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

$I = f(V_b)$

$V_1 = I \cdot R_n$

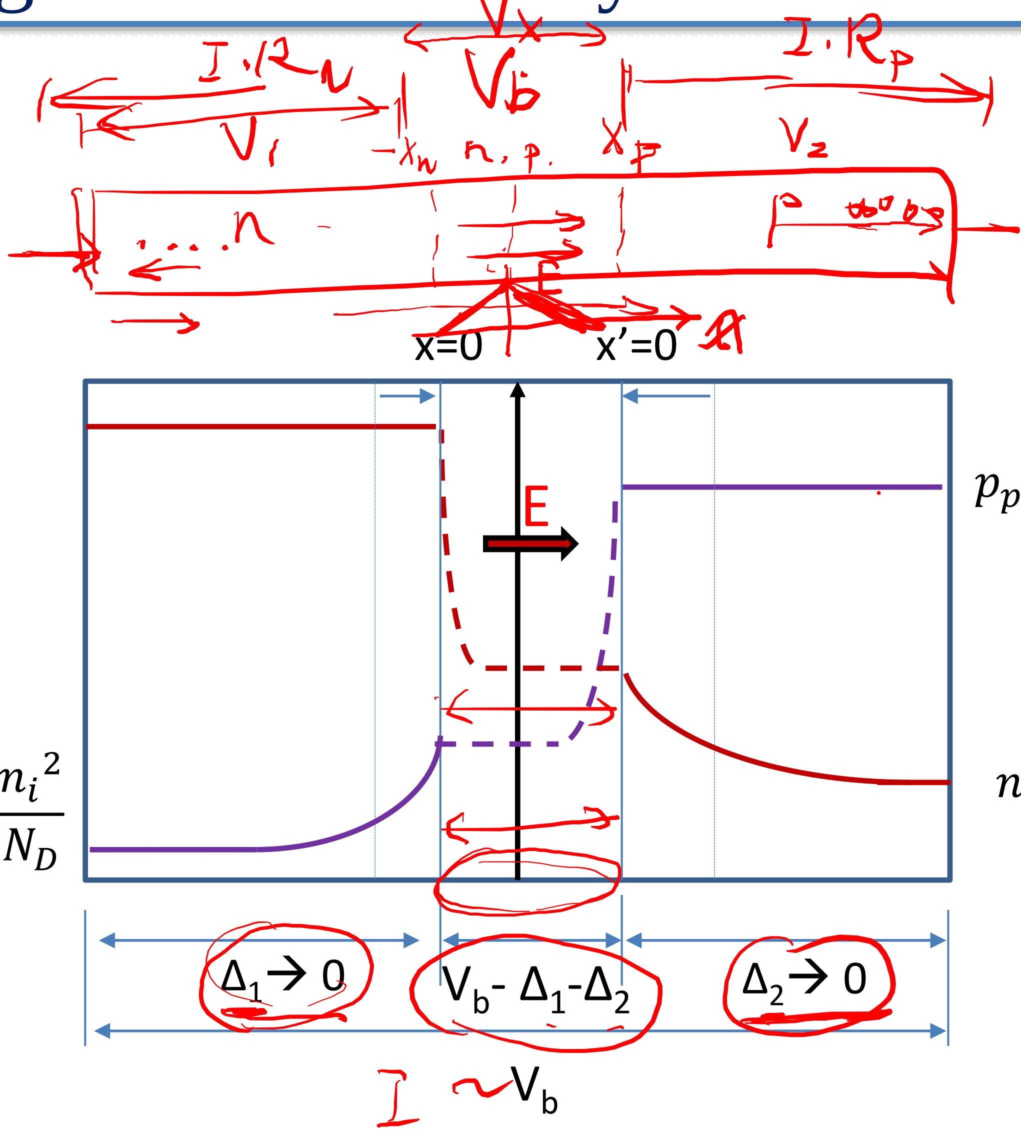
$V_2 = I \cdot R_p$

$V_b = V_1 + V_2 + V_x$

$V_x = I \cdot R_x$

