# VE320 – Summer 2024

# 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

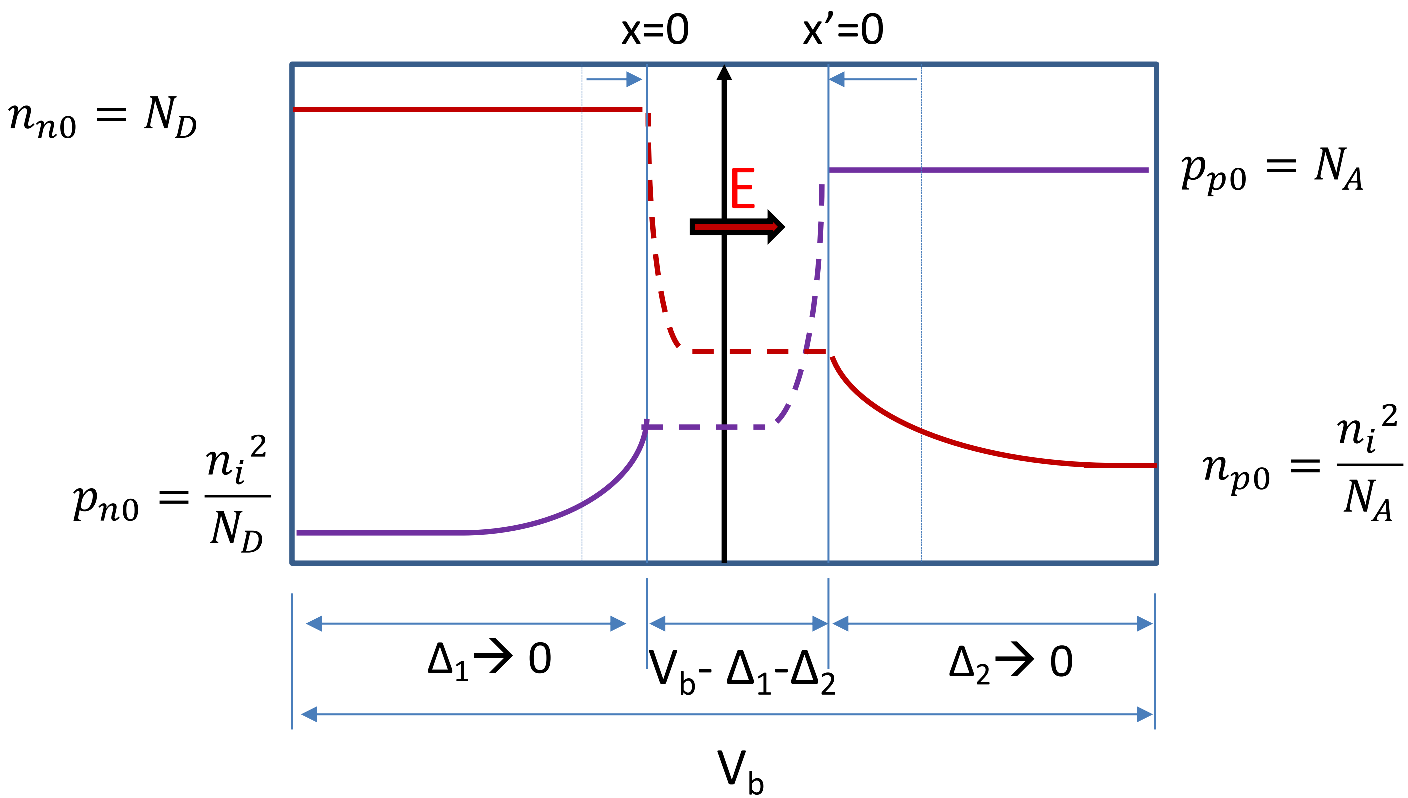
8.4 A few more points on pn junctions (not in the textbook)

# 8.0 The logic behind the way to derive current

Explain why there is no current flow when the pn junction is reverse biased.

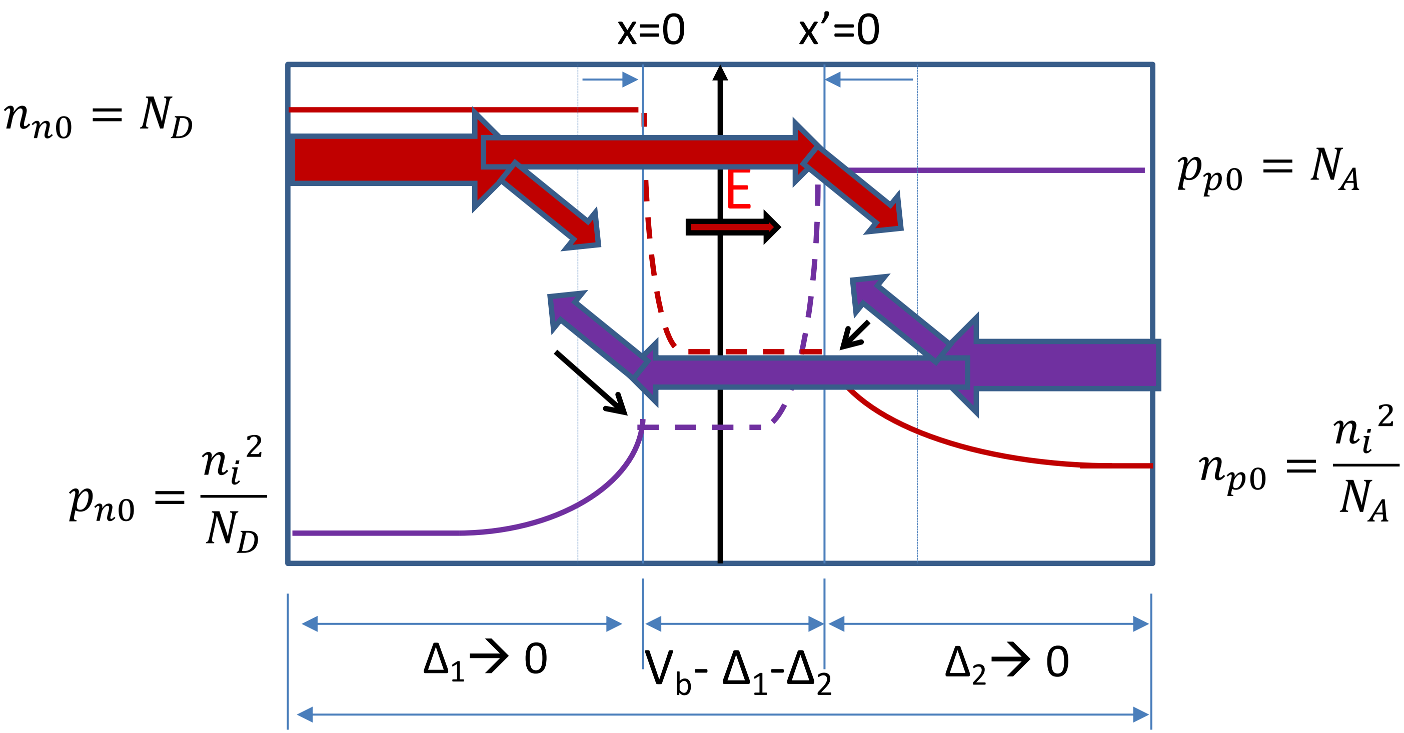
What happens the pn junction is forward biased?

# 8.0 The logic behind the way to derive current



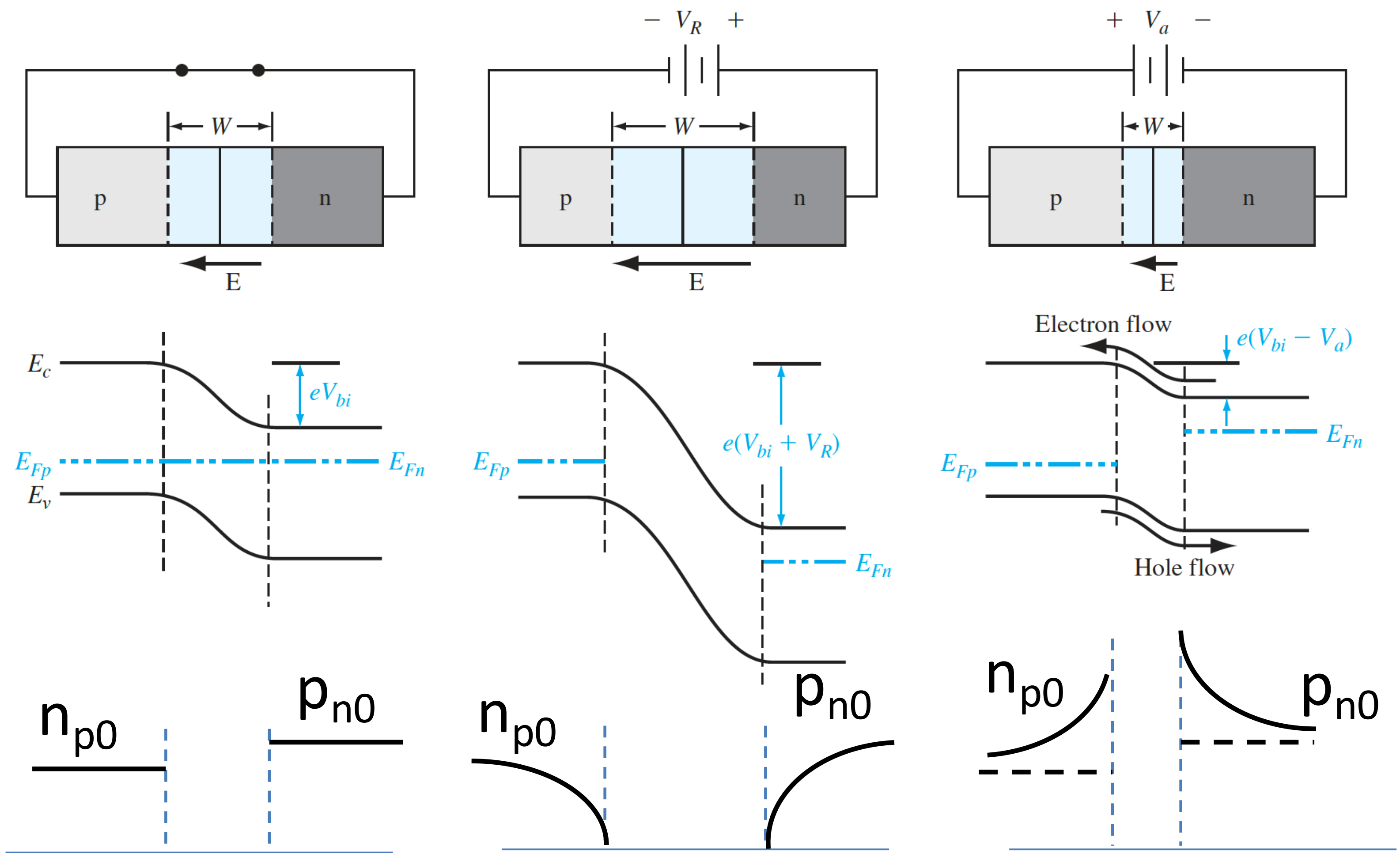
# 8.0 The logic behind the way to derive current

