VE320 – Summer 2021

Introduction to Semiconductor Devices

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Chapter 8 The pn Junction Diode

Outline

8.1 pn junction current

8.2 Generation-recombination currents

8.3 High-injection levels

8.4 A few more points on pn junctions (not in the textbook)

8.0 The logic behind the way to derive current

$I = f(V_b)$

$V_1 = I \cdot R_n$

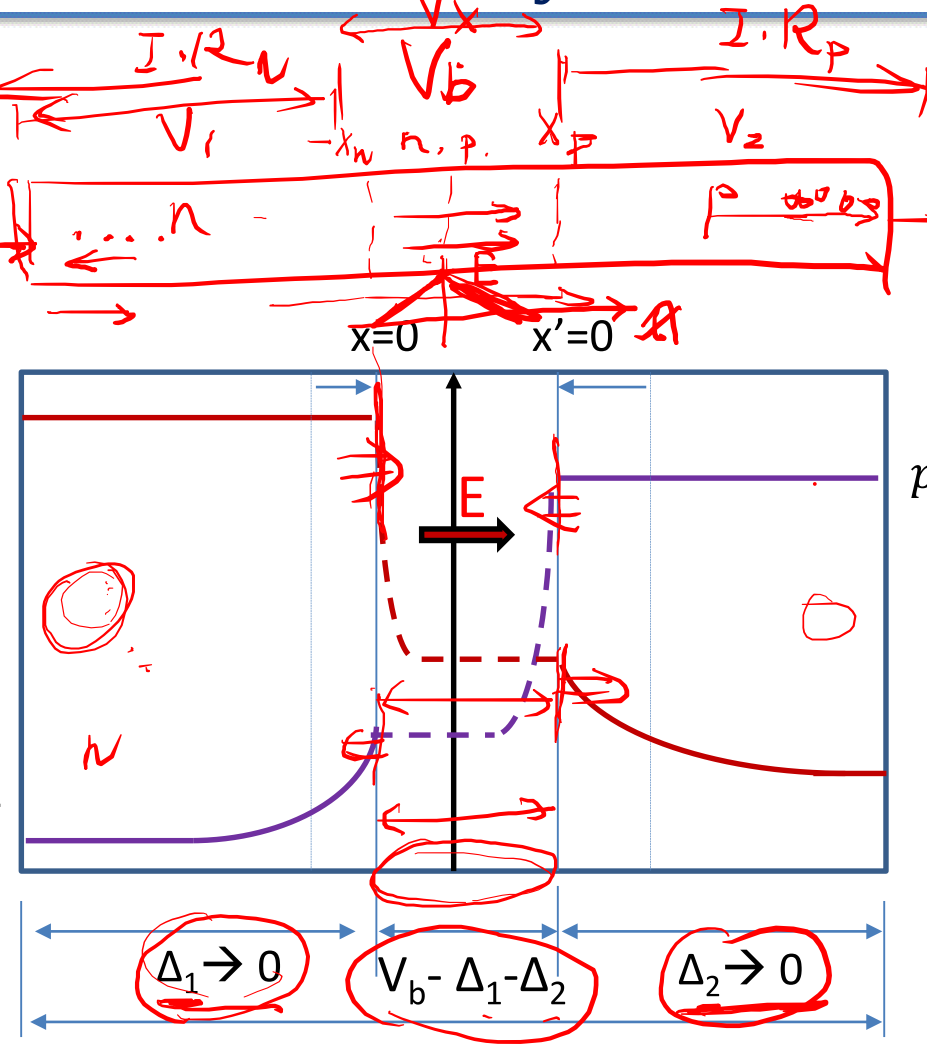
$n_{n0} = N_D$

$V_2 = I \cdot R_p$

$V_b = V_1 + V_2 + V_x$

$V_x = I \cdot R_x$

$$p_{n0} = \frac{n_i^2}{N_D}$$



$J = J_n + J_p$

$= J_{drift\,n} + J_{diff\,n}$

$+ \cancel{J_{drift\,p}}^{\,0} + J_{diff\,p}$

$$p_{p0} = N_A$$

$$n_{p0} = \frac{n_i^2}{N_A}$$

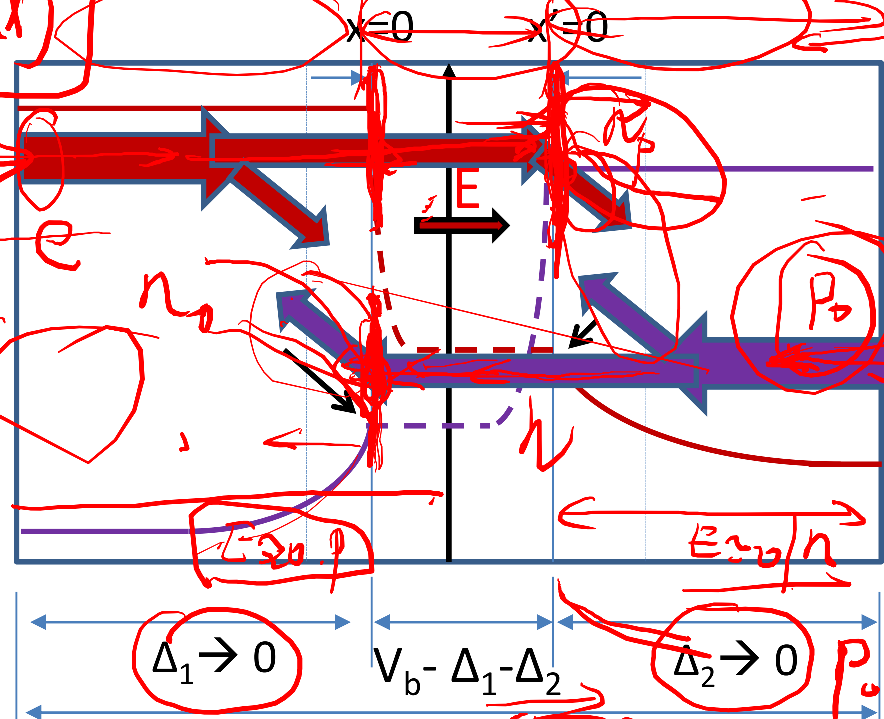
$I \sim V_b$

8.0 The logic behind the way to derive current

Total current I_t is uniform at every x → $I_t = I_n(x=0) + I_h(x=0) = I_n(x'=0) + I_h(x'=0)$

$n_{n0} = N_D$

$p_{p0} = N_A$



$p_{n0} = \dfrac{n_i^2}{N_D}$

$n_{p0} = \dfrac{n_i^2}{N_A}$

E_{app} n p+ E +V forward

$I_t = I_p(x) + I_n(x)$

minority

J_{np} n_p diffusion

J_{pn} p_n diffusion

$\dfrac{dI(x)}{dx} \rightarrow 0$

$I = I(x)$

$E \approx 0$ p

$E \approx 0$ n

$I = \mu_n q n E + \mu_p q p E$

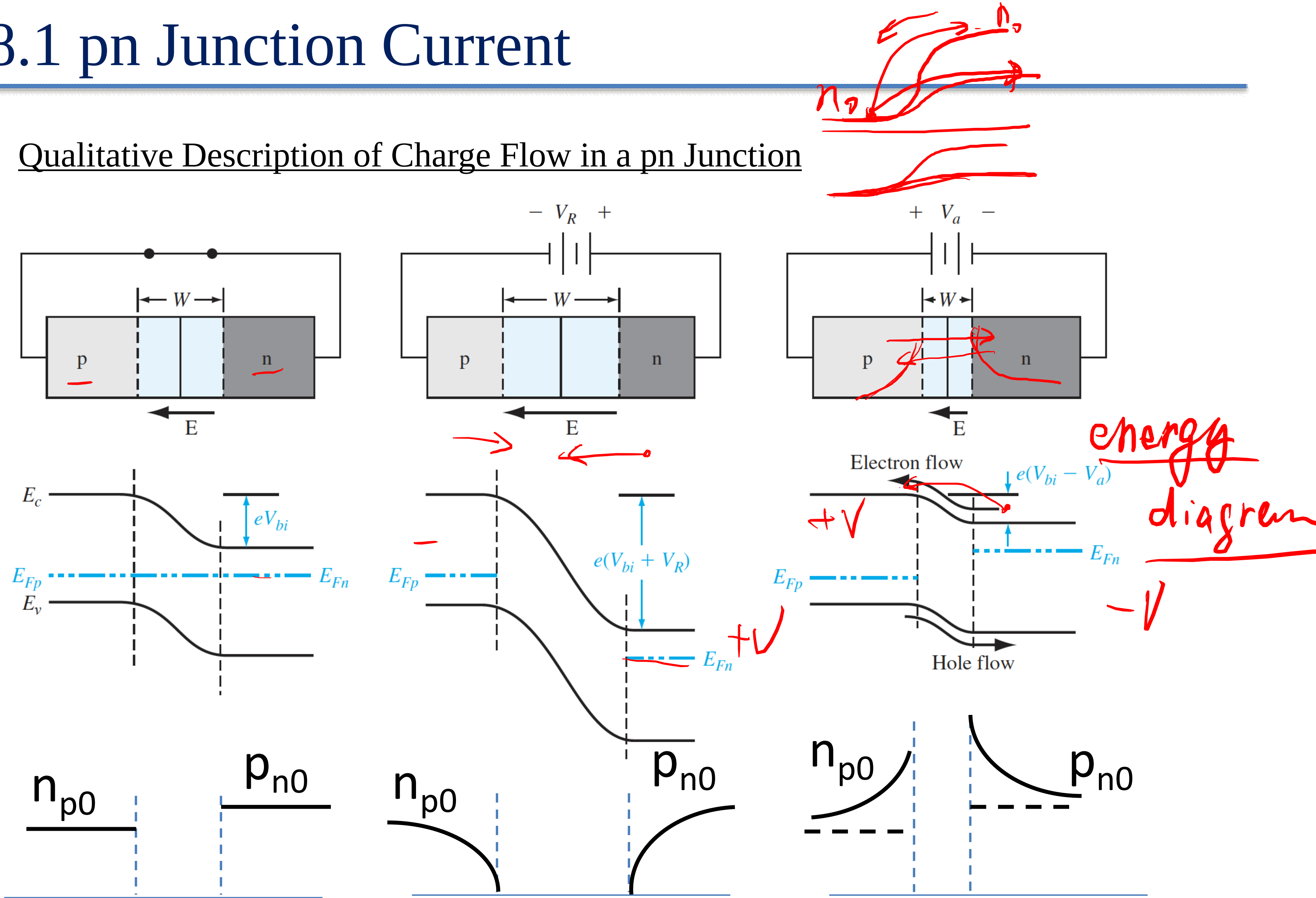
$p_0 \cdot E \cdot \mu$

$I \approx 0$ reverse

n p E_{in} E_{app}

8.1 pn Junction Current

<u>Qualitative Description of Charge Flow in a pn Junction</u>



8.1 pn Junction Current

Goal: to find the analytical expression of current

$n(x)$

$$\frac{\partial n}{\partial t} = D_n \frac{\partial^2 n}{\partial x^2} + \mu_n E \frac{\partial n}{\partial x} + n\mu_n \frac{\partial E}{\partial x} - \frac{\Delta n}{\tau} + G_{ex}$$

Electrons as minority

$p(x)$

$$\frac{\partial p}{\partial t} = D_p \frac{\partial^2 p}{\partial x^2} - \mu_p E \frac{\partial p}{\partial x} - p\mu_p \frac{\partial E}{\partial x} - \frac{\Delta p}{\tau} + G_{ex}$$

holes as minority

$$D_p \frac{d^2 n}{dx^2} - \frac{n-n_0}{\tau} = 0$$

$$\boxed{D_n \frac{d^2 \Delta n}{dx^2} - \frac{\Delta n}{\tau} = 0}$$

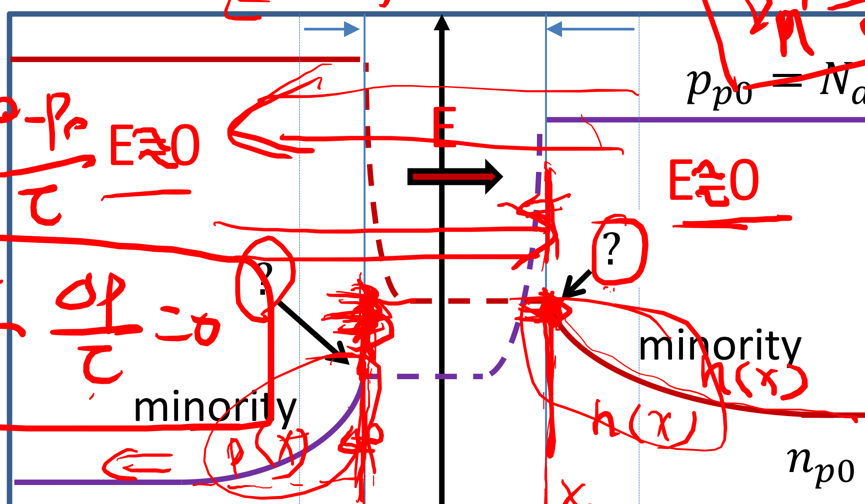
- How to simplify?
- Boundary condition?
- how to get total current from minority currents?

$$0 = D_p \frac{\partial^2 p}{\partial x^2} - \frac{p-p_0}{\tau}$$

$$\boxed{D_p \frac{d^2 \Delta p}{dx^2} - \frac{\Delta p}{\tau} = 0}$$

$n_{n0} = N_d$

$p_{n0} = \frac{n_i^2}{N_d}$



$p_{p0} = N_a$

$n_{p0} = \frac{n_i^2}{N_a}$

$p(-x_n)$ $n(x_p)$

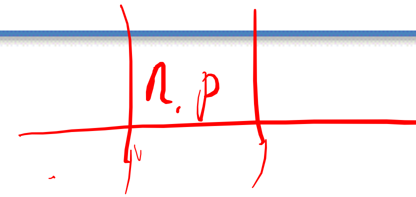
$x \to \infty$

$n(x) = n_{p0}$

$n(x) - n_{p0} = \Delta n(x)$

$$\frac{dn(x)}{dx} = \frac{d\Delta n(x)}{dx}$$

8.1 pn Junction Current



Assumptions of an ideal PN junction

1. The abrupt depletion layer approximation applies. The space charge regions have abrupt boundaries, and the semiconductor is neutral outside of the depletion region.