$n_{n0} = N_D$

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

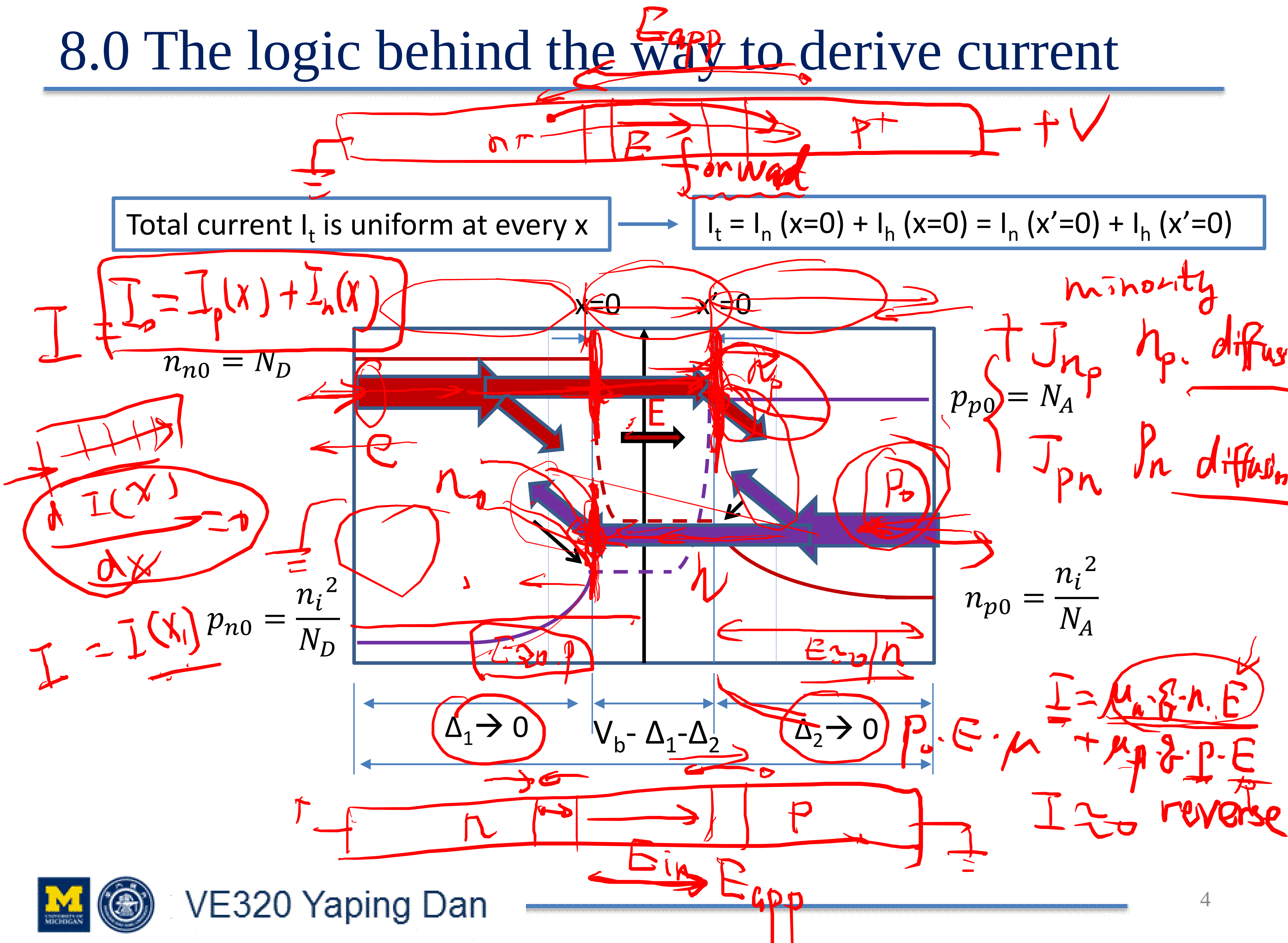


$p_{p0} = N_A$

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