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

Qualitative Description of Charge Flow in a pn Junction



# 8.1 pn Junction Current

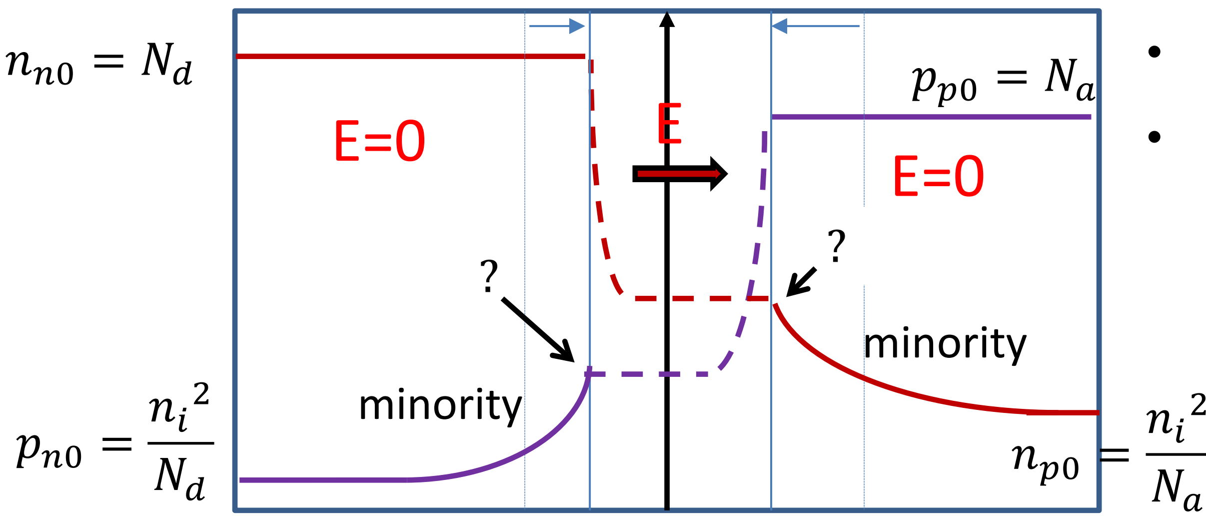
Goal: to find the analytical expression of current

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

Electrons as minority

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

holes as minority




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

# 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.

**2.** The Maxwell–Boltzmann approximation applies to carrier statistics.

**3.** The concepts of low injection and complete ionization apply.

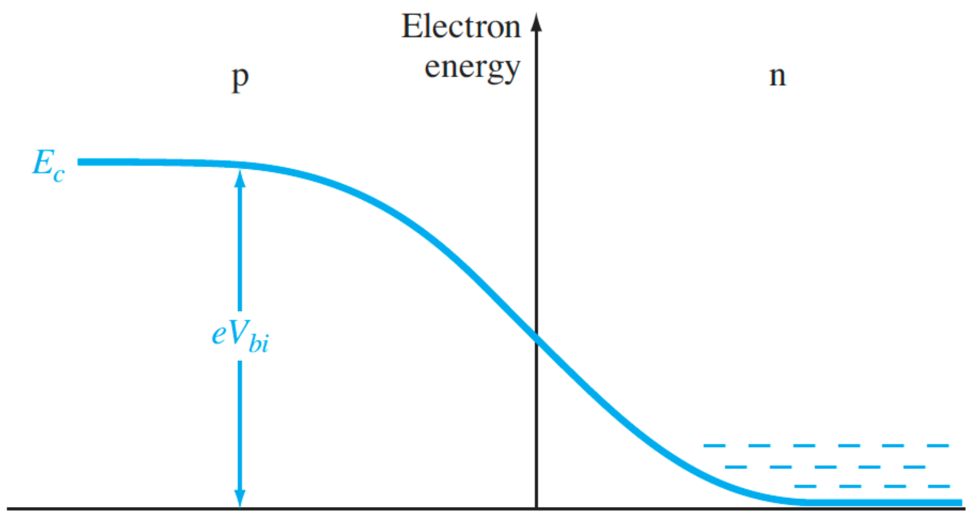
**4a.** The total current is a constant throughout the entire pn structure.

**4b.** The individual electron and hole currents are continuous functions through the pn structure.

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

# 8.1 pn Junction Current

Boundary condition



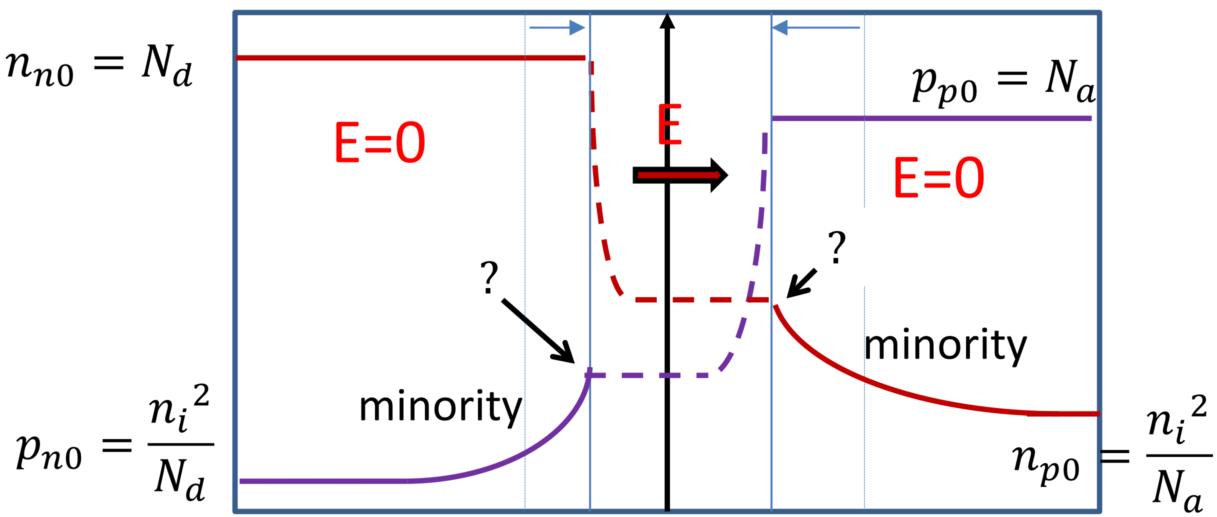

$$V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

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

# 8.1 pn Junction Current

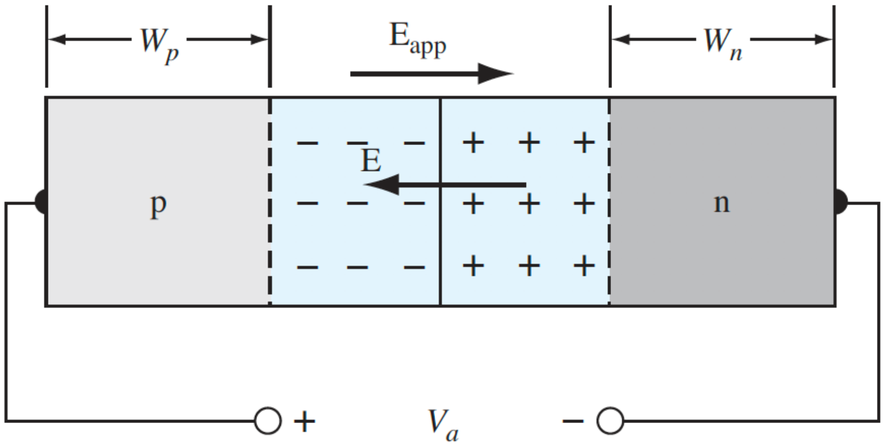
Boundary condition

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

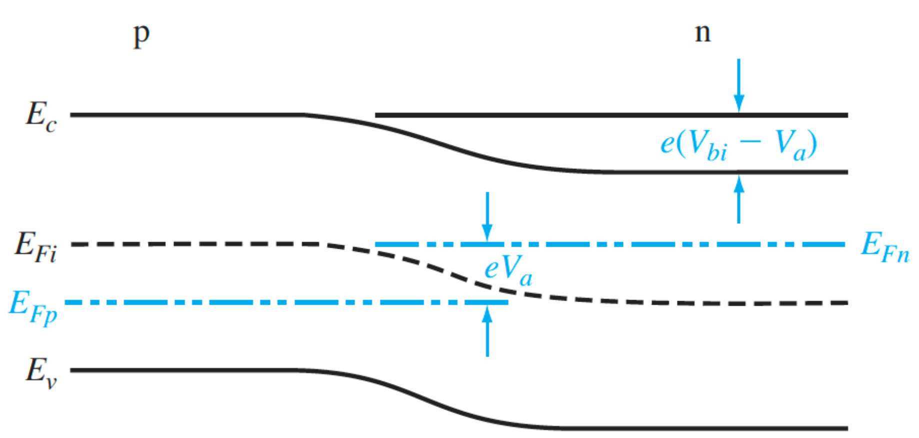


# 8.1 pn Junction Current

<u>Boundary condition</u>



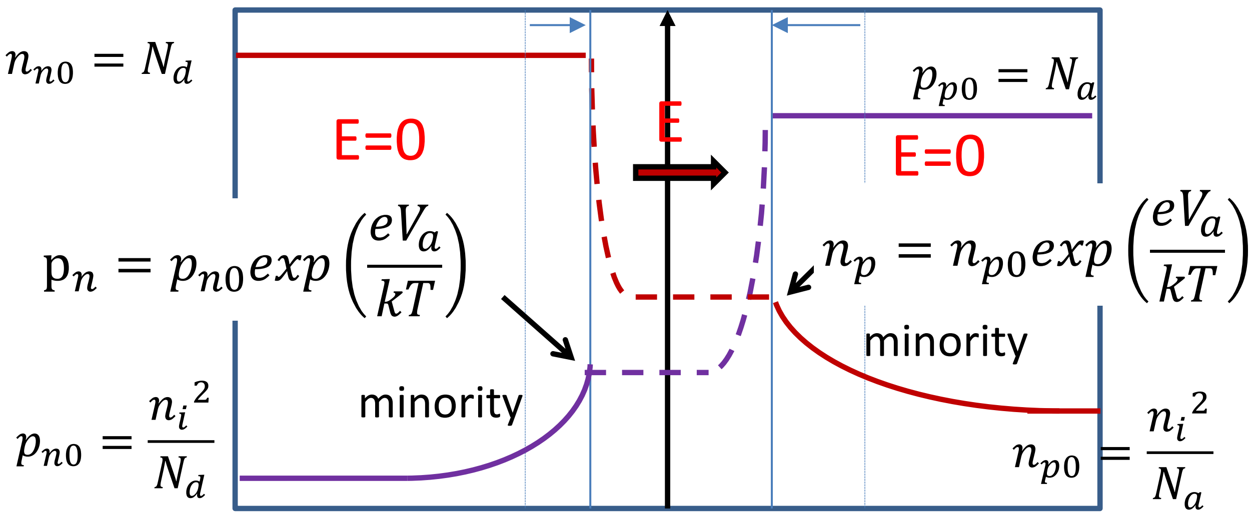

(a)




(b)