$n = N_c \exp\left(\frac{E_F - E_c}{kT}\right)$ $p = N_v \exp\left(\frac{E_v - E_F}{kT}\right)$

2. The Maxwell–Boltzmann approximation applies to carrier statistics.
3. The concepts of low injection and complete ionization apply. $N_d = n_{n0}$ $N_a = p_{p0}$

4a. The total current is a constant throughout the entire pn structure.

4b. The individual electron and hole currents are continuous functions through the pn structure. $I_p(x)$ continuous $I_n(x)$

4c. The individual electron and hole currents are constant throughout the depletion region.

no loss of electrons & holes in the depletion

no recombination

8.1 pn Junction Current

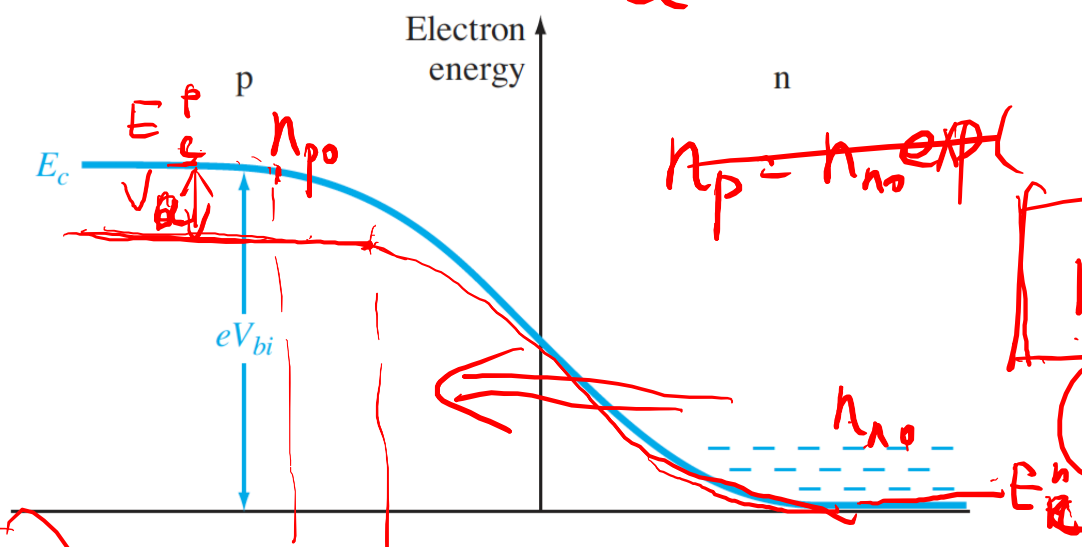
$$n_p = n_{n0}\exp\left(-\frac{qV_b}{kT}\right)\exp\left(\frac{qV_a}{kT}\right)$$

Boundary condition

$$n_o = N_c\exp\left(\frac{E_F-(E_{c0}-V_a)}{kT}\right) \quad V_a$$

$$\frac{n_p}{n_{n0}} = \exp\left(-\frac{q(V_b-V_a)}{kT}\right)$$

$$\frac{kT}{q}$$



$$\cancel{n_p = n_{n0}\exp(}$$

$$V_{bi} = V_t \ln\left(\frac{N_aN_d}{n_i^2}\right) \qquad V_t = \frac{kT}{q}$$

$$\boxed{n_p = n_{p0}\exp\left(\frac{qV_a}{kT}\right)}$$

$$n_{p0} = n_{n0}\exp\left(\frac{-eV_{bi}}{kT}\right)$$

$$\frac{n_{p0}}{n_{n0}} = \exp\left(\frac{E_c^n-E_c^p}{kT}\right) = \exp\left(-\frac{qV_{bi}}{kT}\right)$$

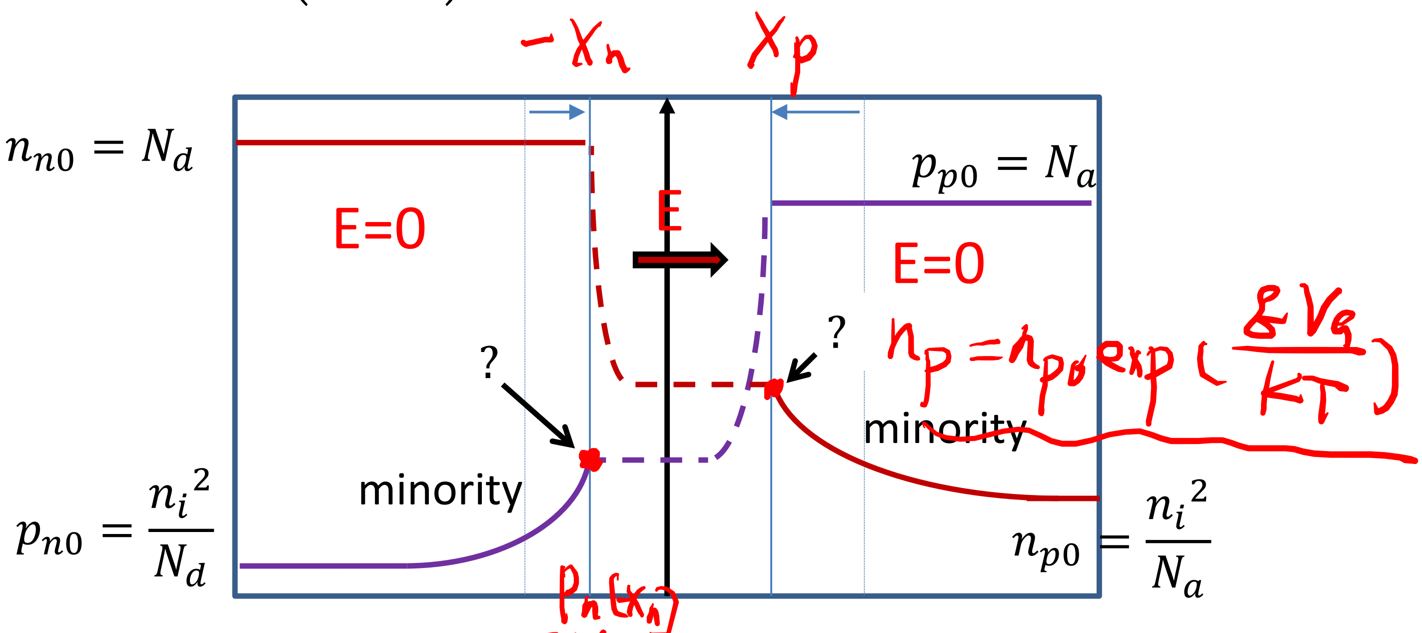
$$n_{n0} = N_c\exp\left(\frac{E_F-E_c^n}{kT}\right)$$

$$n_{p0} = N_c\exp\left(\frac{E_F-E_c^p}{kT}\right)$$

8.1 pn Junction Current

Boundary condition

$$p_{n0} = p_{p0} exp\left(\frac{-eV_{bi}}{kT}\right)$$

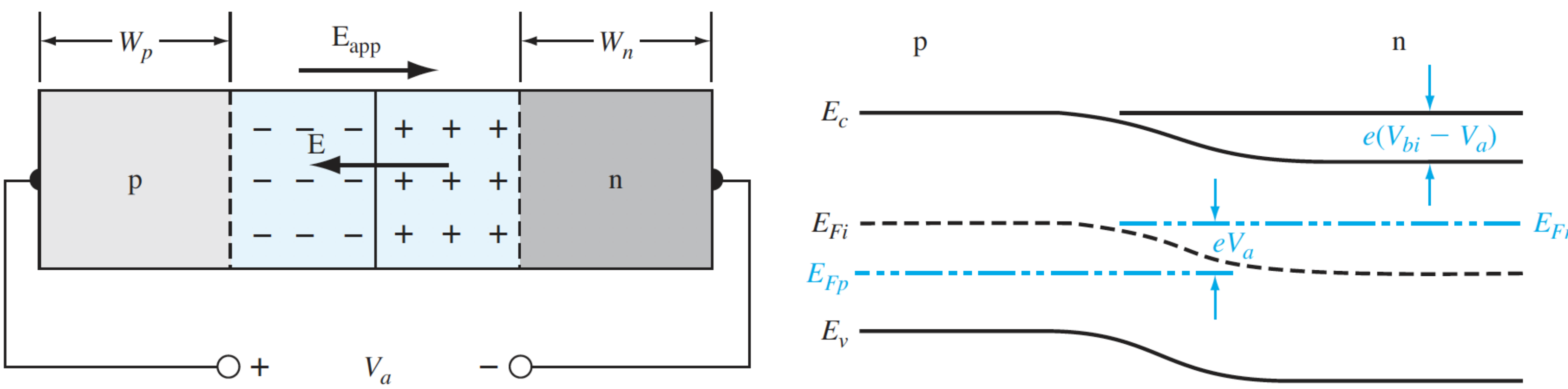


$$P_n(-x_n) = P_{n0} \exp\left(\frac{eV_a}{kT}\right)$$

8.1 pn Junction Current

Boundary condition

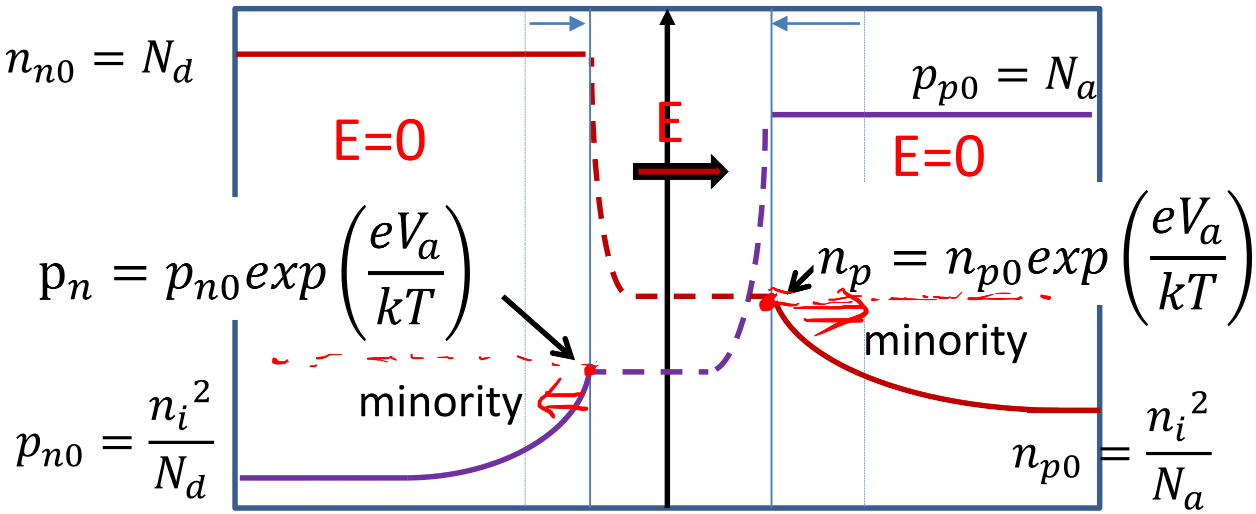
$$p_{no} = p_{no} \exp\left(\frac{qV_a}{KT}\right) \qquad n_p = n_{p0} \exp\left(\frac{qV_a}{KT}\right)$$