8.0 The logic behind the way to derive current

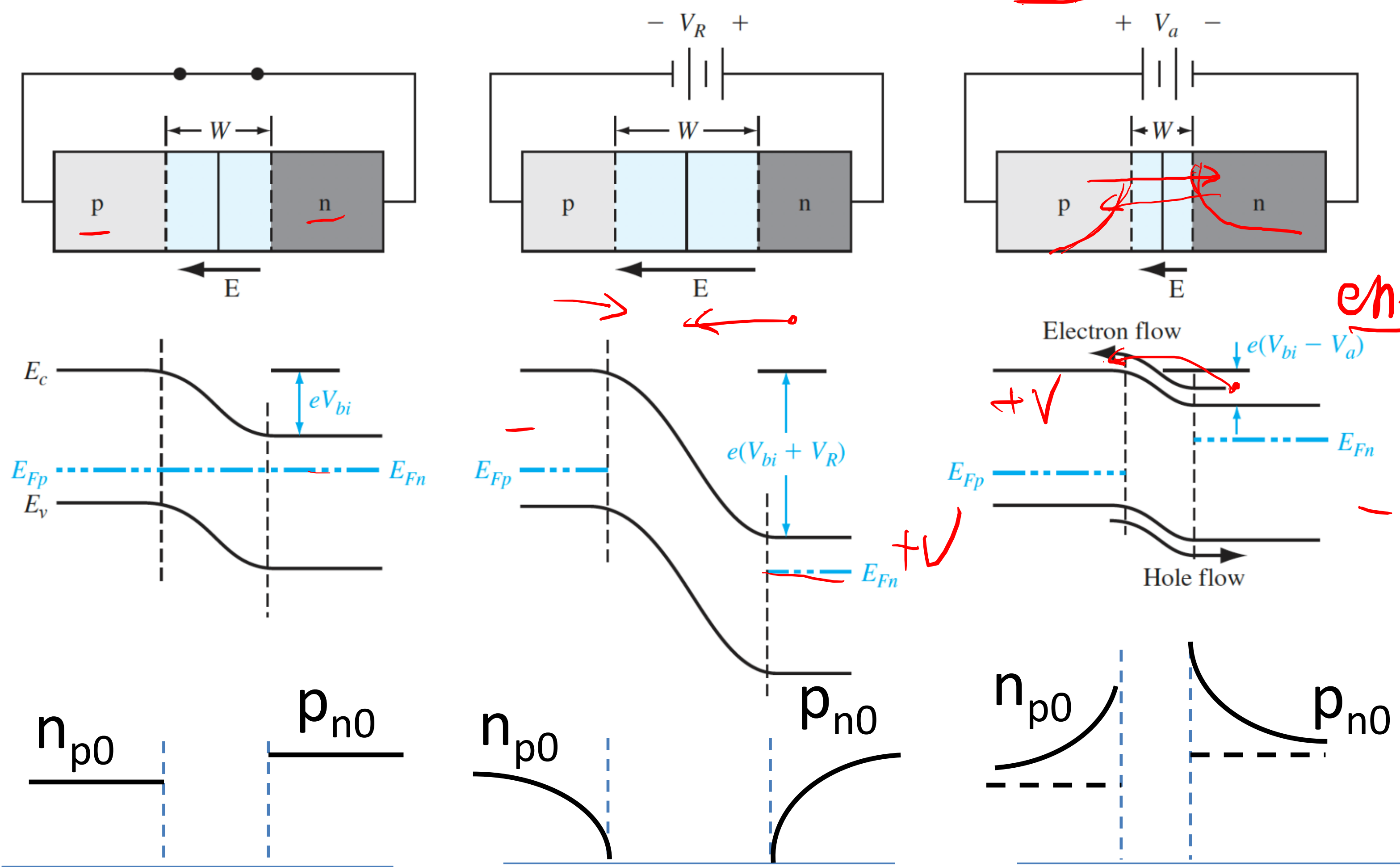
Total current I_t is uniform at every x → $I_t = I_n\,(x=0) + I_h\,(x=0) = I_n\,(x'=0) + I_h\,(x'=0)$



