q \mu_p \frac{d}{dx}(E_I/q)} - \cancel{\mu_p p \frac{d}{dx} E_I} \qquad \frac{d}{dx}(-qV) = \frac{d}{dx}(E_I)$$

$$+ q\mu_p p \frac{d}{dx}(E_{fp}/q) \qquad \mathcal{E} = -\frac{d}{dx}V = +\frac{d}{dx}(E_I/q)$$

$$=$$

$$\boxed{\begin{aligned} J_p(x) &= \sigma_p \frac{d}{dx}(E_{fp}(x)/q) \\ J_n(x) &= \sigma_n \frac{d}{dx}(E_{fn}(x)/q) \end{aligned}}$$

$$\mathcal{E} = \frac{d}{dx}(E_I/q)$$

$$p = n_i \exp\left(\frac{E_I - E_{fp}}{kT}\right)$$

$$E_{fp} \Rightarrow V_{fp} = \left(E_{fp}/-q\right)$$

quasi-Fermi potential for hole

$$-\frac{dV_{fp}}{dx} = \mathcal{E}_{fp}$$ ← quasi Fermi field for hole

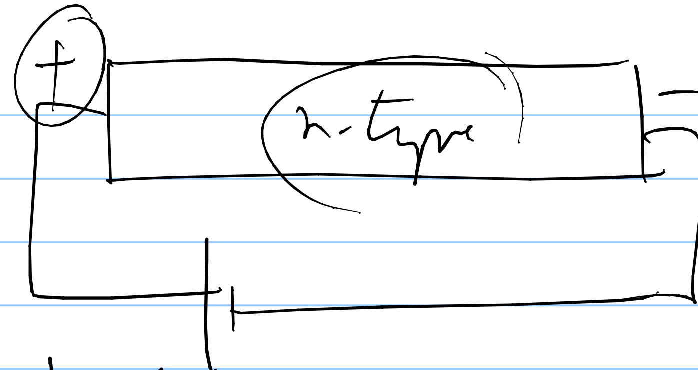
$$\mathcal{E}_{fn} = -\frac{d}{dx}\left(V_{fn}\right)$$

quasifermi-potential for electron

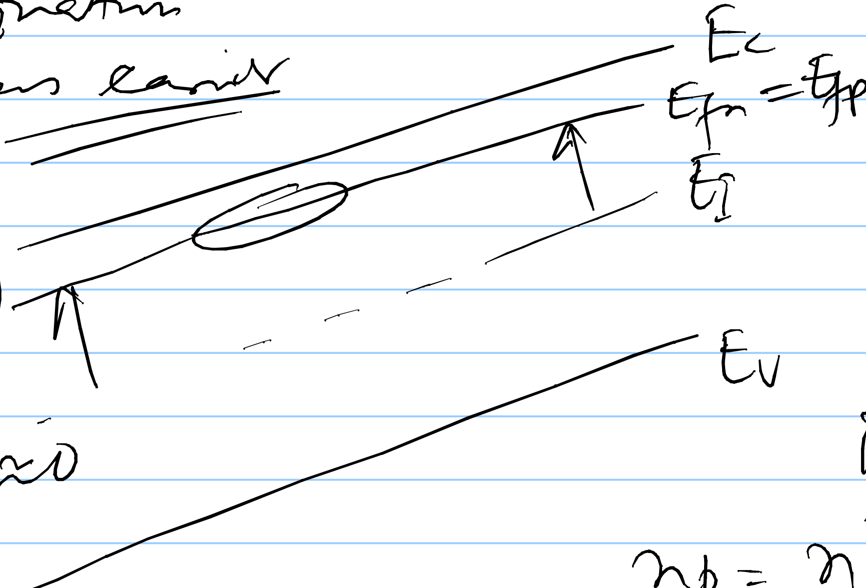
q-F-field for electron

$$V_{fn} = \left(E_{fn}/-q\right)$$

$$\underline{\mathcal{E}_{fn}} = -\frac{d}{dx}V_{fn} = \frac{d}{dx}\left(E_{fn}/q\right)$$