(a) (b)

8.1 pn Junction Current

Boundary condition



Check your understanding

Problem Example #1

Consider a silicon pn junction at T = 300K. Assume the doping concentration in the n region is $N_d = 10^{16}\ cm^{-3}$ and the doping concentration in the p region is $N_a = 6 \times 10^{15}\ cm^{-3}$. Assume a forward bias of 0.6V is applied to the pn junction. Calculate the minority concentration at the edge of the depletion region.

$$n_{n0} = N_a = 10^{16}\ cm^{-3} \qquad p_{p0} = 6\times10^{15}\ cm^{-3}$$

$$p_{n0} = \frac{n_i^2}{n_{n0}} = \frac{(1.5\times10^{10})^2}{10^{16}} = 2.25\times10^{4}\ cm^{-3}$$

$$p_n(-x_n) = p_{n0}\exp\left(\frac{qV_a}{kT}\right) = 2.25\times10^{4}\exp\left(\frac{0.6}{0.0259}\right)$$

$$= 2.59\times10^{14}\ cm^{-3}$$

$$n_{p0} = \frac{n_i^2}{p_{p0}} = \frac{(1.5\times10^{10})^2}{6\times10^{15}} = \cancel{3.99}\times10^{4}\ cm^{-3}$$

3.75

4.31×10^{14}

$\frac{0.6}{0.0259}$

$$n_p(x_p) = n_{p0}\exp\left(\frac{qV_a}{kT}\right) = 3.75\times10^{4}\, e^{\frac{0.6}{0.0259}}$$

8.1 pn Junction Current

$\Delta p(x) = A e^{x/\sqrt{D_p\tau}}$

$\Delta p(x) = A e^{x/\sqrt{D_p\tau_p}} + B e^{-x/\sqrt{D_p\tau_p}}$

<u>Minority carrier distribution</u>

$p_n(x=-x_n) = p_{n0} e^{qV_a/kT}$

$p_n(x_p)$

$$\boxed{D_p \frac{\partial^2 \Delta p}{\partial x^2} - \frac{\Delta p}{\tau_p} = 0}$$

$\Delta p(x = x_p) = p_n - p_{n0}$

$$\frac{d^2\Delta p}{dx^2} = \frac{1}{D_p\tau_p}\Delta p$$

$$\boxed{\frac{\partial p}{\partial t} = D_p \frac{\partial^2 p}{\partial x^2} - \mu_p E \frac{\partial p}{\partial x} - p\mu_p \frac{\partial E}{\partial x} - \frac{\Delta p}{\tau} + G_{ex}}$$

0, Δp, 0, 0, 0

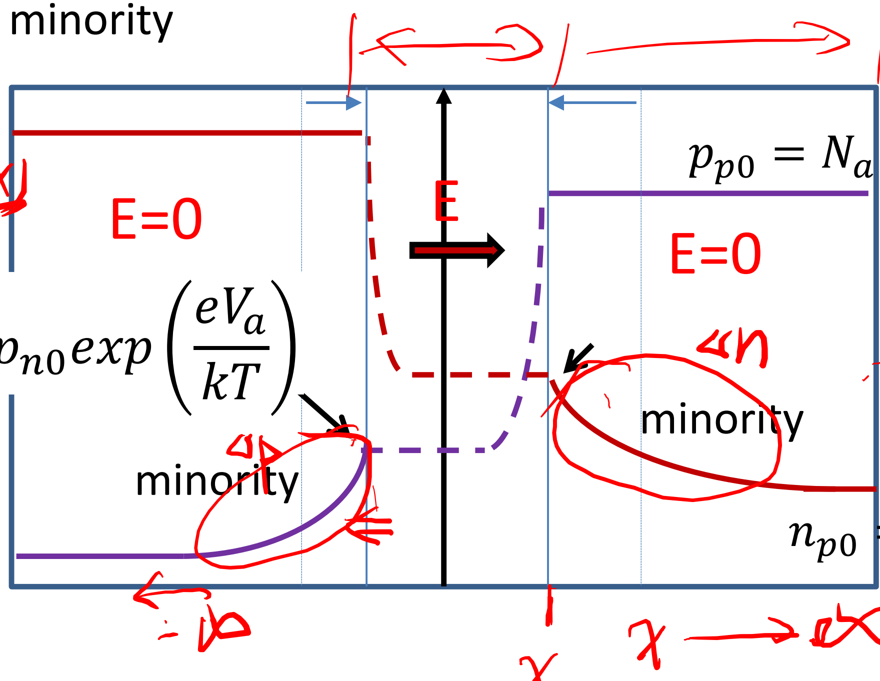
holes as minority

$F = -D_p \frac{d\Delta p(x)}{dx}$

$n_{n0} = N_d$

$p_n = p_{n0} exp\left(\frac{eV_a}{kT}\right)$

$p_{n0} = \frac{{n_i}^2}{N_d}$



$n_{p0} = \frac{{n_i}^2}{N_a}$

- How to simplify?
- Boundary condition?
- how to get total current from minority currents?

8.1 pn Junction Current

Minority carrier distribution

$$\delta p_n(x) = p_n(x) - p_{n0} = Ae^{x/L_p} + Be^{-x/L_p} \quad (x \le -x_p)$$

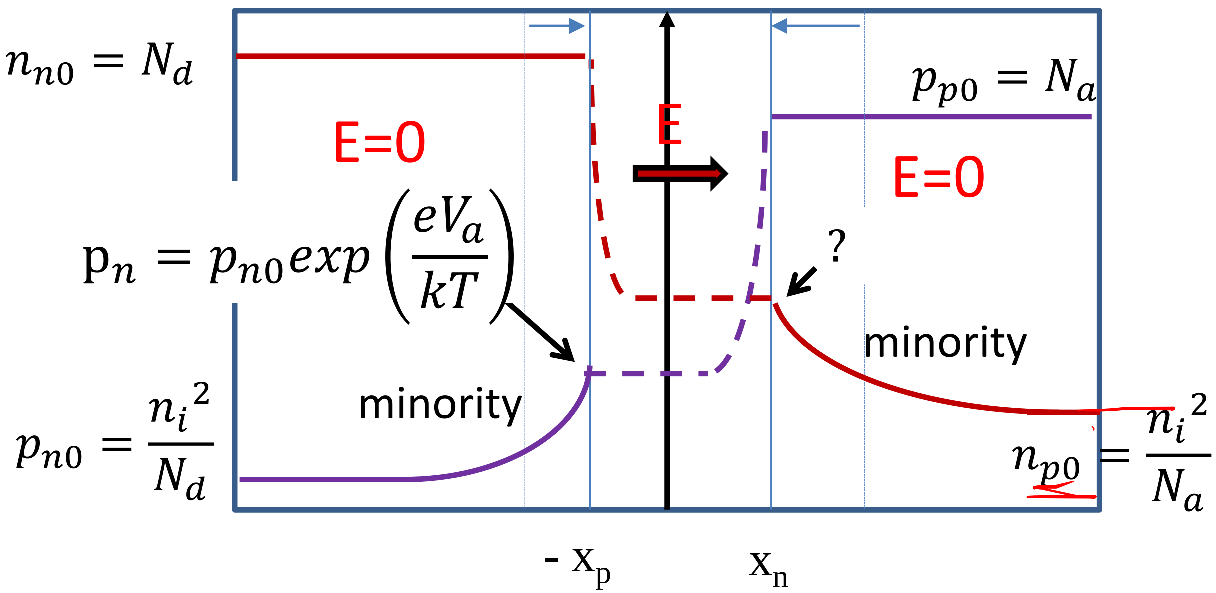
$$\delta n_p(x) = n_p(x) - n_{p0} = Ce^{x/L_n} + De^{-x/L_n} \quad (x \ge x_n)$$

$$p_n(x_n) = p_{n0} \exp\left(\frac{eV_a}{kT}\right)$$

$$n_p(-x_p) = n_{p0} \exp\left(\frac{eV_a}{kT}\right)$$

$$p_n(x \to +\infty) = p_{n0}$$

$$n_p(x \to +\infty) = n_{p0}$$

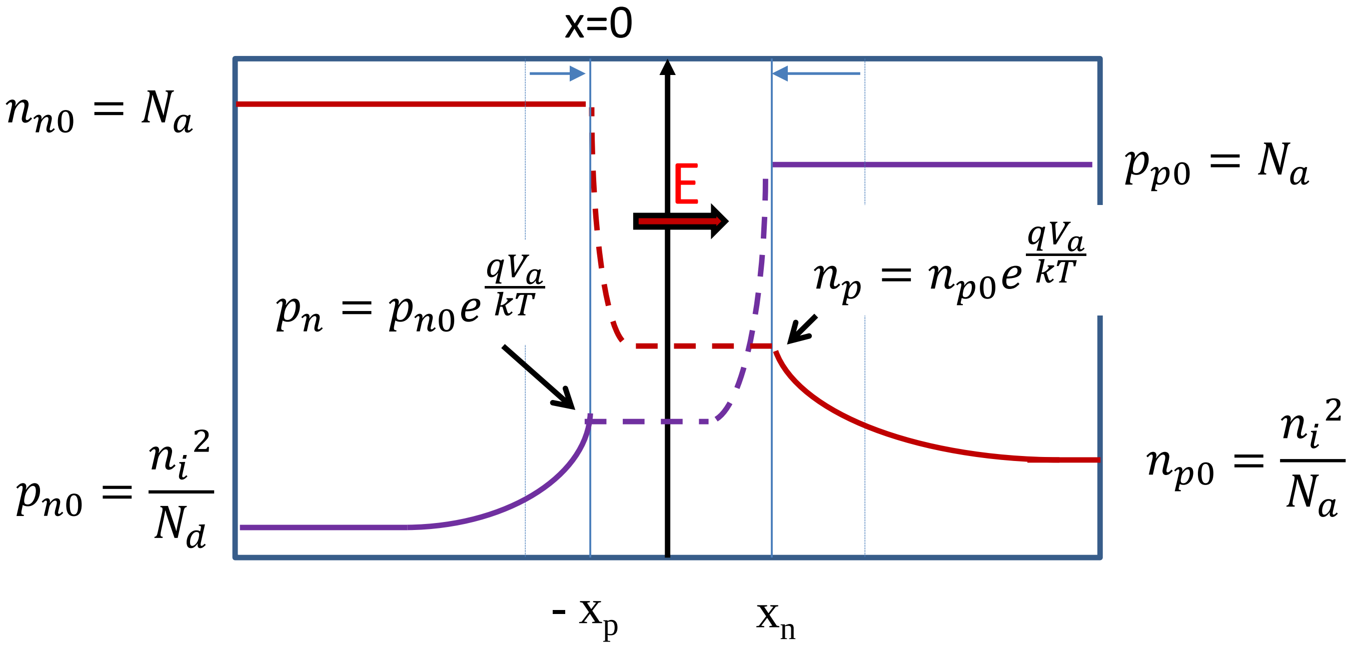


8.1 pn Junction Current

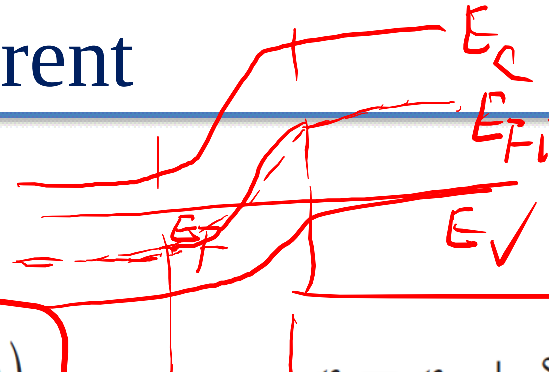
Minority carrier distribution

$$\Rightarrow \Delta p = p_n(x) - p_{n0} = p_{n0}(e^{\frac{qV_a}{kT}} - 1)e^{(x+x_p)/L_p}$$

$$\Rightarrow \Delta n = n_p(x) - n_{p0} = n_{p0}(e^{\frac{qV_a}{kT}} - 1)e^{(x_n-x)/L_n}$$