# 8.1 pn Junction Current

Boundary condition



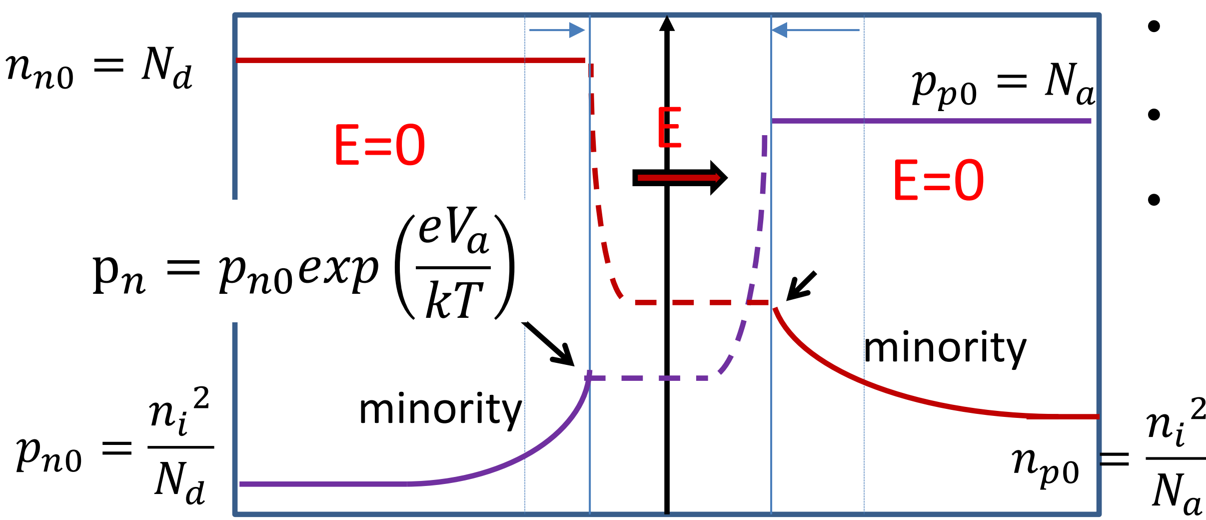
# Check your understanding

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.

# 8.1 pn Junction Current

Minority carrier distribution (simplify continuity equation)

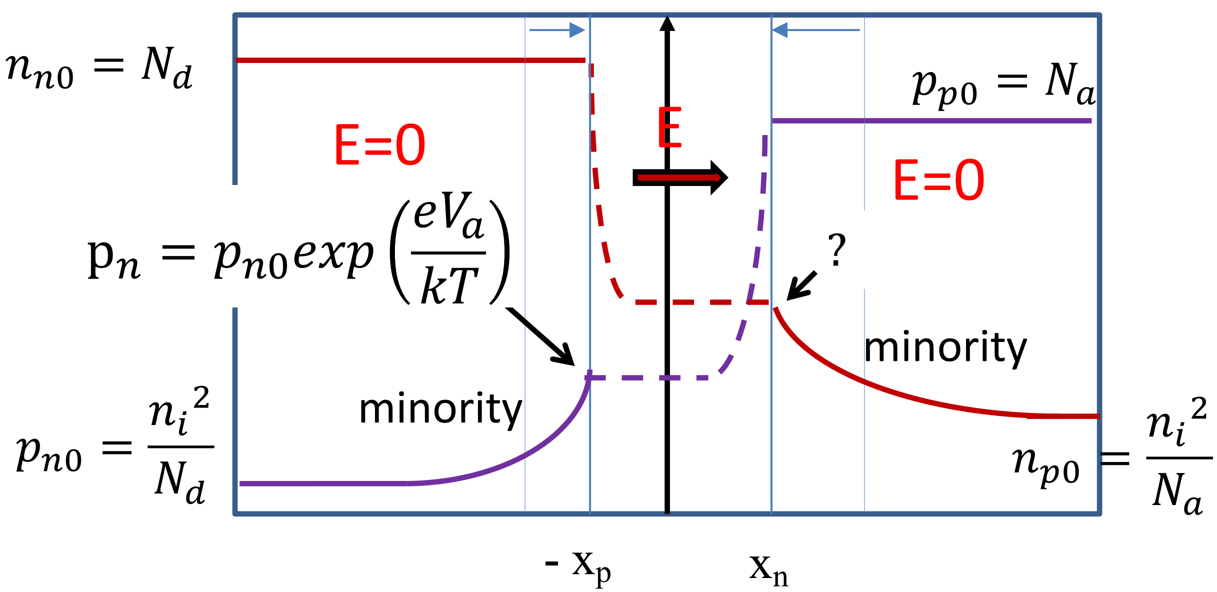



- How to simplify?
- Boundary condition?
- how to get total current

  from minority currents?

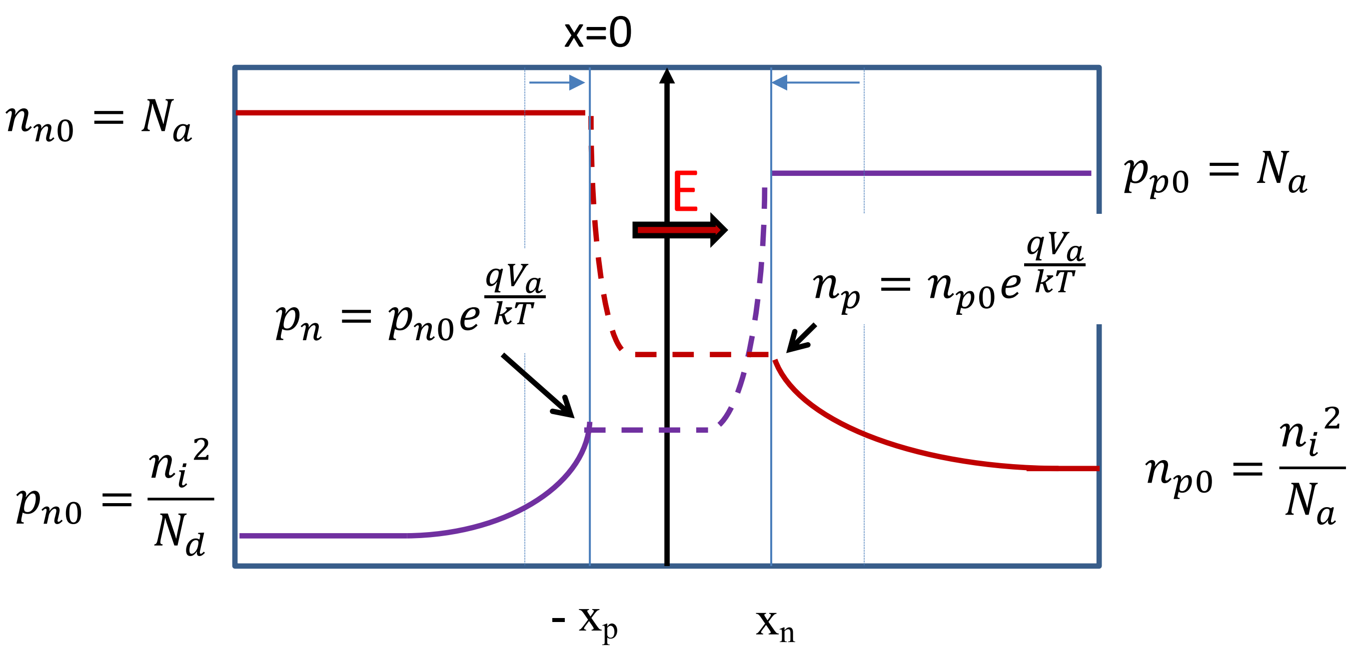
# 8.1 pn Junction Current

Minority carrier distribution (solution + boundary condition)



# 8.1 pn Junction Current

Minority carrier distribution (excess carriers)

