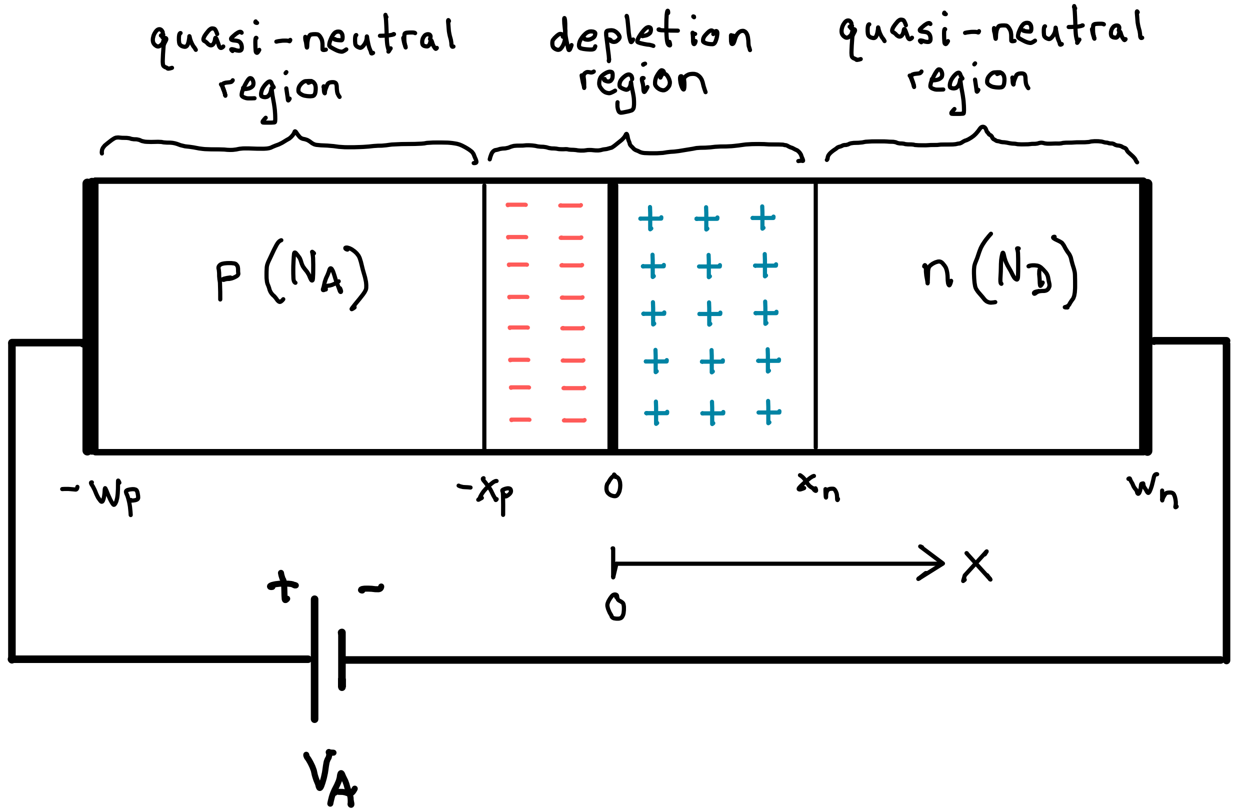
Currents in p-n Junctions



Assumptions:

- In quasi-neutral regions, majority carrier concentration = doping density
  $\rightarrow n_{n_0} \approx N_D, \quad p_{p_0} = N_A$

- Minority carrier concentration at $-x_p$ and x_n are (see Law of the Junction, next page):

$$\rightarrow n_p(-x_p) = n_{p_0} e^{qV_A/kT} \qquad \left(n_{p_0} \approx \frac{n_i^2}{N_A} \right)$$

$$\rightarrow p_n(x_n) = p_{n_0} e^{qV_A/kT} \qquad \left(p_{n_0} \approx \frac{n_i^2}{N_D} \right)$$

Long-Base Diode ($w_n >> x_n$, $w_p >> x_p$)

Law of the Junction:

In depl. reg. $p(x) = p_{p_0} e^{-q\phi(x)/kT}$ and $n(x) = n_{n_0} e^{-q\phi'(x)/kT}$

$V_A = 0$:

$$p(x_{n_0}) = p_{p_0} e^{-qV_{bi}/kT} = p_{n_0}$$

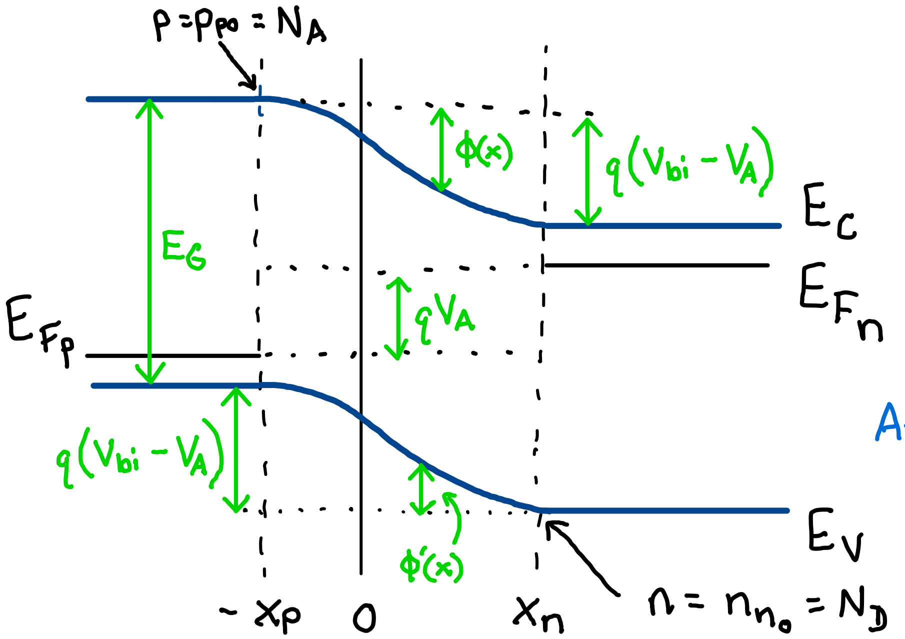
$$n(-x_{p_0}) = n_{n_0} e^{-qV_{bi}/kT} = n_{p_0}$$

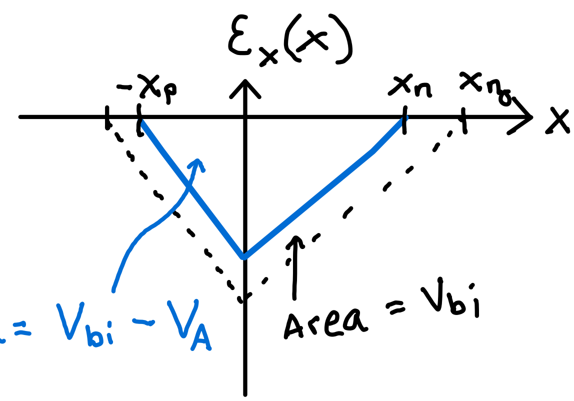
$V_A \neq 0$:

$$p(x_n) = p_{p_0} e^{-q(V_{bi}-V_A)/kT} = p_{n_0} e^{qV_A/kT}$$

$$n(-x_p) = n_{n_0} e^{-q(V_{bi}-V_A)/kT} = n_{p_0} e^{qV_A/kT}$$

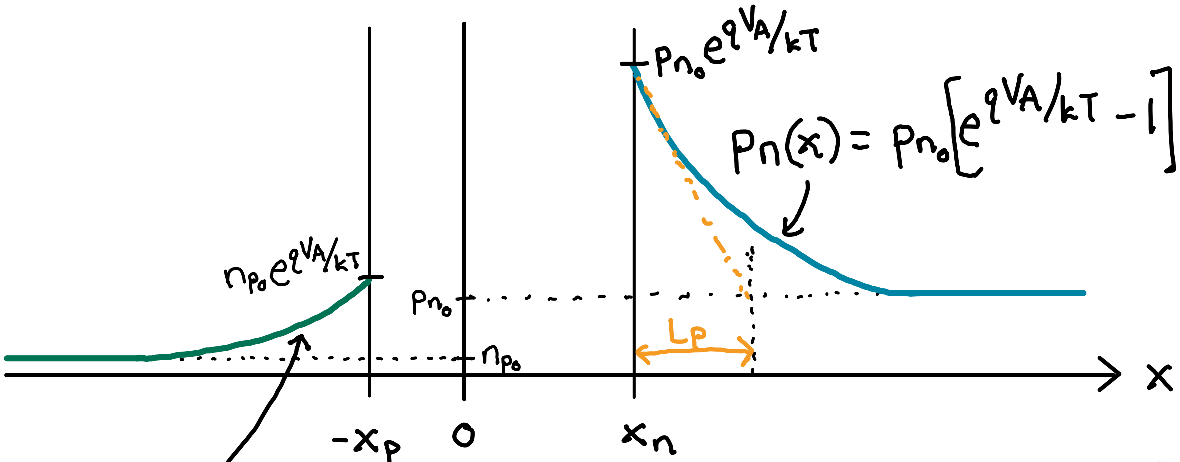
Forward Bias ($V_A > 0$):





- Reduced electrostatic (E-field) barrier in the depletion region causes excess minority carriers to be injected across the depletion region (after which they become minority carriers)

- Excess minority carriers then diffuse into quasi-neutral region and recombine with majority carriers



$$p_n(x) = p_{n_0}\left[e^{qV_A/kT} - 1\right] \cdot \exp\left[\frac{-(x - x_n)}{L_p}\right] + p_{n_0}$$

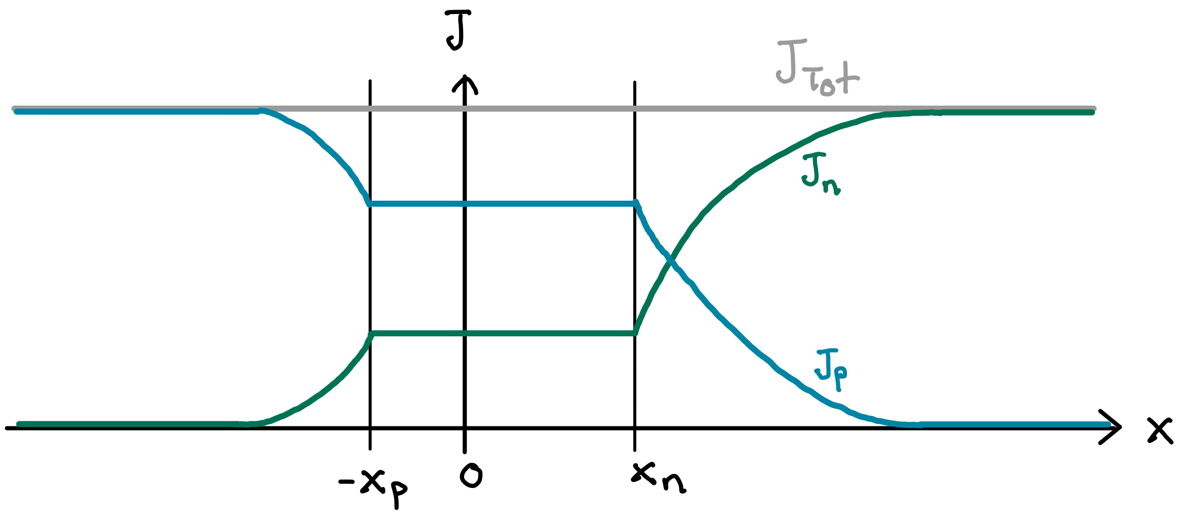
$$n_p(x) = n_{p_0}\left[e^{qV_A/kT} - 1\right] \cdot \exp\left[\frac{-(x_p - x)}{L_n}\right] + n_{p_0}$$

$$L_p \equiv \sqrt{D_p \tau_p}$$

D_p: diffusion coefficient

τ_p: minority carrier lifetime

- $p_n(x)$ and $n_p(x)$ above are obtained by solving continuity equation subject to appropriate boundary conditions (see Muller / Kamins Ch. 5)