8.1 pn Junction Current



Minority carrier distribution

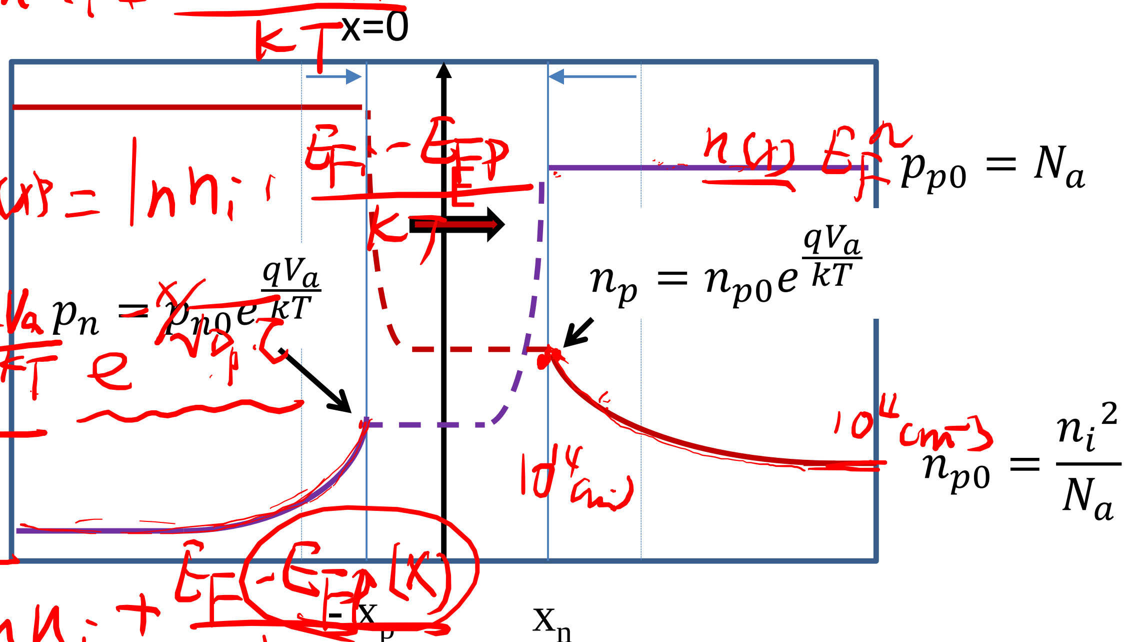
$$\ln\left[\, p_n = p_o + \delta p = n_i \exp\left(\frac{E_{Fi}-E_{Fp}}{kT}\right)\right.$$

$$n = n_o + \delta n = n_i \exp\left(\frac{E_{Fn}-E_{Fi}}{kT}\right)$$

$$\ln \delta p = \ln p_n = \ln n_i + \frac{E_{Fi}-E_{Fp}}{kT}$$

$$\ln \delta p(x) \approx \ln p_n(x) = \ln n_i + \frac{E_{Fi}-E_{Fp}}{kT}$$

$$\delta p(x) = p_{no}\, e^{\frac{qV_a}{kT}}\, e^{-\frac{x}{\sqrt{D_p \tau}}}$$



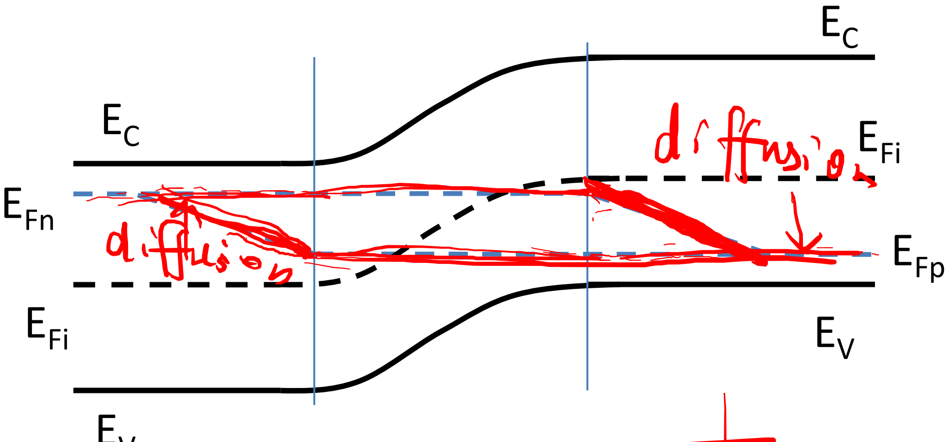
$$-\frac{x}{\sqrt{D_p \tau}} = \ln n_i + \frac{E_{Fi}-E_{Fp}(x)}{kT}$$

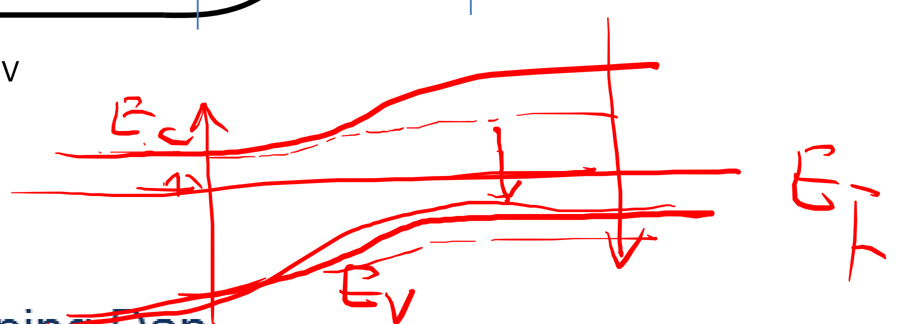
8.1 pn Junction Current

Minority carrier distribution

$$p = p_o + \delta p = n_i \exp\left(\frac{E_{Fi} - E_{Fp}}{kT}\right) \qquad n = n_o + \delta n = n_i \exp\left(\frac{E_{Fn} - E_{Fi}}{kT}\right)$$

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





8.1 pn Junction Current

Minority carrier distribution

$$p = p_o + \delta p = n_i \exp\left(\frac{E_{Fi} - E_{Fp}}{kT}\right) \qquad n = n_o + \delta n = n_i \exp\left(\frac{E_{Fn} - E_{Fi}}{kT}\right)$$

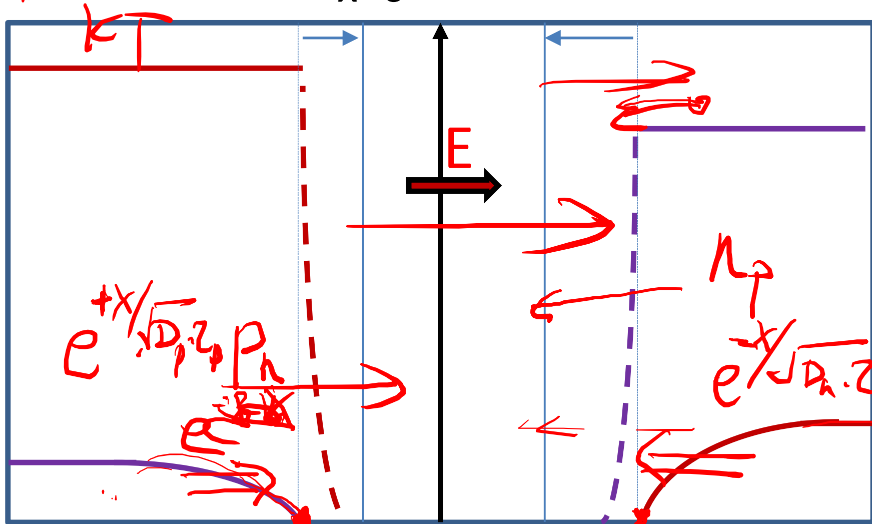
$$np = n_i^2 \exp\left(\frac{E_{Fn} - E_{Fp}}{kT}\right)$$

$$-\frac{x}{\sqrt{D_p \tau_p}} \sim -\frac{E_{Fp}(x)}{kT}$$

x=0

$n_{n0} = N_a$

$p_{p0} = N_a$



$p_{n0} = \frac{n_i^2}{N_d}$

$n_{p0} = \frac{n_i^2}{N_a}$

$-x_p$ $\quad x_n$

$$p_n = p_{n0} e^{qV_a/kT} \rightarrow 0$$

8.1 pn Junction Current

$$J = J_s\left(e^{\frac{qV_a}{kT}} - 1\right)$$

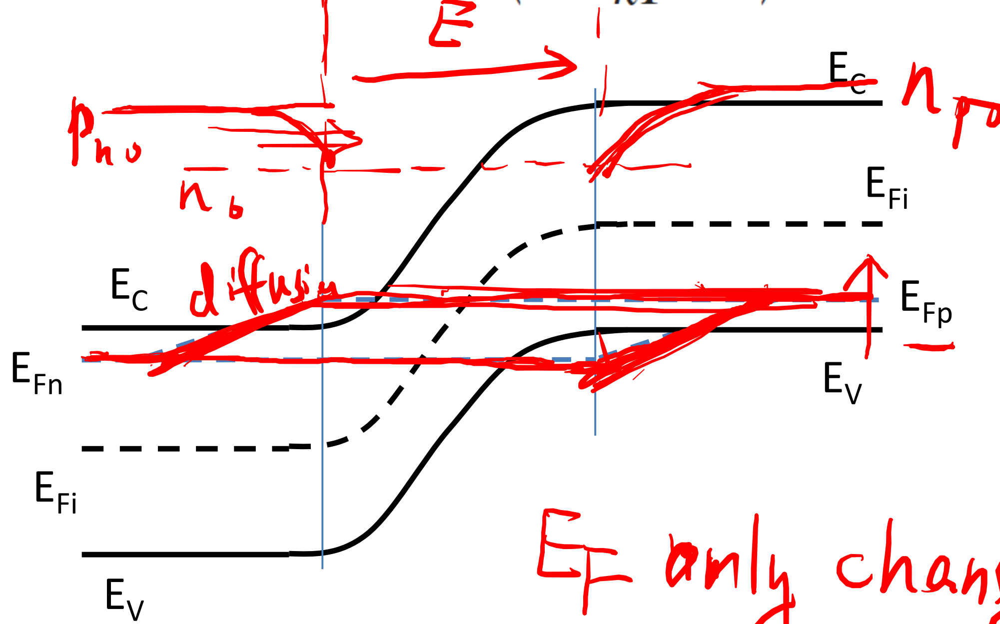
Minority carrier distribution

$$p = p_o + \delta p = n_i \exp\left(\frac{E_{Fi} - E_{Fp}}{kT}\right)$$

E_F

$$n = n_o + \delta n = n_i \exp\left(\frac{E_{Fn} - E_{Fi}}{kT}\right)$$

n_{n0} $$np = n_i^2 \exp\left(\frac{E_{Fn} - E_{Fp}}{kT}\right)$$ p_{p0}



E_F only changes in a region where minorities diffuse

8.1 pn Junction Current

- charge carrier transport: forward bias

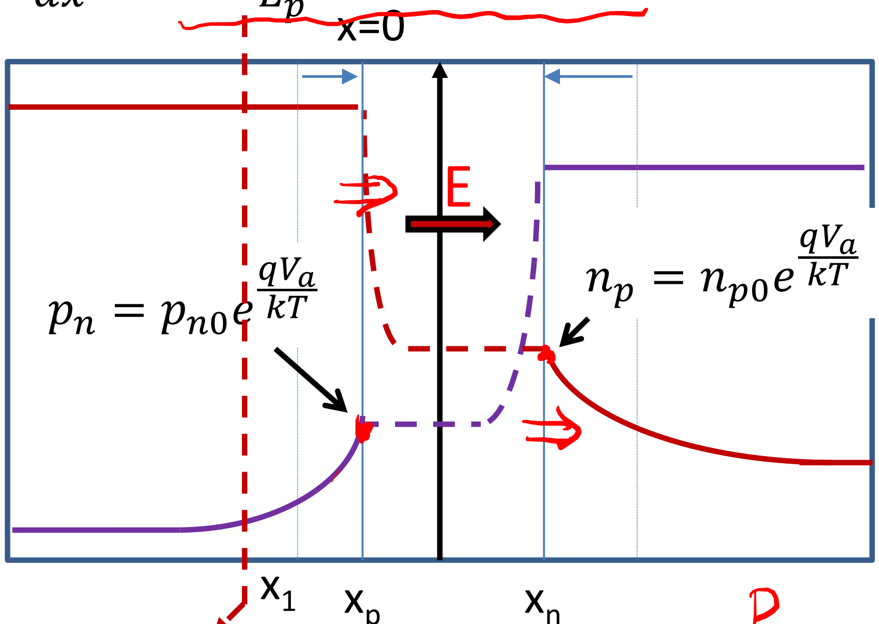
$$J_{n,diff} = qD_n \frac{dn_p}{dx} = -\frac{qD_n n_{p0}}{L_n}\left(e^{\frac{qV_a}{kT}} - 1\right)e^{\frac{x_n - x}{L_n}}$$