In this NE situation
there is no excess carrier



$$J_n = \sigma_n \frac{d}{dx}(E_{fn}/q)$$

$$J_p = \sigma_p \frac{d}{dx}(E_{fp}/q) \approx 0$$

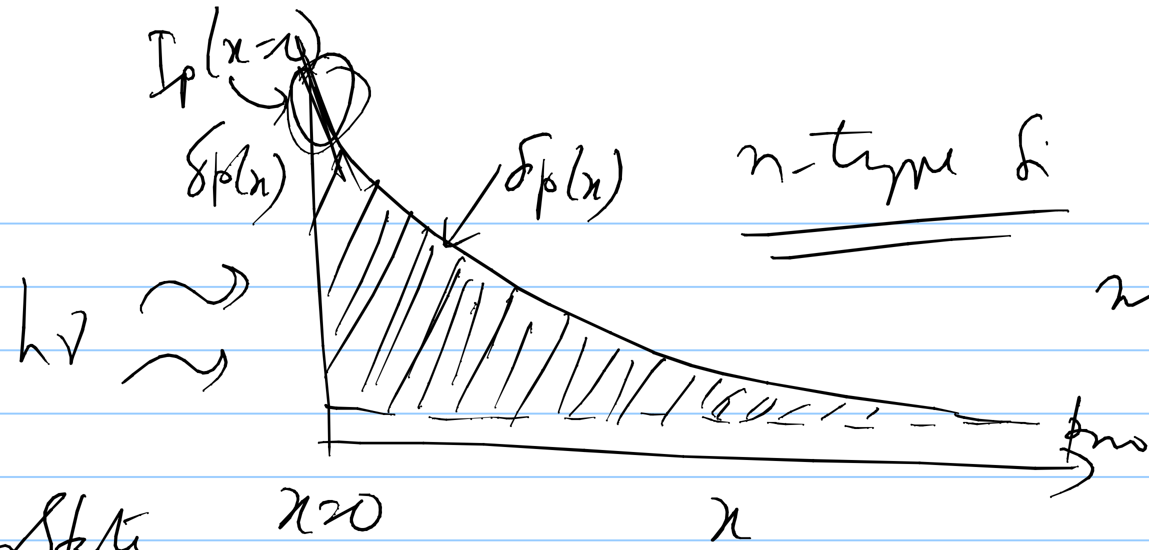
$$np = n_i^2$$

$$n = n_i \exp\left(\frac{E_{fn} - E_I}{kT}\right)$$

$$p = n_i \exp\left(\frac{E_I - E_{fp}}{kT}\right)$$

$$np = n_i^2 \exp\left(\frac{E_{fn} - E_{fp}}{kT}\right)$$

$$J \approx J_n \qquad \mathcal{E}_{fn} = \mathcal{E} \qquad J_n = \sigma_n \mathcal{E}$$



n-type Si

no electric field.

Steady State

$$\delta p(x) = \delta p(x=0)\, e^{-x/L_p}$$

$$Q_p = qA \int_0^{\infty} \delta p(x)\, dx = qA L_p\, \delta p(x=0)$$

$$\frac{Q_p}{\tau_p} = \frac{qA L_p\, \delta p(x=0)}{\tau_p} = qA \sqrt{\frac{D_p}{\tau_p}}\, \delta p(x=0)$$

$$I_p(x=0) = -qAD_p \frac{d}{dx}\delta p(x)\Big|_{x=0} = \frac{qAD_p\, \delta p(x=0)}{L_p}$$

$$\boxed{I_p(x=0) = \frac{Q_p}{\tau_p}}$$

Q_p = Excess hole charge

τ_p = hole life time

$I_p(x=0)$ = hole current at $\underline{\underline{x=0}}$

$$\left.\begin{aligned} L_p &= 10^{-3}\,cm \\ \tau_p &= 1\,\mu sec \\ \delta p(x=0) &= 10^{16}/cm^3 \\ A &= 10^{-3}\,cm^2 \end{aligned}\right\} \quad \underline{\underline{I_p(x=0)}} = \frac{Q_p}{\tau_p} = ?$$