- $J_p(x_n) = J_p(-x_p)$ (assuming no recombination of injected carriers in depl reg)
  and
  $J_n(-x_p) = J_n(x_n)$

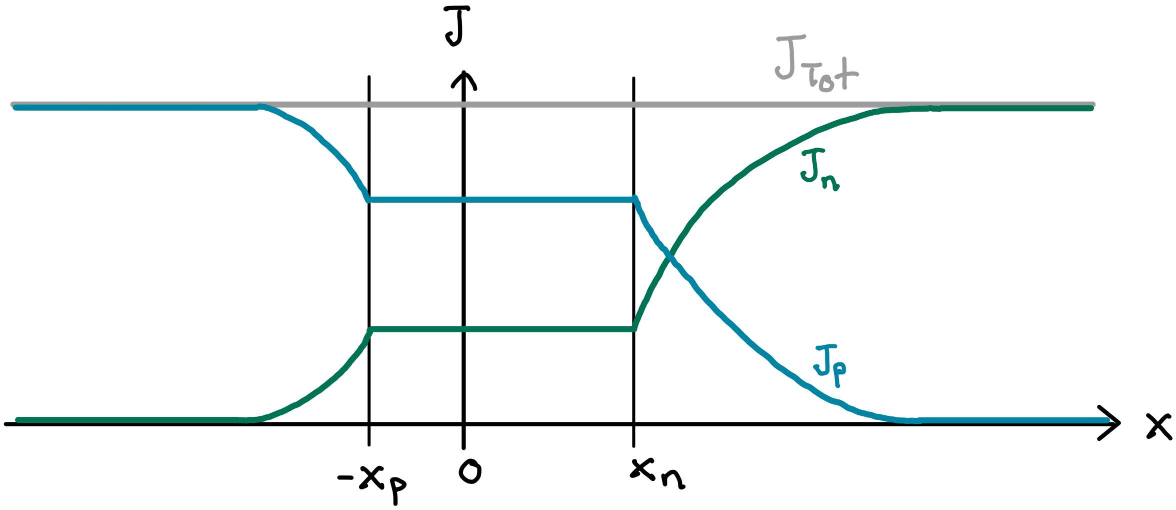
- <u>From diffusion eqn:</u>

$$J_p(x \geq x_n) = -qD_p \frac{dp_n(x)}{dx} = qD_p \frac{n_i^2}{N_D L_p}\left(e^{qV_A/kT} - 1\right)\exp\left[\frac{-(x-x_n)}{L_p}\right]$$

$$J_n(x \leq -x_p) = -qD_n \frac{dn_p(x)}{dx} = qD_n \frac{n_i^2}{N_A L_n}\left(e^{qV_A/kT} - 1\right)\exp\left[\frac{-(x_p-x)}{L_n}\right]$$

$$J_{Tot} = J_n(x_n) + J_p(x_n) = J_n(-x_p) + J_p(x_n)$$

$$\boxed{J_{Tot} = qn_i^2\left[\frac{D_n}{N_A L_n} + \frac{D_p}{N_D L_p}\right]\left(e^{qV_A/kT} - 1\right) = J_0\left(e^{qV/kT} - 1\right)}$$



$$\boxed{J_{Tot} = q n_i^2 \left[\frac{D_n}{N_A L_n} + \frac{D_p}{N_D L_p} \right] \left(e^{qV_A/kT} - 1 \right) = J_0 \left(e^{qV/kT} - 1 \right)}$$