8.1 pn Junction Current

n_0 n_0

Qualitative Description of Charge Flow in a pn Junction



energy diagram

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

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

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

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

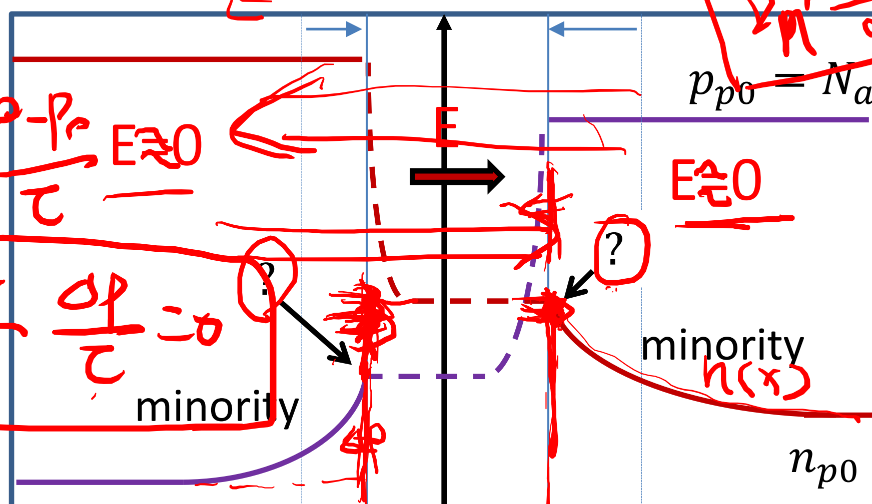
$$0 = D_p \frac{\partial^2 p}{\partial x^2} - \frac{p-p_0}{\tau}$$

$E \approx 0$

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

$n_{n0} = N_d$

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



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

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

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

8.1 pn Junction Current

Assumptions of an ideal PN junction

n, p

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

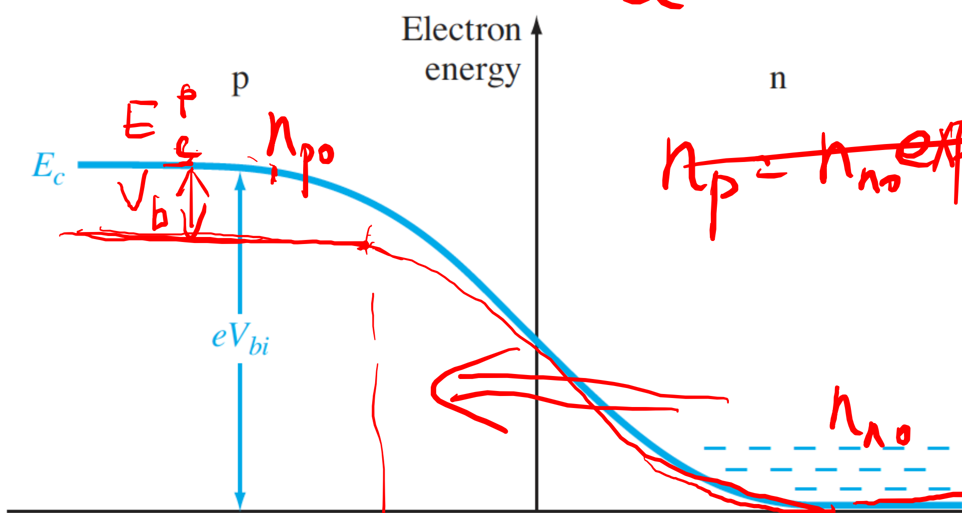
$$n_p = \underbrace{n_{n0} \exp\left(-\frac{qV_b}{kT}\right)} \exp\left(\frac{qV_a}{kT}\right)$$

<u>Boundary condition</u>

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

V_a

$\frac{kT}{q}$



~~$n_p = n_{n0}$ exp(~~

$$V_{bi} = \underbrace{\frac{kT}{q}}_{}V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

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

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

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

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

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