$$J_{p,diff} = -qD_p \frac{dp_n}{dx} = -\frac{qD_p p_{n0}}{L_p}\left(e^{\frac{qV_a}{kT}} - 1\right)e^{\frac{x + xp}{L_p}}$$

$$J = J_{n,diff}\Big|_{x_n} + J_{p,diff}\Big|_{-x_p}$$

$n_{n0} = N_d$

$p_{p0} = N_a$



$p_{n0} = \frac{n_i^2}{N_d}$

$n_{p0} = \frac{n_i^2}{N_a}$

P

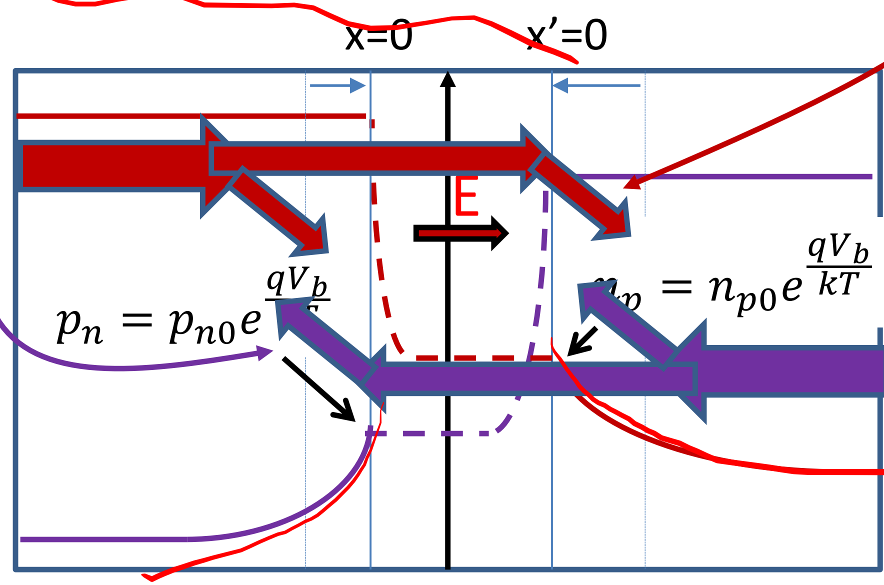
8.1 pn Junction Current

- charge carrier transport: forward bias

$$J_{n,diff} = qD_n \frac{dn_p}{dx} = -\frac{qD_n n_{p0}}{L_n}(e^{\frac{qV_a}{kT}} - 1)e^{\frac{x_n - x}{L_n}}$$

$$J = J_n|_{x'=0} + J_n|_{x=0}$$

$$J_{p,diff} = -qD_p \frac{dp_n}{dx} = -\frac{qD_p p_{n0}}{L_p}(e^{\frac{qV_a}{kT}} - 1)e^{\frac{x+xp}{L_p}}$$



$$n_{n0} = N_D$$

$$p_{p0} = N_A$$

$$n_p = n_{p0}e^{\frac{qV_b}{kT}}$$

$$p_n = p_{n0}e^{\frac{qV_b}{kT}}$$

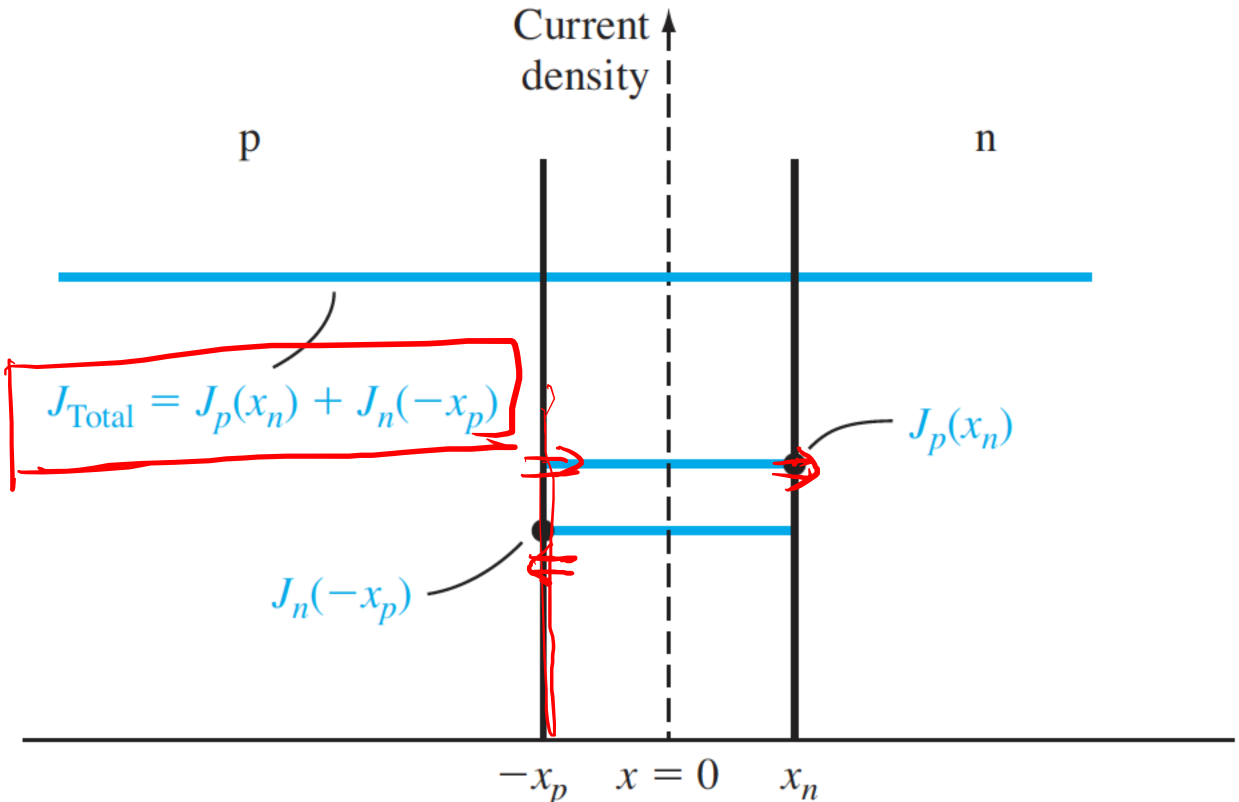
$$p_{n0} = \frac{n_i^2}{N_D}$$

$$n_{p0} = \frac{n_i^2}{N_A}$$

Assumption: No recombination-generation in depletion region.

8.1 pn Junction Current

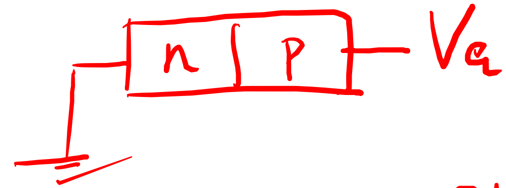
- Ideal pn junction current



Assumption: No recombination-generation in depletion region.

8.1 pn Junction Current

- Ideal pn junction current

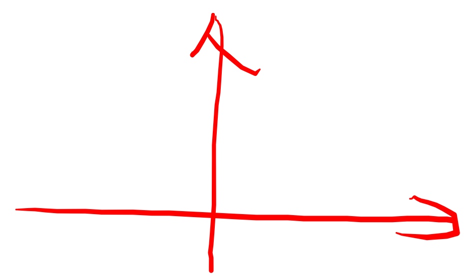


$$J = J_n|_{x'=0} + J_n|_{x=0}$$

$$J = J_s(e^{\frac{qV_b}{kT}} - 1)$$

$$J_s = \frac{qD_n n_{p0}}{L_n} + \frac{qD_p p_{n0}}{L_p}$$

$$J = J_s(e^{\frac{qV_a}{kT}} - 1)$$



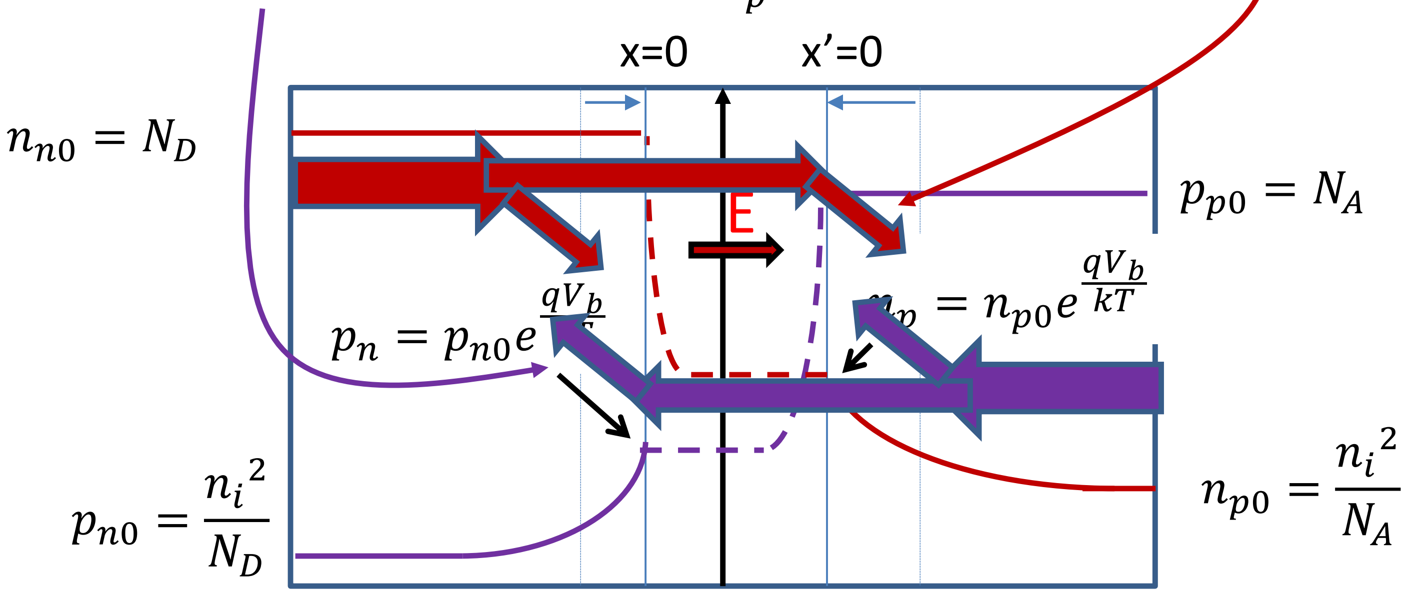
8.1 pn Junction Current

- charge carrier transport: <u>forward bias: current ratio</u>

$$J_n = qD_n \frac{dn_p}{dx} = -\frac{qD_n n_{p0}}{L_n}\left(e^{\frac{qV_b}{kT}} - 1\right)$$

$$J_p = -qD_p \frac{dp_n}{dx} = -\frac{qD_p p_{n0}}{L_p}\left(e^{\frac{qV_b}{kT}} - 1\right)$$

$$\boxed{\frac{J_n}{J_p} = \frac{D_n n_{p0}/L_n}{D_p p_{n0}/L_p}}$$



Assumption: No recombination-generation in depletion region.