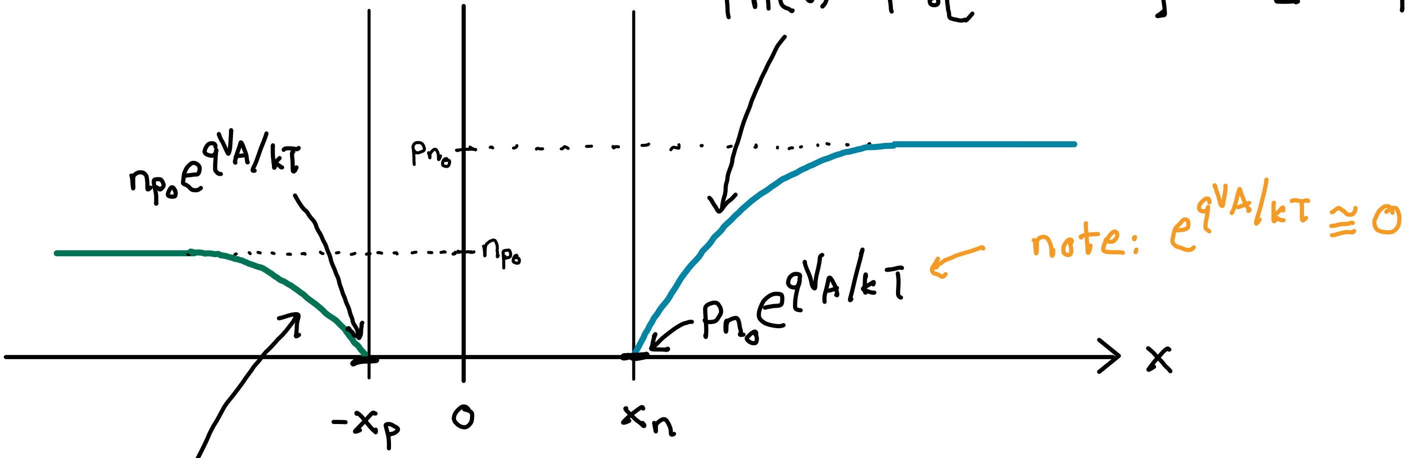
$$\left.\begin{aligned} J_n(x_n) &= \frac{q n_i^2 D_n}{N_A L_n} \left(e^{qV_A/kT} - 1 \right) \\ J_p(x_n) &= \frac{q n_i^2 D_p}{N_D L_p} \left(e^{qV_A/kT} - 1 \right) \end{aligned} \right\} \text{Electron and hole currents injected through depl. reg.}$$

$$\frac{J_n(x_n)}{J_p(x_n)} = \frac{D_n L_p N_D}{D_p L_n N_A}$$

- Effects of doping one side much more heavily than the other (e.g., n^+-p^- junction)

Reverse Bias ($V_A < 0$):

$$p_n(x) = p_{n_0}\left[e^{qV_A/kT} - 1\right]\cdot \exp\left[\frac{-(x - x_n)}{L_p}\right] + p_{n_0}$$



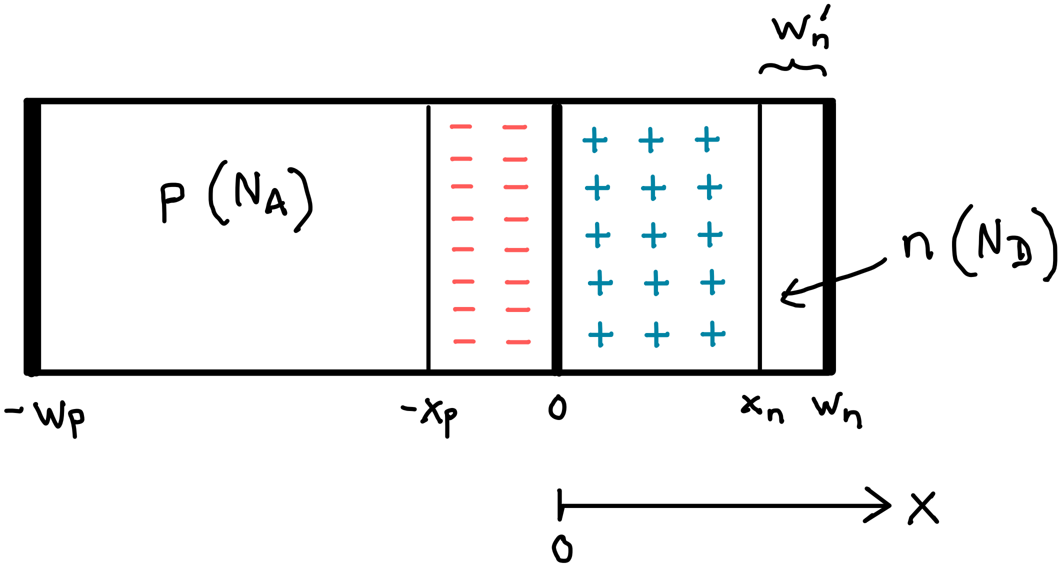
$$n_p(x) = n_{p_0}\left[e^{qV_A/kT} - 1\right]\cdot \exp\left[\frac{-(x_p - x)}{L_n}\right] + n_{p_0}$$