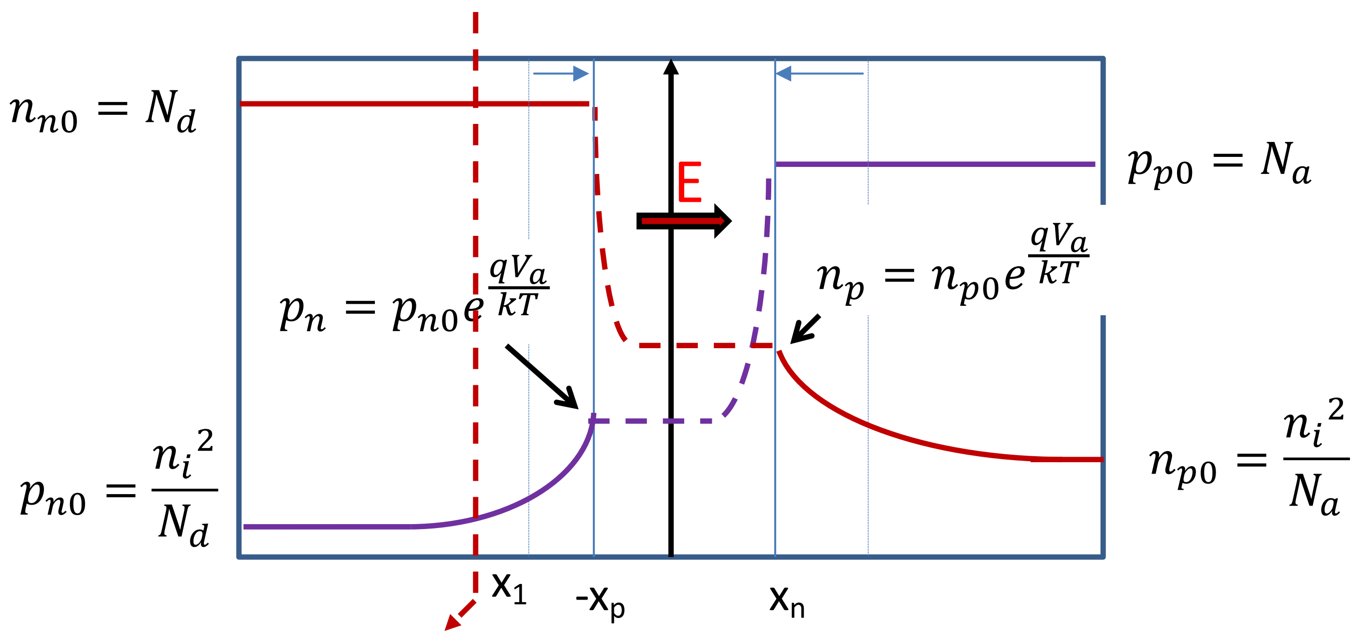


# 8.1 pn Junction Current

Minority carrier distribution

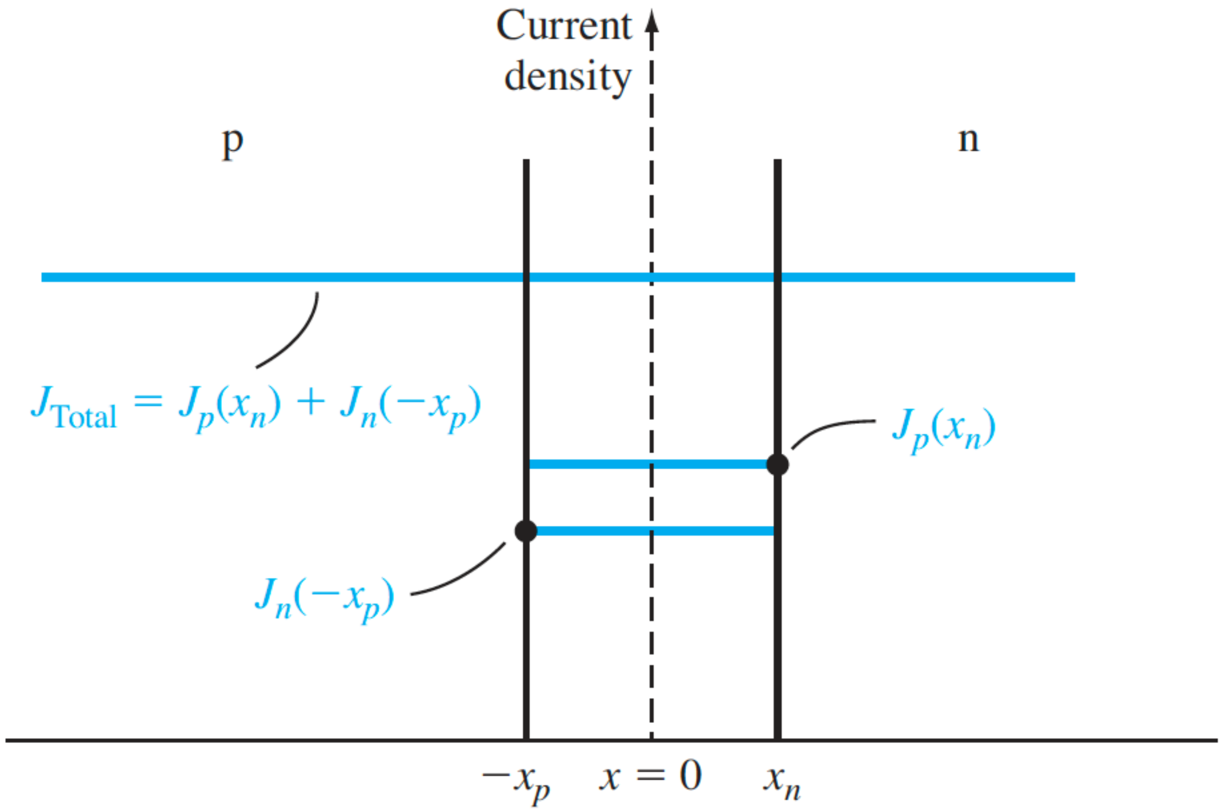
# 8.1 pn Junction Current

- charge carrier transport: current density



# 8.1 pn Junction Current

- Ideal pn junction current




Assumption: No recombination-generation in depletion region.

# 8.1 pn Junction Current

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

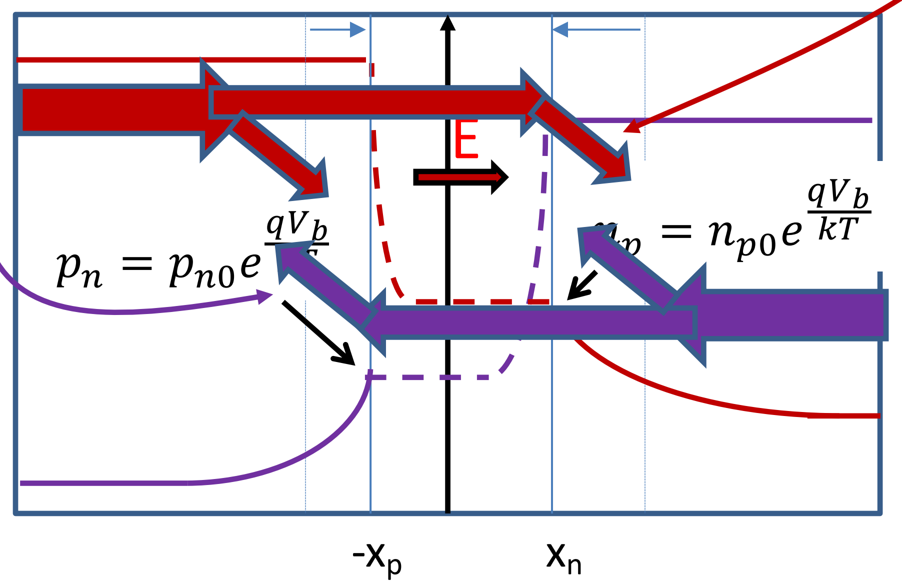
$$J_{n,diff} = qD_n\frac{dn_p}{dx} = -\frac{qD_n n_{p0}}{L_n}(e^{\frac{qV_a}{kT}}-1)e^{\frac{x_n-x}{L_n}}$$

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

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

$n_{n0} = N_D$

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




$p_{p0} = N_A$

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

Assumption: No recombination-generation in depletion region.

# 8.1 pn Junction Current

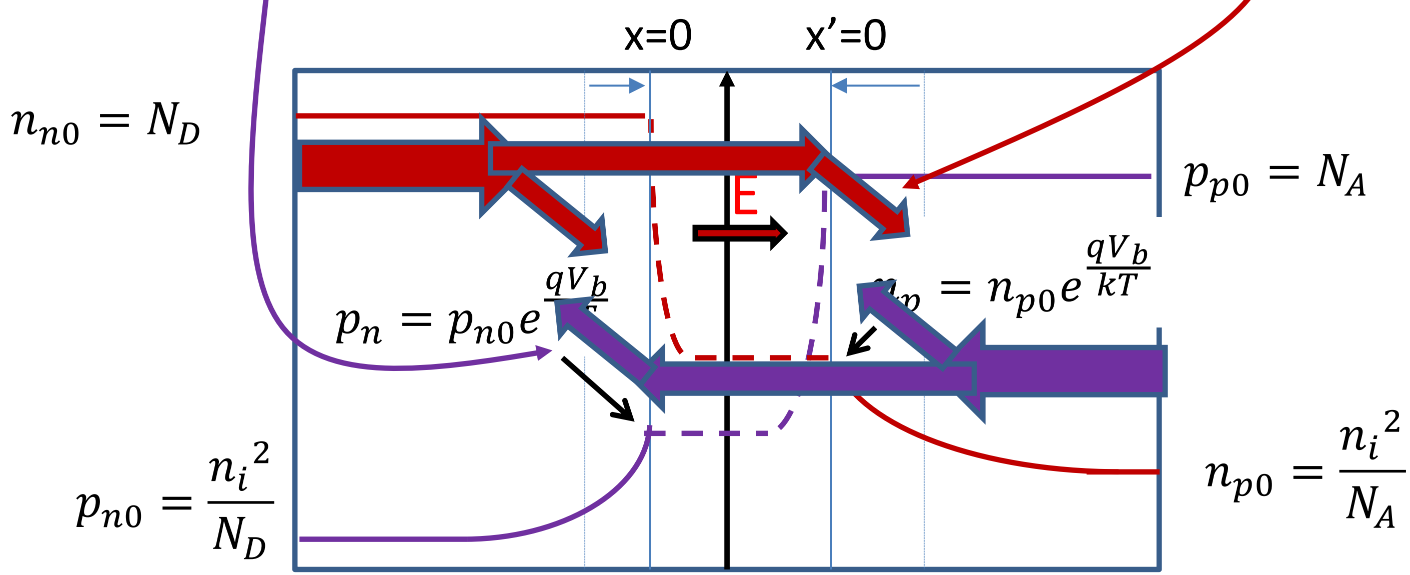
- Ideal pn junction current

# 8.1 pn Junction Current

- charge carrier transport: current ratio at forward bias (remember this, important)

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

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




Assumption: No recombination-generation in depletion region.

# 8.1 pn Junction Current

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

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

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

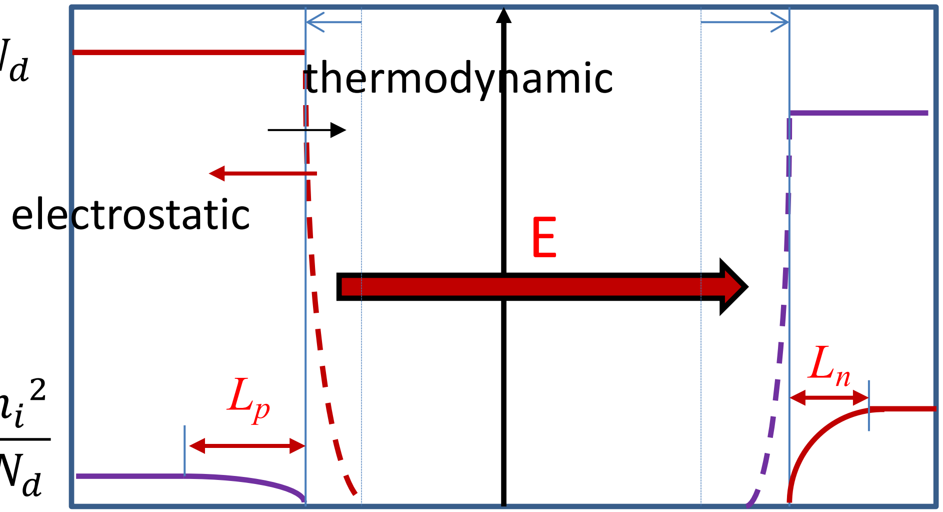
$$\boxed{J = J_n|_{x'=0} + J_n|_{x=0}}$$

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

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

$n_{n0} = N_d$

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



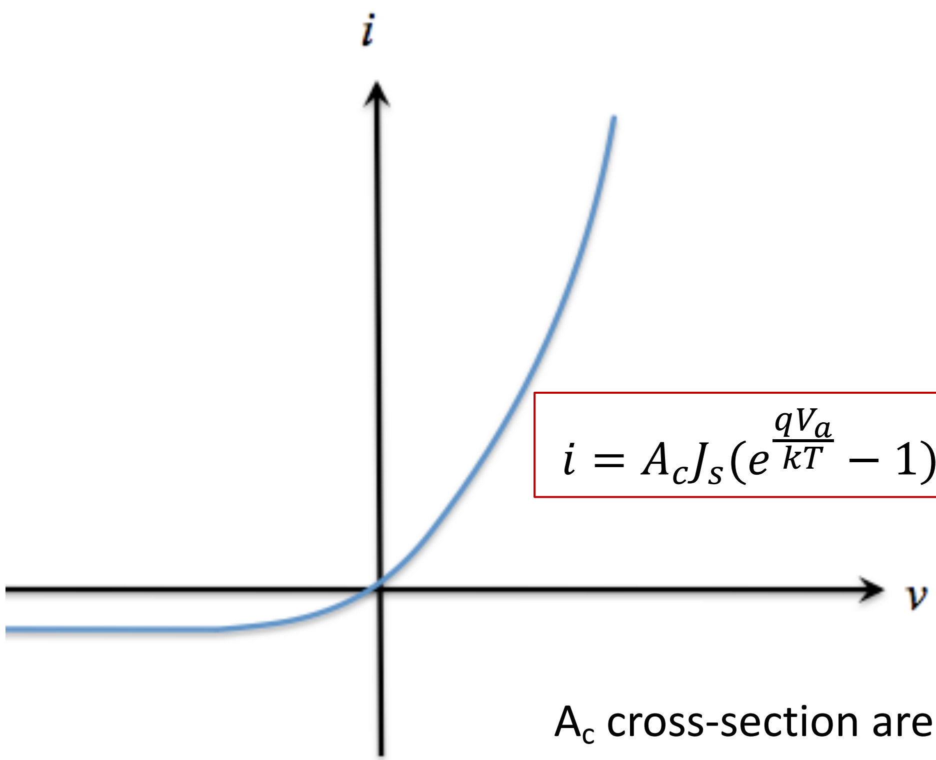

$p_{p0} = N_a$

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

Assumption: No recombination-generation in depletion region.