8.1 pn Junction Current

- charge carrier transport: reverse bias

$$J_n = qD_n \frac{dn_p}{dx} = \frac{qD_n n_{p0}}{L_n}$$

$$J_p = -qD_p \frac{dp_n}{dx} = \frac{qD_p p_{n0}}{L_p}$$

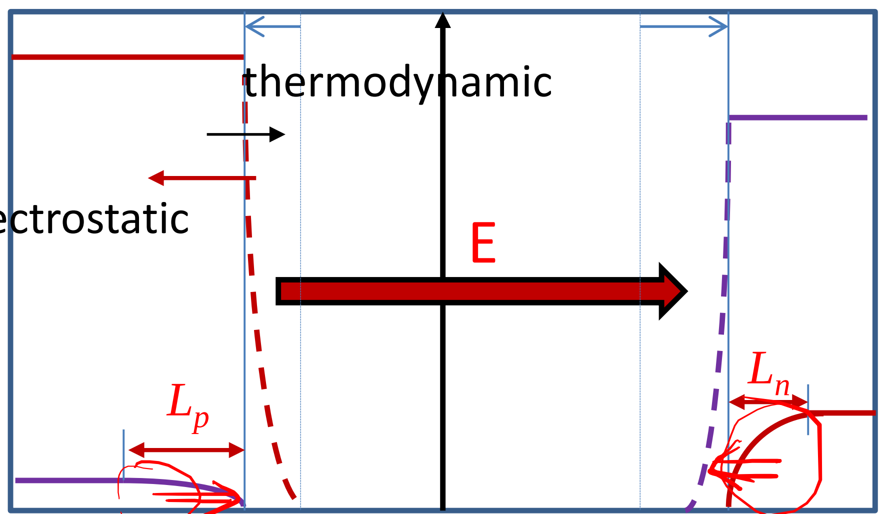
$$\boxed{J = J_n|_{x'=0} + J_n|_{x=0}}$$

$$\boxed{J = J_s\left(e^{\frac{qV_b}{kT}} - 1\right) = -J_s}$$

$$\boxed{J_s = \frac{qD_n n_{p0}}{L_n} + \frac{qD_p p_{n0}}{L_p}}$$

$n_{n0} = N_d$

$p_{n0} = \frac{n_i^2}{N_d}$



$p_{p0} = N_a$

$n_{p0} = \frac{n_i^2}{N_a}$

Assumption: No recombination-generation in depletion region.

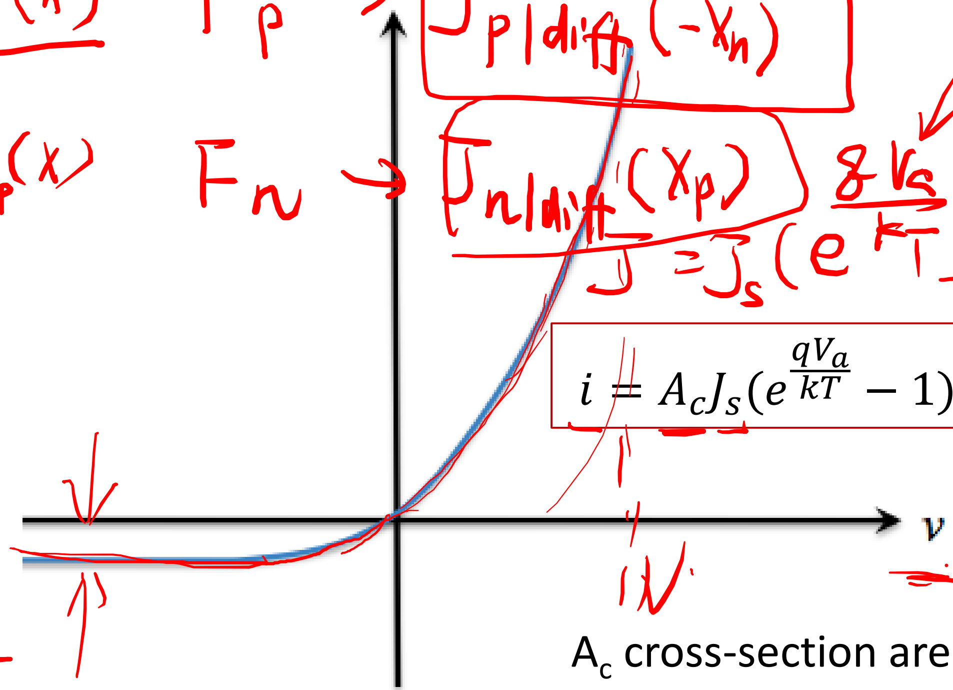
8.1 pn Junction Current

- charge carrier transport: <u>forward bias</u>

$\Delta p_n(x)$ $F_p \rightarrow J_p|_{diff}(-x_n)$

$\Delta n_p(x)$ $F_n \rightarrow J_n|_{diff}(x_p)$

$J = J_s(e^{\frac{qV_a}{kT}} - 1)$



$-J_s$

$$i = A_c J_s(e^{\frac{qV_a}{kT}} - 1)$$

A_c cross-section area

V_b

$$J = J_n|_{x'=0} + J_n|_{x=0}$$

$$J = J_s(e^{\frac{qV_a}{kT}} - 1)$$

$$J_s = \frac{qD_n n_{p0}}{L_n} + \frac{qD_p p_{n0}}{L_p}$$

$\frac{kT}{q} = 0.0259V$

$25.9mV$

Check your understanding

Problem Example #2

Given the following parameters in a silicon pn junction, determine the ideal reverse-saturation current density of this pn junction at 300K.

leakage

$N_a = N_d = 10^{16}\ \text{cm}^{-3}$ $\qquad n_i = 1.5 \times 10^{10}\ \text{cm}^{-3}$

$D_n = 25\ \text{cm}^2/\text{s}$ $\qquad \tau_{p0} = \tau_{n0} = 5 \times 10^{-7}\ \text{s}$

$D_p = 10\ \text{cm}^2/\text{s}$ $\qquad \epsilon_r = 11.7$

$$n_{p0} = \frac{n_i^2}{n_{n0}} = \frac{n_i^2}{N_d} = \frac{(1.5\times10^{10})^2}{10^{16}} = 2.25\times10^{4}$$

$$J = J_s\left(e^{\frac{qV_a}{kT}} - 1\right)$$

$$L_p = \sqrt{D_p \cdot \tau_p} = \sqrt{10 \times 5\times10^{-7}} = 2.23\times10^{-3}\ \text{cm}$$

$$V_a \to \ominus \qquad e^{\frac{qV_a}{kT}} \to 0$$

$$L_n = \sqrt{D_n \cdot \tau_n} = \sqrt{25 \times 5\times10^{-7}} = 3.5\times10^{-3}\ \text{cm}$$

$$J = -J_s = \frac{qD_n \cdot n_{p0}}{L_n} + \frac{qD_p \cdot p_{n0}}{L_p} = 1.6\times10^{-19}\left(\frac{25\times10^4}{3.5\times10^{-3}} + \frac{10\times10^4}{2.2\times10^{-3}}\right)$$

$$= -4.16\times10^{-11}\ \text{A/cm}^2$$

Outline

no reco generation

8.1 pn junction current ideal pN junction

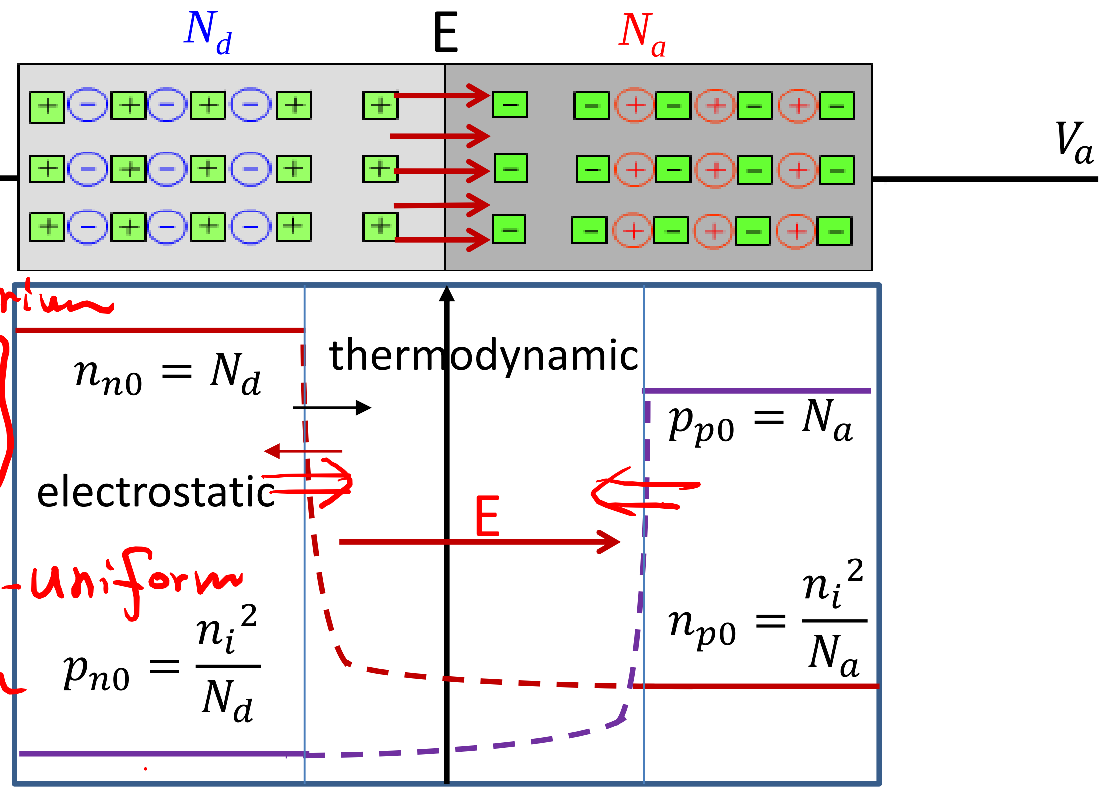
8.2 Generation-recombination currents $J - V_a$

8.3 High-injection levels

8.4 A few more points on pn junctions (not in the textbook)

8.2 Generation-recombination currents

Zero Bias V_a=0



thermal equilibrium

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

regardless non-uniform

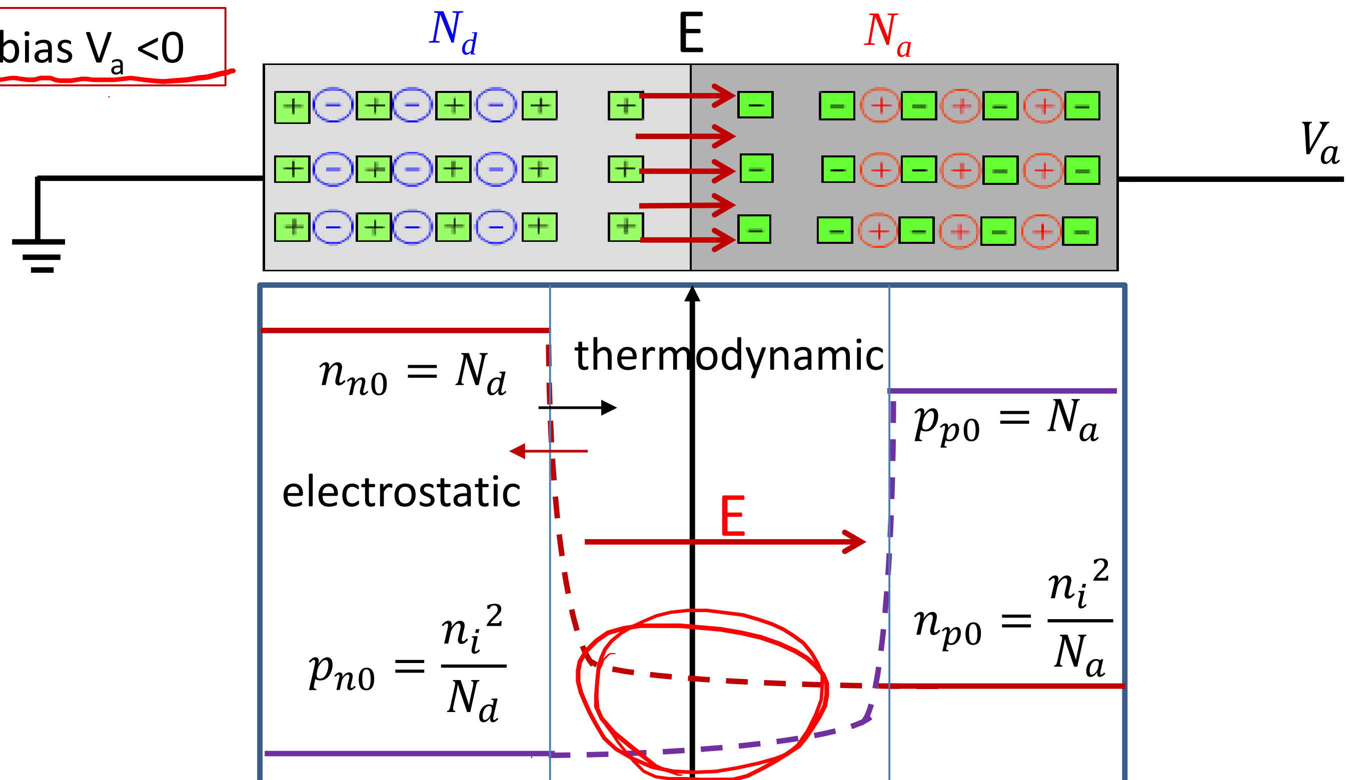
p.n

$$R_n = \frac{(np - n_i^2)}{\tau_p\left[n + n_i \exp\left(\frac{E_t - E_i}{kT}\right)\right] + \tau_n\left[p + n_i \exp\left(\frac{E_i - E_t}{kT}\right)\right]} = 0$$

$$\textit{In depletion region}: \; np = n_i^2 \exp\left(\frac{qV_a}{kT}\right)$$

8.2 Generation-recombination currents

Reverse bias $V_a < 0$



$$R_n = \frac{(\overset{0}{np} - n_i^2)}{\tau_p\left[\underset{0}{n} + n_i \exp\left(\frac{E_t - E_i}{kT}\right)\right] + \tau_n\left[\underset{0}{p} + n_i \exp\left(\frac{E_i - E_t}{kT}\right)\right]}$$

$$R_n = -\frac{n_i^2}{\tau_p n_i \exp\left(\frac{E_t - E_i}{kT}\right) + \tau_n n_i \exp\left(\frac{E_i - E_t}{kT}\right)}$$