- Reverse bias current results from minority carries in the quasi-neutral regions diffusing into the depletion region and being swept across by the $\mathcal{E}$-field

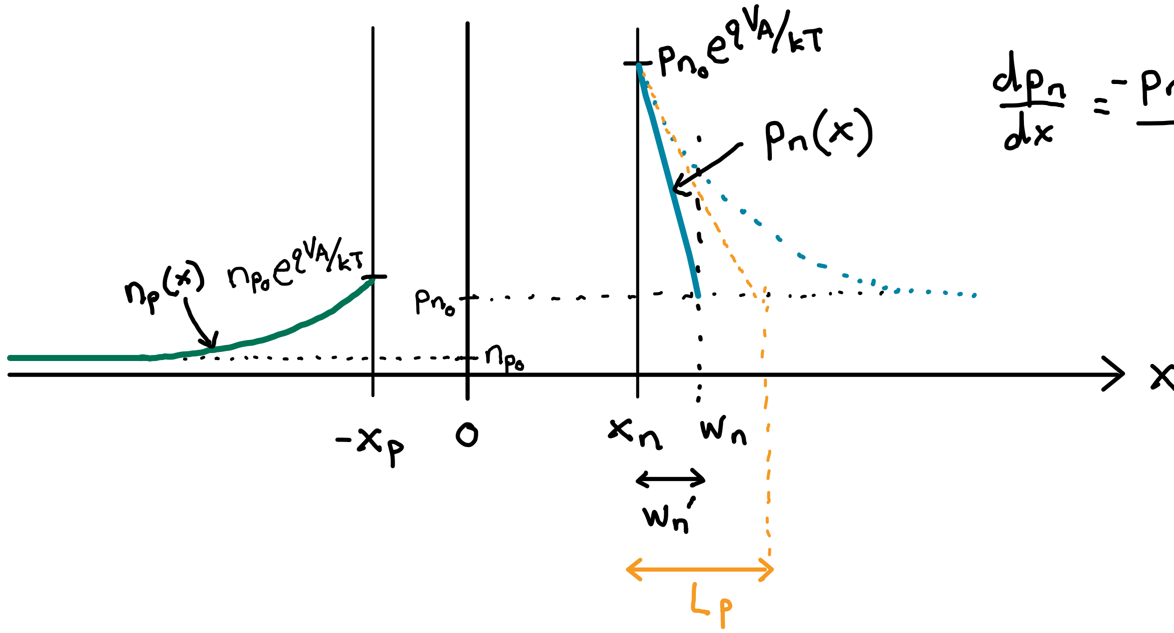
- $J_{tot} = J_0\left(e^{qV_A/kT} - 1\right)$ (same as forward bias)

- Any additional carriers (e^-'s or h^+'s) introduced into the depletion region, or in quasi-neutral region but within a diffusion length of the depletion region, add to the current (operating principle of photodiodes and BJTs)

Short-base diode ($w_n' << L_p$)



Forward Bias ($V > 0$):



$$\frac{dp_n}{dx} = \frac{-p_{n_0}\left(e^{qV_A/kT} - 1\right)}{w_n'}$$

$$J_p(x_n) = -qD_p \frac{dp_n}{dx} = \frac{q n_i^2 D_p}{N_D w_n'}\left(e^{qV_A/kT} - 1\right)$$

same as long-base diode only with w_n' replacing L_p