# 8.1 pn Junction Current

- charge carrier transport: forward bias




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

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

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

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

$A_c$ cross-section area

# 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.

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

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

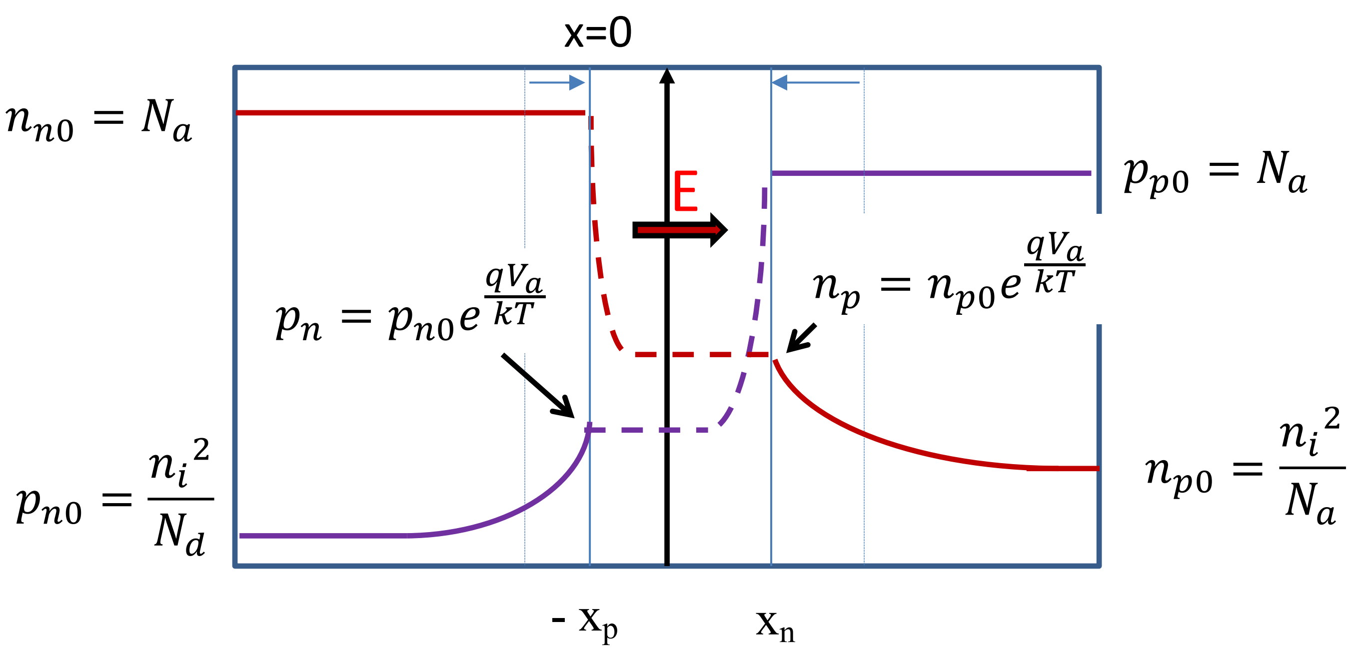
$$D_p = 10\ \text{cm}^2/\text{s} \qquad \epsilon_r = 11.7$$

# 8.1 pn Junction Current

Minority carrier distribution

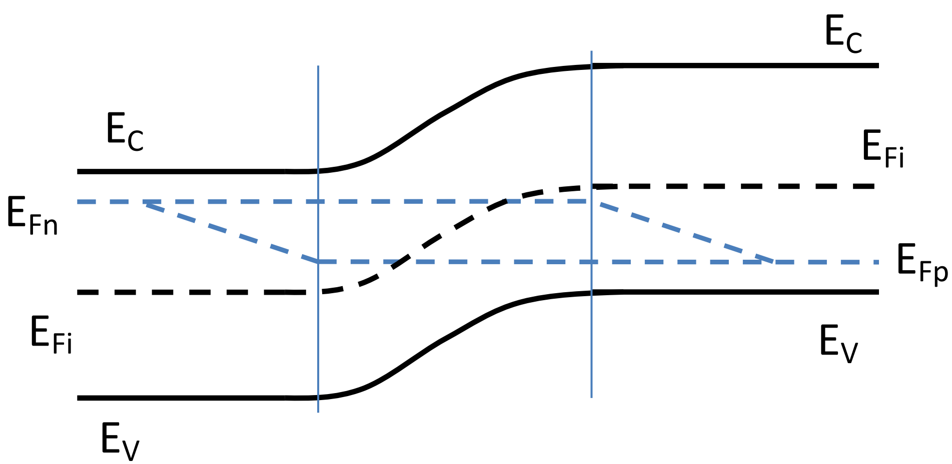
$$p = p_o + \delta p = n_i \exp\left(\frac{E_{Fi} - E_{Fp}}{kT}\right)$$

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



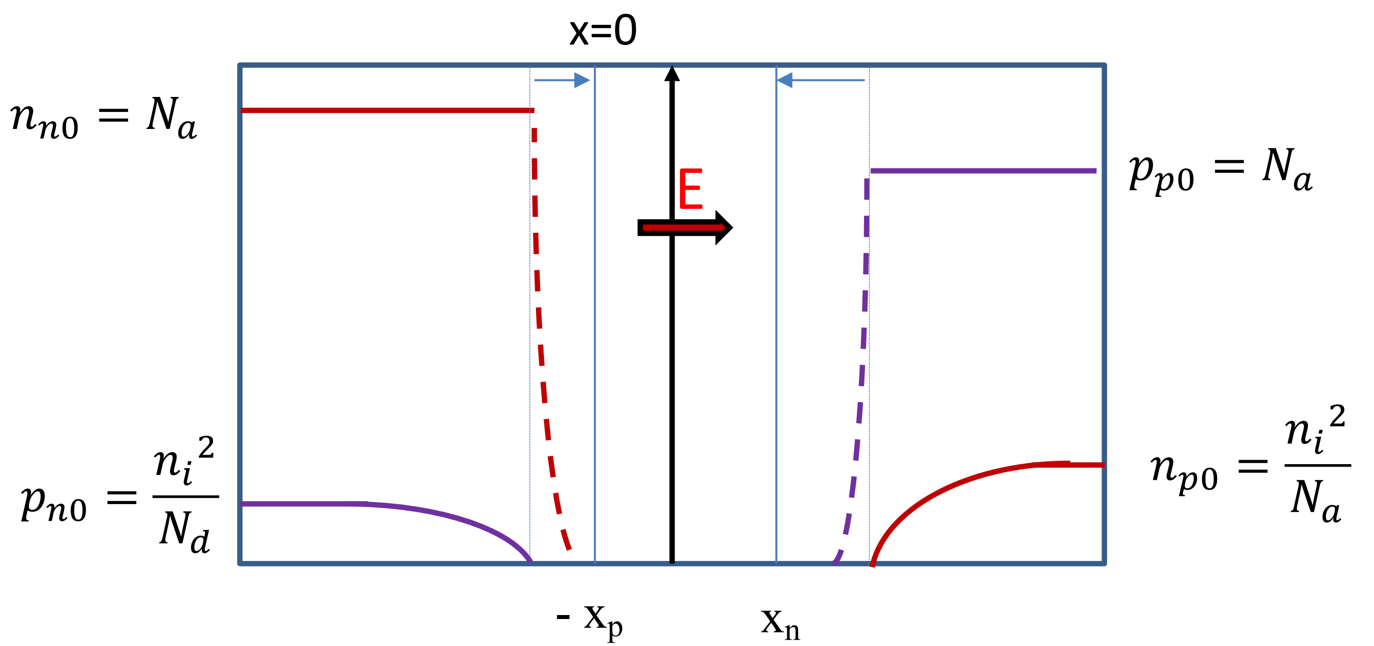
# 8.1 pn Junction Current

Minority carrier distribution (Quasi Fermi level on excess carrier distribution)



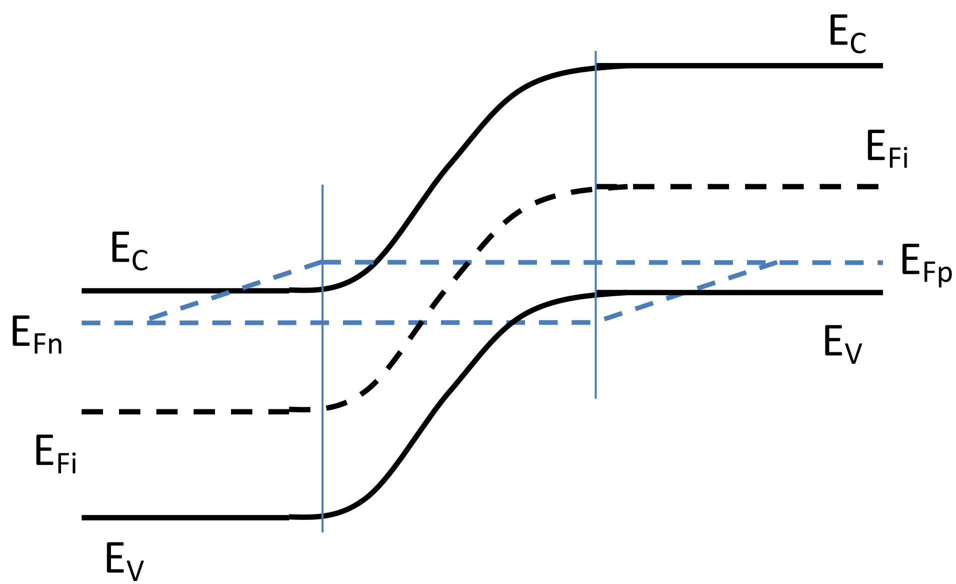
# 8.1 pn Junction Current

Minority carrier distribution (reverse bias)



# 8.1 pn Junction Current

Minority carrier distribution (Quasi Fermi level on carrier concentration)