8.2 Generation-recombination currents

Reverse bias V_a <0

To simplify the calculation, we assume

$$\boxed{E_t = E_i, \tau_n = \tau_p = \tau}$$

$$\boxed{R_n = \frac{-n_i}{2\tau} = -G_0}$$

$$\boxed{R_n = \frac{(\cancelto{0}{np} - n_i^2)}{\tau_p\left[\cancelto{0}{n} + n_i \exp\left(\frac{E_t - E_i}{kT}\right)\right] + \tau_n\left[\cancelto{0}{p} + n_i \exp\left(\frac{E_i - E_t}{kT}\right)\right]}}$$

$$= -\frac{n_i^2}{\tau n_i + \tau n_i} = -\frac{n_i}{2\tau}$$

E_g

$n_i = \sqrt{N_c N_v}\, \exp\left(\frac{-E_g}{2kT}\right)$

8.2 Generation-recombination currents

Reverse bias $V_a < 0$

To simplify the calculation, we assume

$$\boxed{E_t = E_i, \tau_n = \tau_p = \tau}$$

$$\boxed{R_n = \frac{-n_i}{2\tau} = -G_0}$$

$$W_{dep} = \sqrt{\frac{2\varepsilon(V_{bi}+V_R)}{q}\,\frac{N_a+N_d}{N_a N_d}}$$

Current density from G-R in the depletion region:

$$J_r = \int_0^W qG_0\,dx = \frac{qW_{dep}n_i}{2\tau}$$

$$R_n = \frac{(\cancelto{0}{np} - n_i^2)}{\tau_p\left[\cancelto{0}{n} + n_i \exp\left(\frac{E_t - E_i}{kT}\right)\right] + \tau_n\left[\cancelto{0}{p} + n_i \exp\left(\frac{E_i - E_t}{kT}\right)\right]}$$

8.2 Generation-recombination currents

Reverse bias V_a <0

To simplify the calculation, we assume

$$\boxed{E_t = E_i, \tau_n = \tau_p = \tau}$$

$$\boxed{R_n = \frac{-n_i}{2\tau} = -G_0}$$

Current density from G-R in the depletion region:

$$J_r = \int_0^W qG_0 dx = \frac{qWn_i}{2\tau}$$

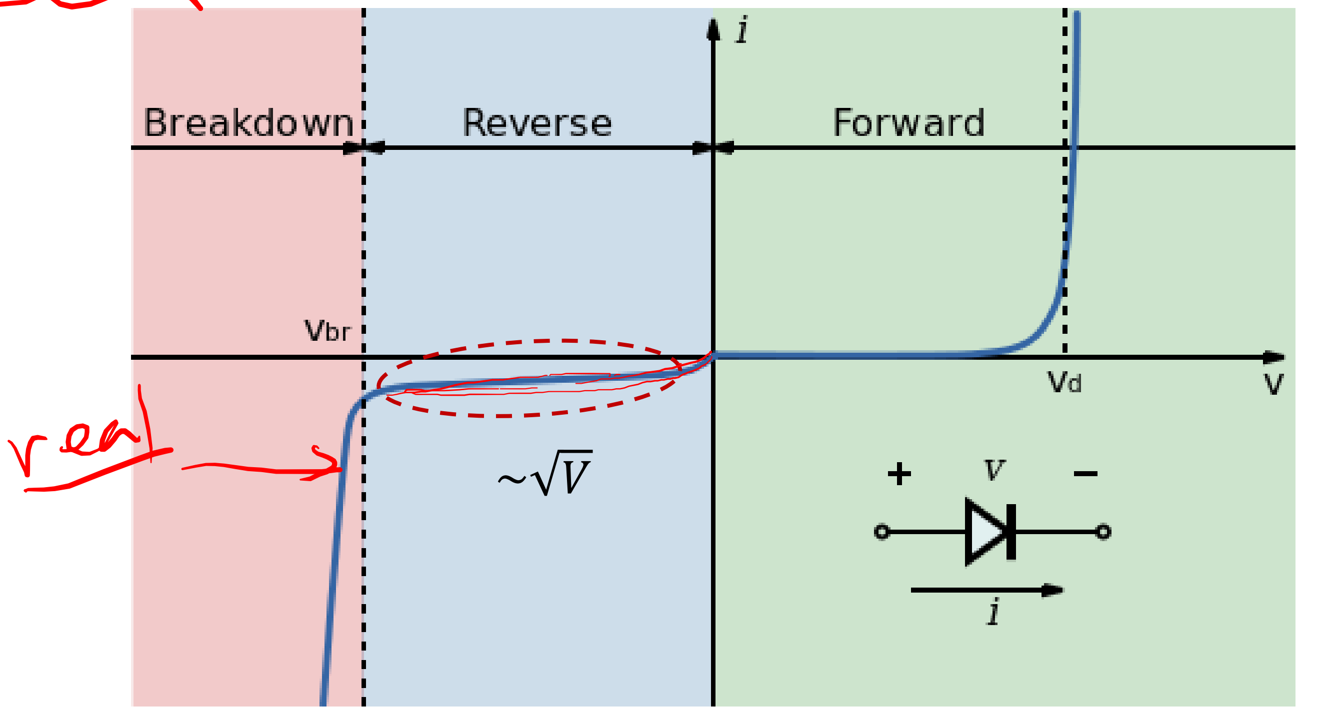
V_R

$$\boxed{W = \overbrace{a + b}^{x_p + x_n} = \sqrt{\frac{2\varepsilon(V_{bi} - V_a)}{q} \frac{N_d + N_a}{N_a N_d}}}$$

$$\boxed{R_n = \frac{\cancelto{0}{(np} - n_i^2)}{\tau_p\left[\cancelto{0}{n} + n_i \exp\left(\frac{E_t - E_i}{kT}\right)\right] + \tau_n\left[\cancelto{0}{p} + n_i \exp\left(\frac{E_i - E_t}{kT}\right)\right]}}$$

8.2 8.2 Generation-recombination currents

Reverse bias V_a <0

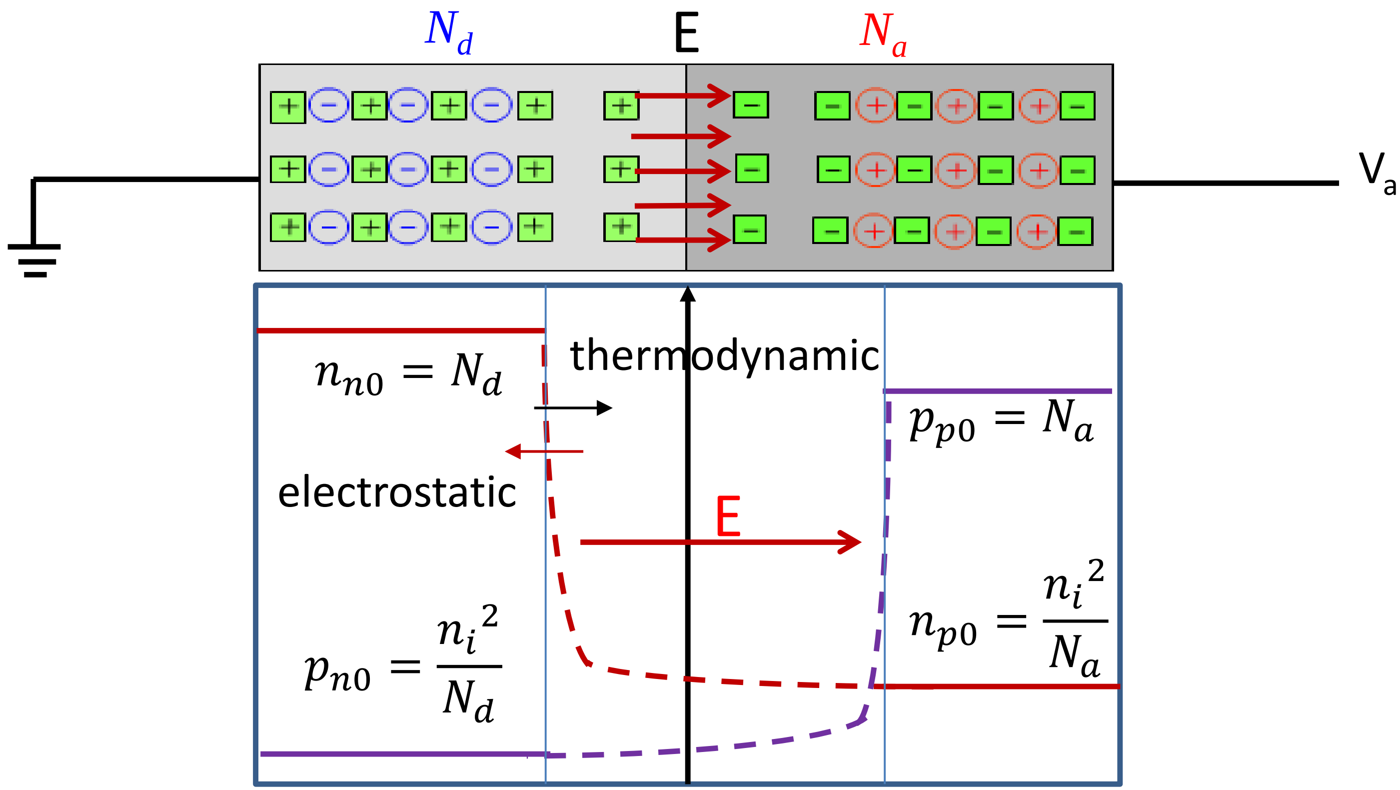


Current density from G-R in the depletion region:

$$J_r = \int_0^W qG\,dx = \frac{qWn_i}{2\tau}$$

$$\boxed{W = a + b = \sqrt{\frac{2\varepsilon(V_{bi} - V_a)}{q}\frac{N_d + N_a}{N_a N_d}}}$$

8.2 Generation-recombination currents



$$In\ depletion\ region:\ np = n_i^2 \exp(\frac{qV_a}{kT})$$

8.2 Generation-recombination currents

$$e^{\frac{qV_a}{2kT}} = x$$

$$\frac{n_i}{2\tau}\frac{x^2-1}{\cancel{x+1}} = \frac{n_i}{2\tau}(x+1) \qquad \cancel{(x+1)}(x-1) \qquad e^{\frac{qV_a}{kT}} = x^2$$

To simplify the calculation, we assume

$$\boxed{E_t = E_i, \tau_n = \tau_p = \tau}$$

$$R_n = \frac{n_i^2\left(e^{\frac{qV_a}{kT}}-1\right)}{\tau\left(n_i e^{\frac{qV_a}{2kT}} + n_i e^{\frac{qV_a}{2kT}} + 2n_i\right)} = \frac{n_i^2\left(e^{\frac{qV_a}{kT}}-1\right)}{2\tau \cdot n_i\left(e^{\frac{qV_a}{2kT}}+1\right)}$$

$$= \frac{n_i}{2\tau}\left(e^{\frac{qV_a}{2kT}}+1\right)$$

When n=p, U reaches its max value.

$$R_n = \frac{np - n_i^2}{\tau_p\left[n + n_i \exp\left(\cancel{\frac{E_t-E_i}{kT}}\right)\right] + \tau_n\left[p + n_i \exp\left(\cancel{\frac{E_i-E_t}{kT}}\right)\right]}$$

$$n = p \qquad n \cdot p = n_i^2 \exp\left(\frac{qV_a}{kT}\right)$$

$$n \simeq p = n_i \exp\left(\frac{qV_a}{2kT}\right)$$

8.2 Generation-recombination currents

Current density from G-R in the depletion region:

For a non-ideal pn junction, the total current density:

8.2 Generation-recombination currents

Forward bias V> 3kT/q=0.078V:

the ideality factor

8.2 Generation-recombination currents

$$J = J_F + J_r = J_s\left[\exp\left(\frac{qV_a}{kT}\right) - 1\right] + \frac{qWn_i}{2\tau}\left[\exp\left(\frac{qV_a}{2kT}\right) - 1\right]$$

Forward bias V> 3kT/q=0.078V:

$$J = J_F + J_r = J_s \exp\left(\frac{qV_a}{kT}\right) + \frac{qWn_i}{2\tau}\exp\left(\frac{qV_a}{2kT}\right) = J_0 \exp\left(\frac{qV_a}{nkT}\right)$$

the ideality factor

Reverse bias:

$$J_0 = -J_s - \frac{qWn_i}{2\tau} = -\left(\frac{qD_n n_{p0}}{L_n} + \frac{qD_p p_{n0}}{L_p}\right) - \frac{qWn_i}{2\tau}$$

Check your understanding

Problem Example #3

A PN junction consisting an n-type semiconductor in contact with another p-type semicondcutor (to be covered later) has a depletion region in which n_0 and p_0 are nearly zero. Suppose a silicon PN junction has defects located at the middle of the semiconductor. The defect concentration is 10^{16} cm^{-3} and the capture rate C_n and C_p for electrons and holes are 10^{-10} cm^{-3}/s. Find the leakage current of the Si PN junction.