# Outline

8.1 pn junction current

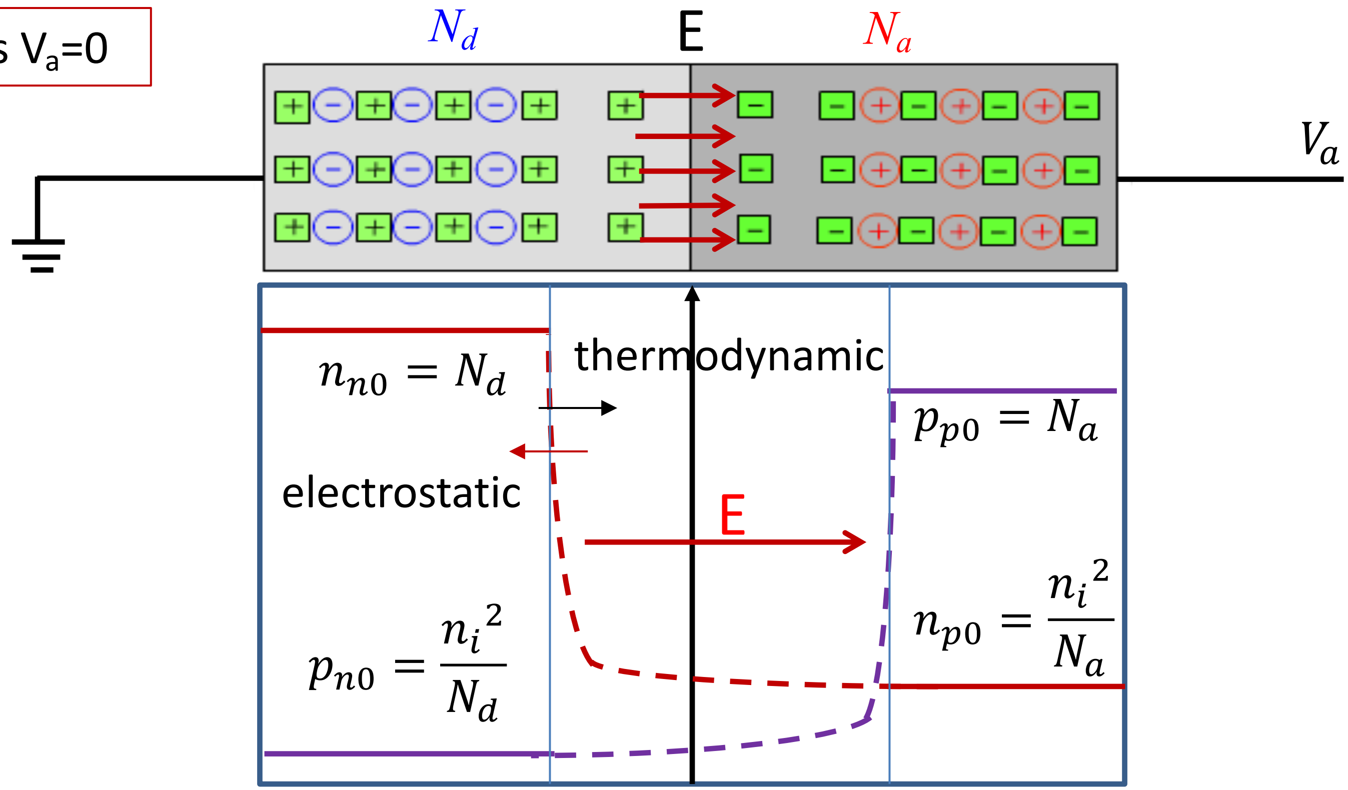
**8.2 Generation-recombination currents**

8.3 High-injection levels

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

# 8.2 Generation-recombination currents

Zero Bias $V_a$=0

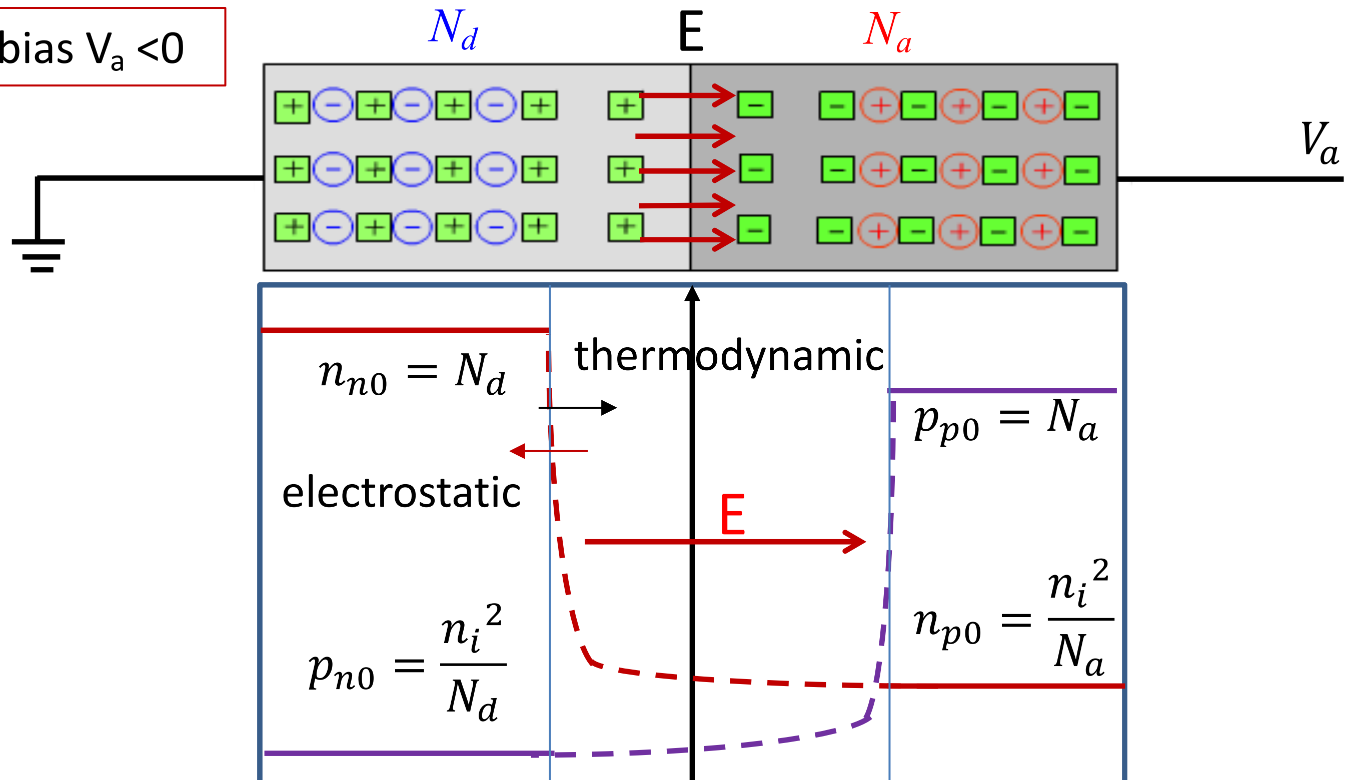



$$R_n = \frac{(np - n_i^2)}{\tau_p \left[n + n_i \exp\left(\frac{E_t - E_i}{kT}\right)\right] + \tau_n \left[p + n_i \exp\left(\frac{E_i - E_t}{kT}\right)\right]}$$

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

# 8.2 Generation-recombination currents

Reverse bias $V_a$ <0




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

# 8.2 Generation-recombination currents

Reverse bias $V_a$ <0

To simplify the calculation, we assume

$$E_t = E_i, \tau_n = \tau_p = \tau$$

# 8.2 Generation-recombination currents

Reverse bias $V_a$ <0

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

Current density from G-R in the depletion region:

# 8.2 Generation-recombination currents

Reverse bias $V_a$ <0

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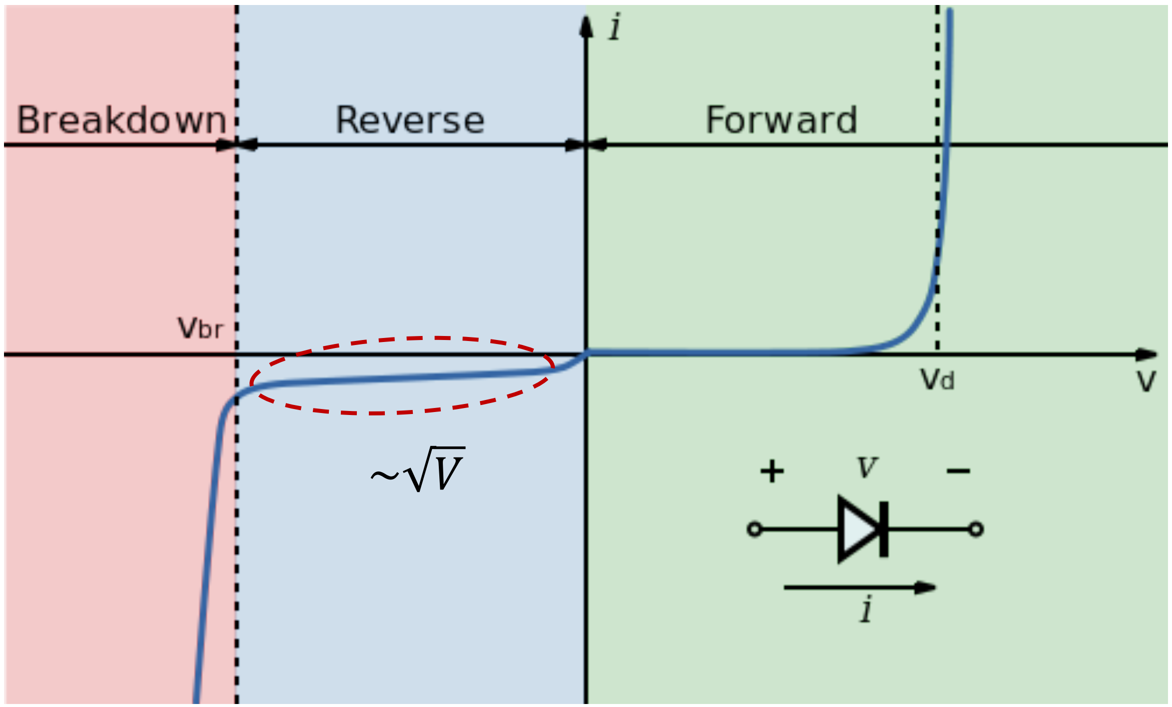
# 8.2 8.2 Generation-recombination currents

Reverse bias $V_a$ <0

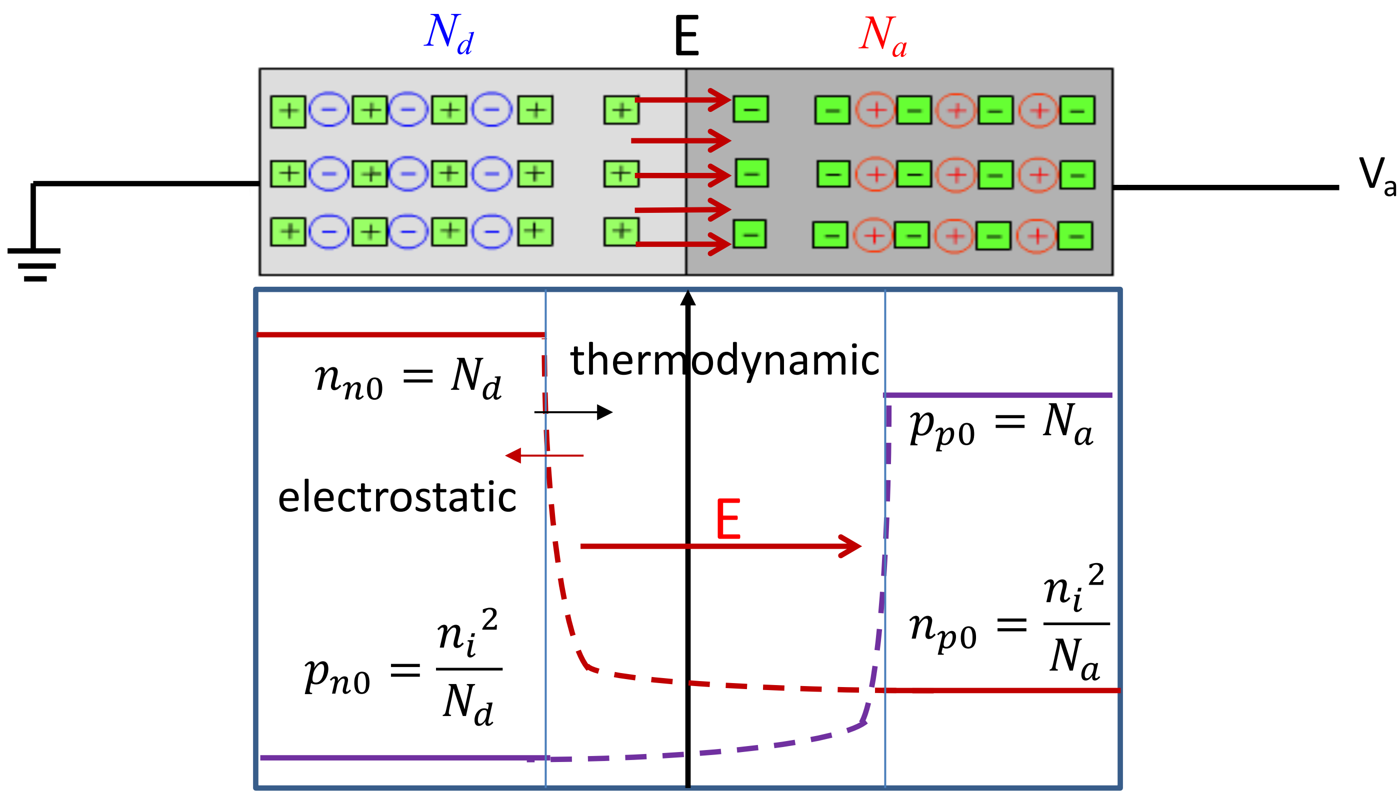



Current density from G-R in the depletion region:

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

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

# 8.2 Generation-recombination currents




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

# 8.2 Generation-recombination currents

To simplify the calculation, we assume

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

When n=p, U reaches its max value.

# 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:

# 8.2 Generation-recombination currents

# Check your understanding

## Problem Example #3

An n-type semiconductor ($10^{17}cm^{-3}$) is in contact with another p-type semicondcutor ($10^{17}cm^{-3}$). Suppose a silicon PN junction has defects located at the middle of the bangap. 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 if the pn junction is reverse biased at 1V ($V_R$=1V）.


Depletion region

$N_t = 10^{16}$ $cm^{-3}$

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

# Outline

8.1 pn junction current

8.2 Generation-recombination currents

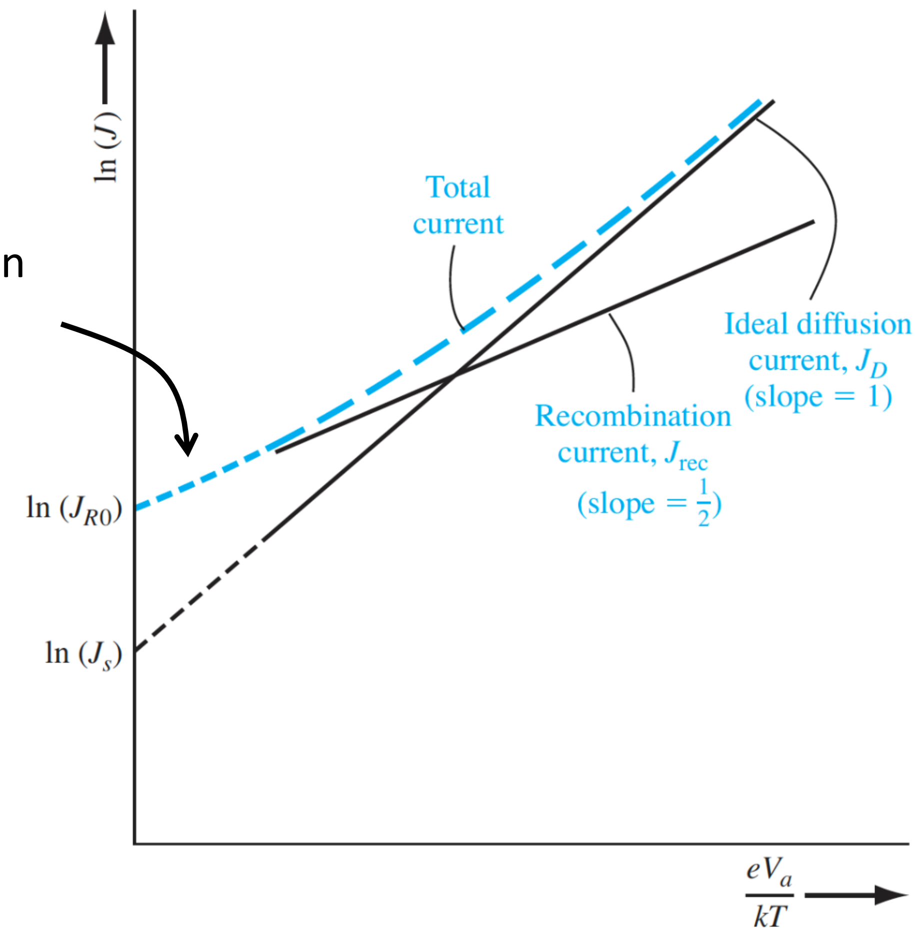
**8.3 High-injection levels**

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

# 8.3 High inject level

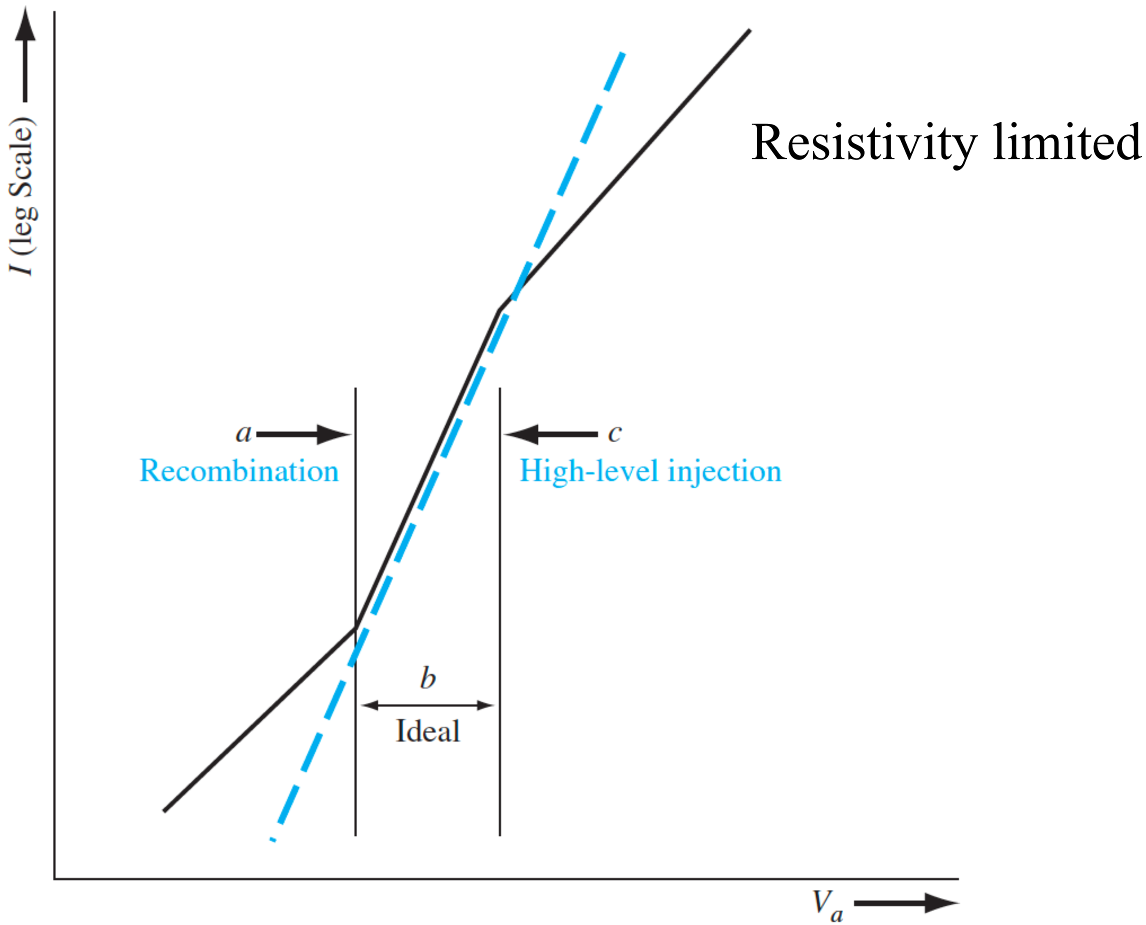
$$J = J_F + J_r = J_s \exp\left(\frac{qV_a}{kT}\right) + \frac{qWn_i}{2\tau}\exp\left(\frac{qV_a}{2kT}\right) = J_0 \exp\left(\frac{qV_a}{nkT}\right)$$

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

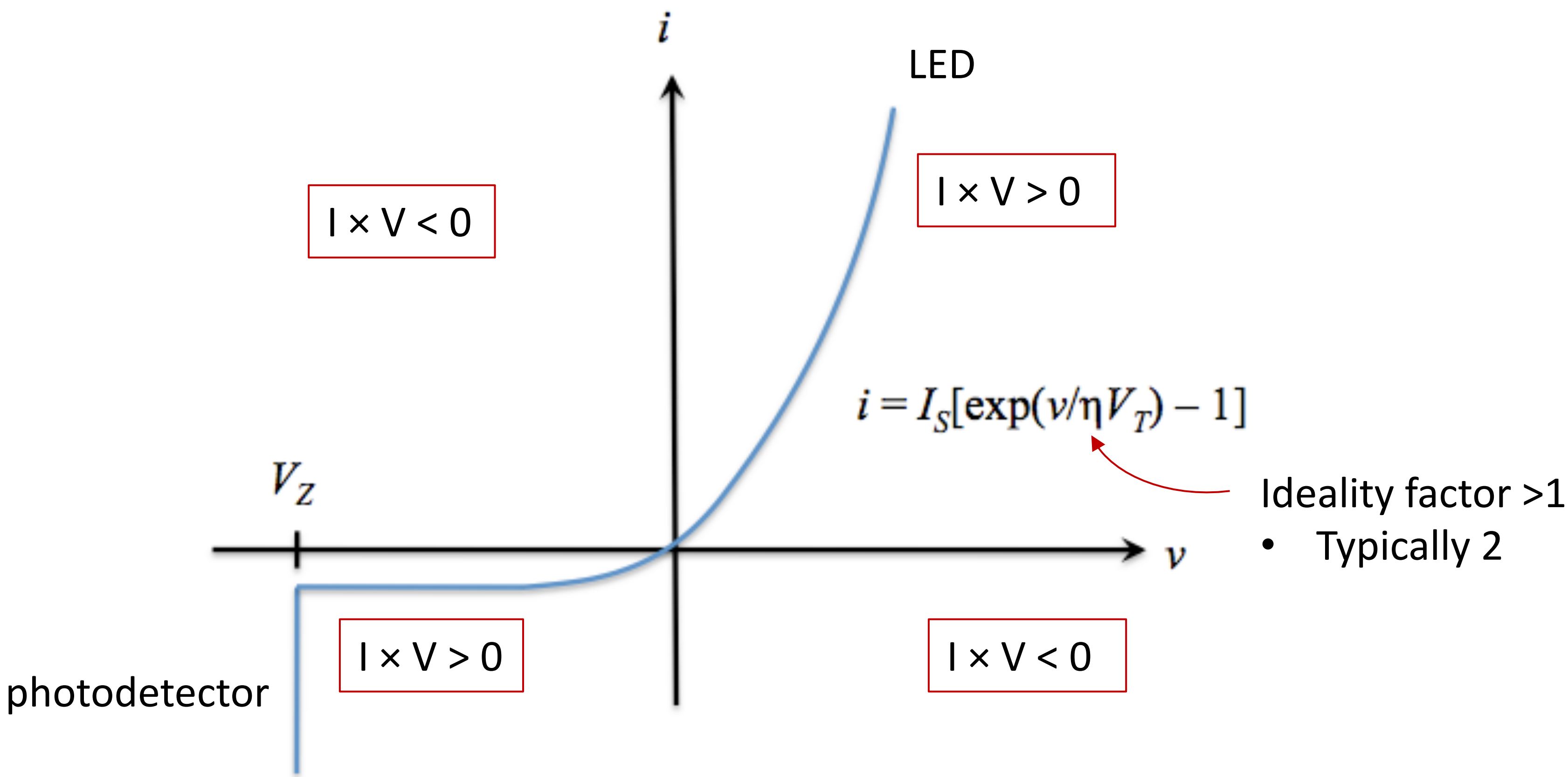
8.2 Generation-recombination currents

8.3 High-injection levels

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

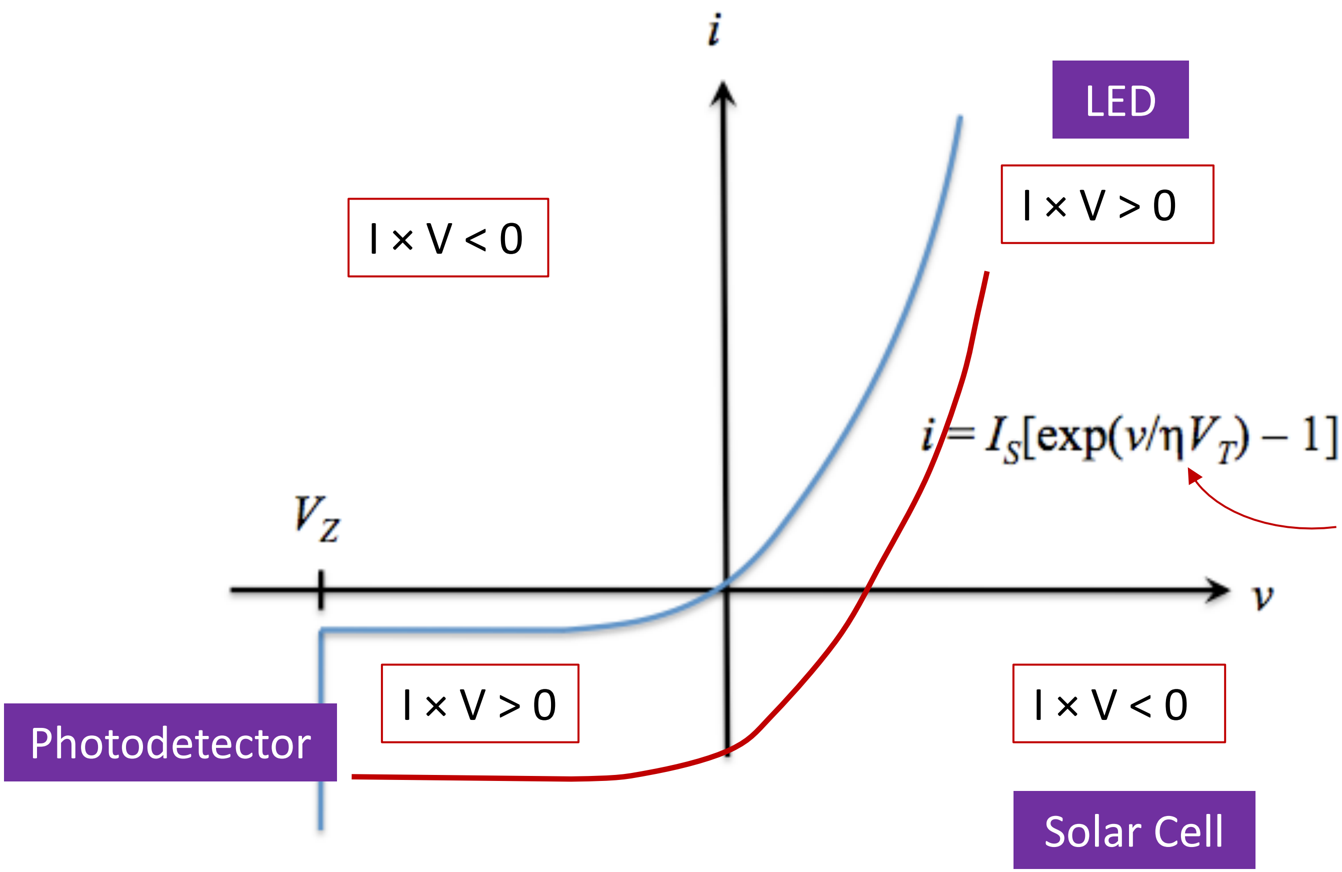
# 8.4 A few points about pn junction

- Energy consumption:



# 8.4 A few points about pn junction

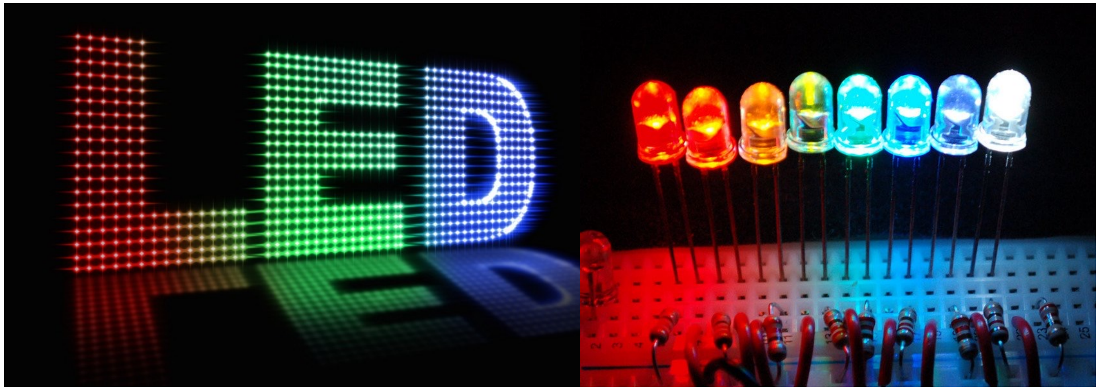
- Energy consumption:




Ideality factor >1

- Typically 2

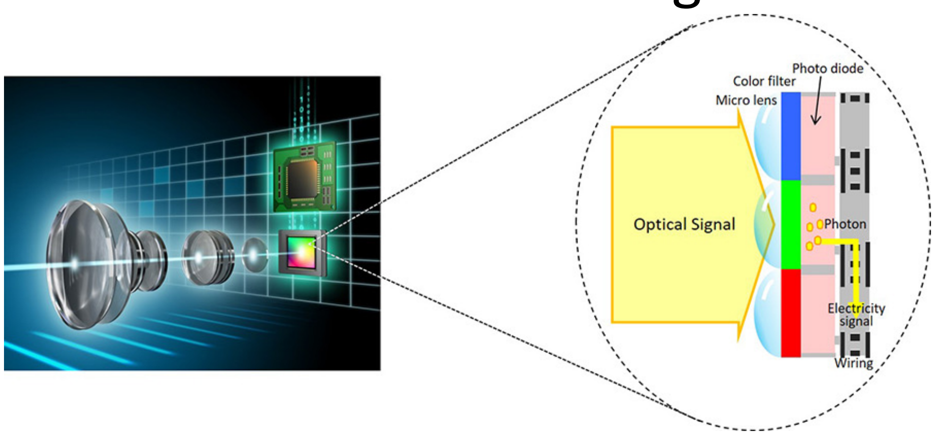
# Introduction to semiconductor devices

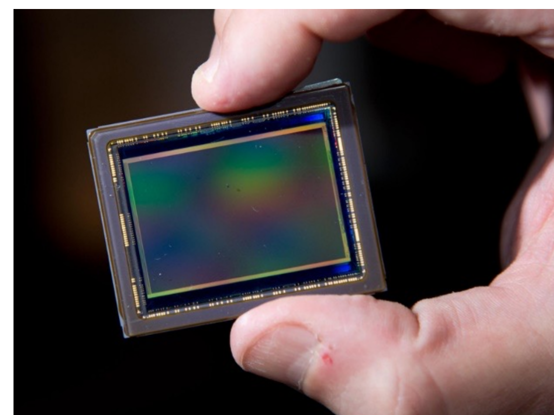


Light emitting diodes

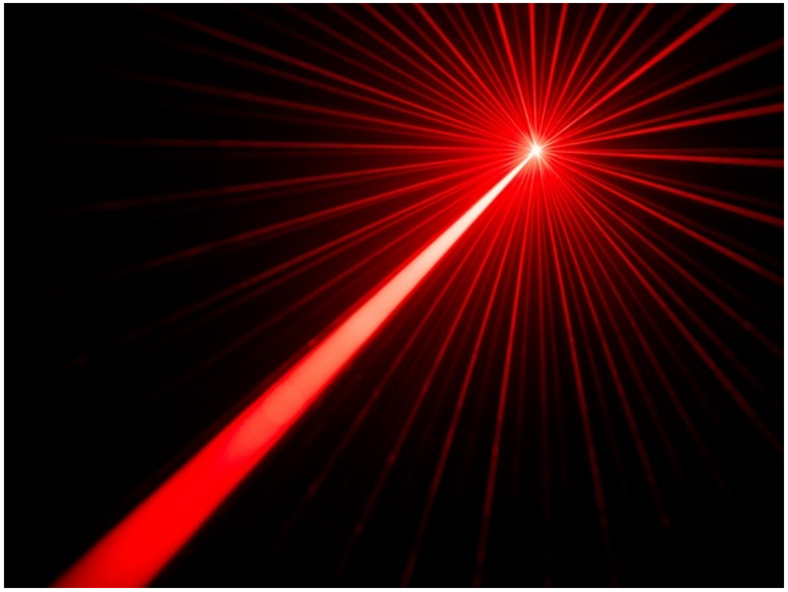
Cold light source

Photodetector: CMOS image sensor



# Introduction to semiconductor devices



Semiconductor lasers

Solar cells