$N_t = 10^{16}$ cm^{-3}
C_n=C_p=10^{-10} cm^{-3}/s

Depletion region

Outline

8.1 pn junction current

8.2 Generation-recombination currents

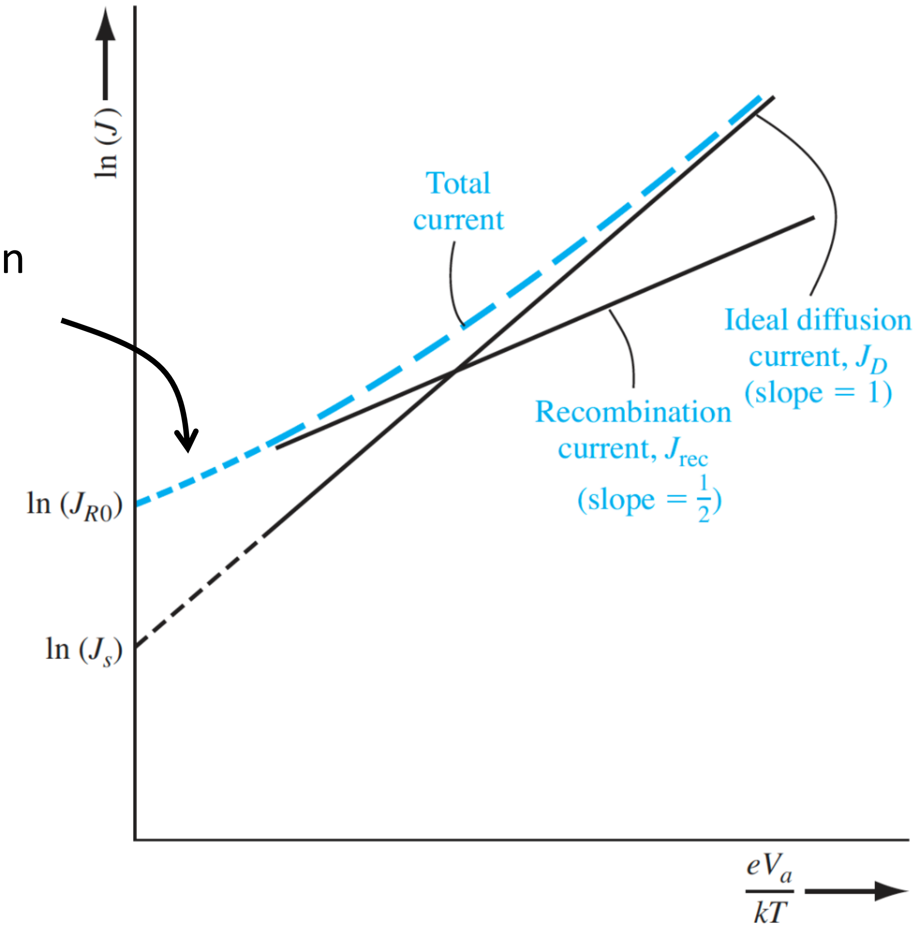
8.3 High-injection levels

8.4 A few more points on pn junctions (not in the textbook)

8.3 High inject level

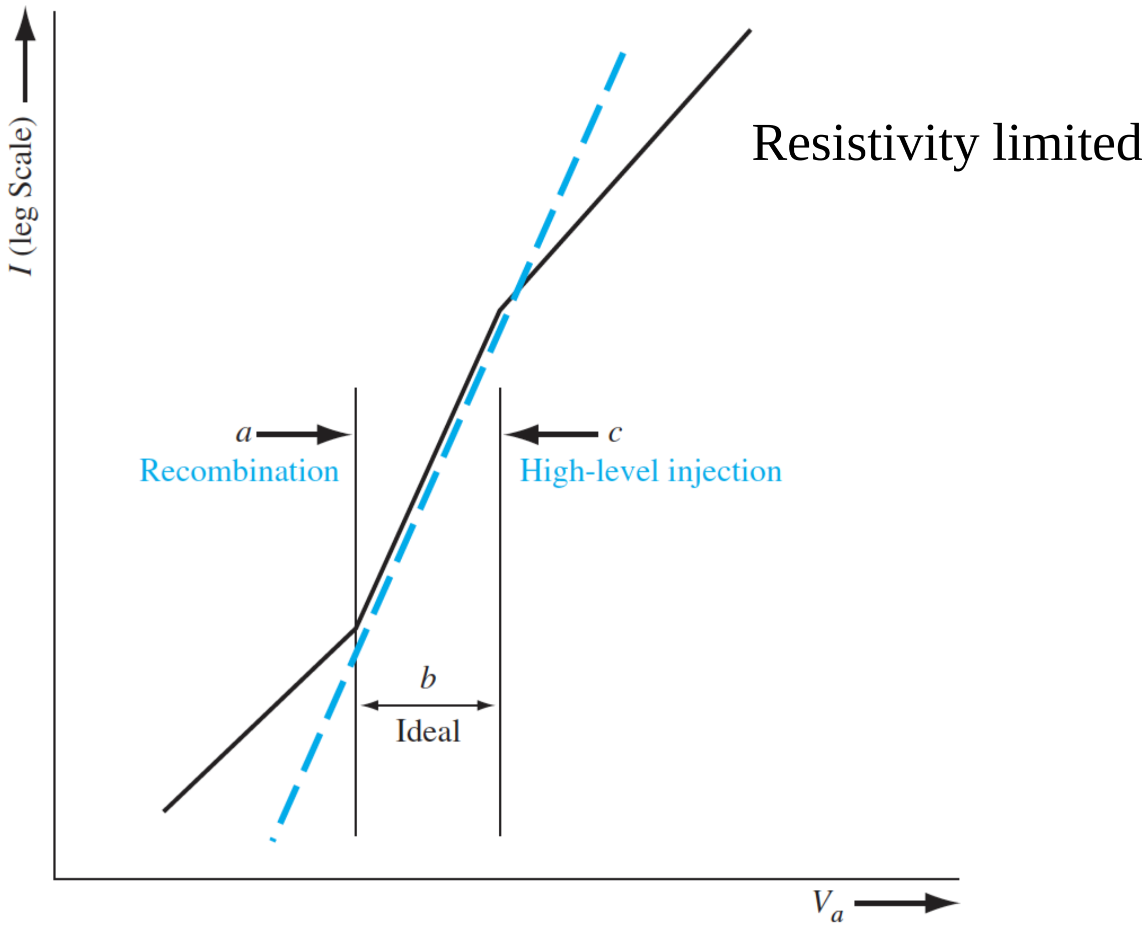
$$J = J_F + J_r = J_s \exp\left(\frac{qV_a}{kT}\right) + \frac{qWn_i}{2\tau}\exp\left(\frac{qV_a}{2kT}\right) = J_0 \exp(\frac{qV_a}{nkT})$$

e-h pairs recombine in the depletion region



8.3 High inject level

$$J = J_F + J_r = J_s \exp\left(\frac{qV_a}{kT}\right) + \frac{qWn_i}{2\tau}\exp\left(\frac{qV_a}{2kT}\right) = J_0 \exp(\frac{qV_a}{nkT})$$



Outline

8.1 pn junction current

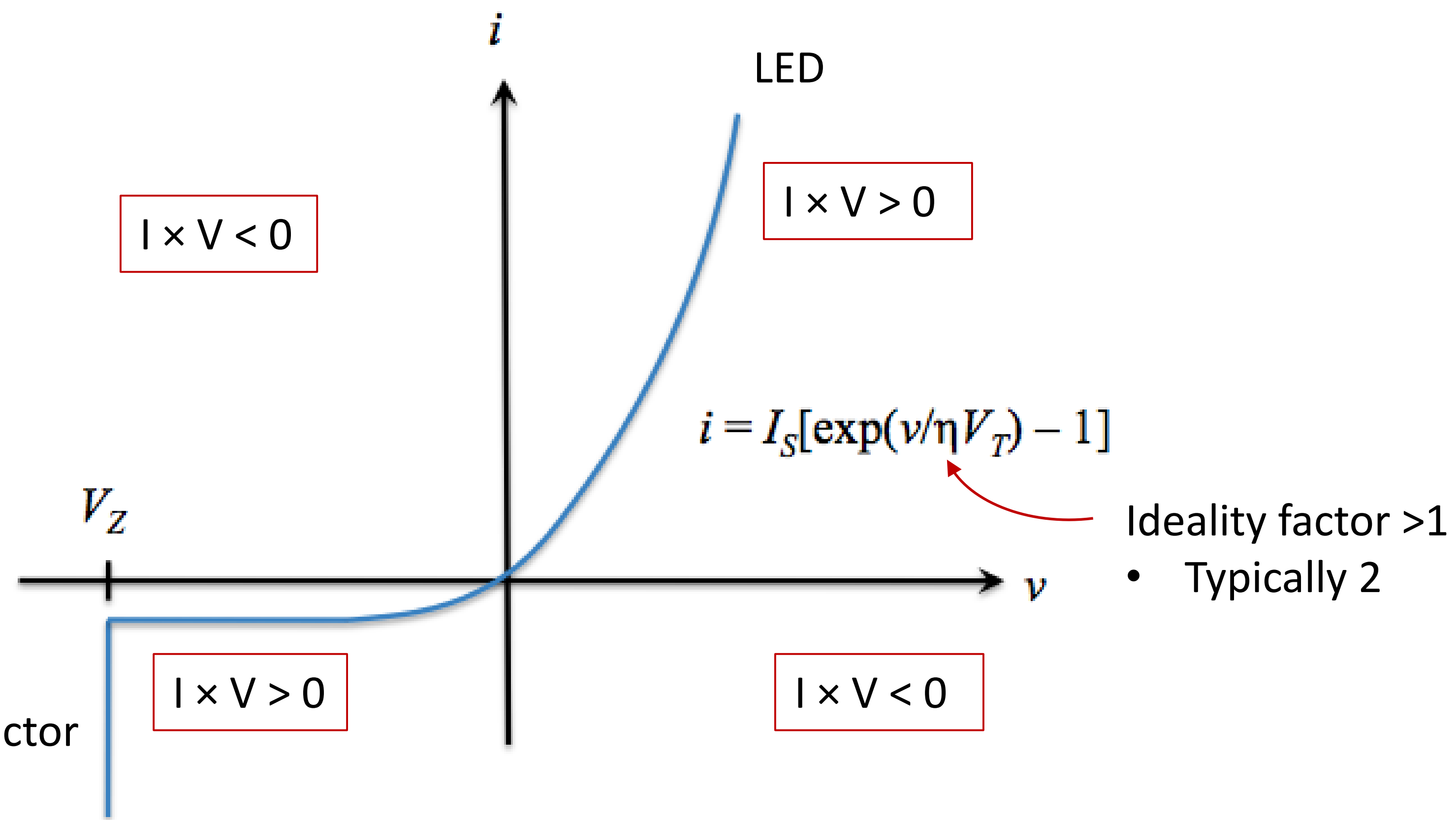
8.2 Generation-recombination currents

8.3 High-injection levels

8.4 A few more points on pn junctions (not in the textbook)

8.4 A few points about pn junction

- Energy consumption:



8.4 A few points about pn junction

- Energy consumption: