2.626 Fundamentals of Photovoltaics

Fall 2008

Charge Separation: How Voltage and Current Are Formed

Lecture 6 – 2.626

Tonio Buonassisi

Concept Quiz Results

- Discussion…

General Announcements

- Books
- Print-Outs of Lecture Notes

Homework Assignment

- Read: Martin Green, Chapter 4
- Read: PVCDROM: Chapters 3 and 4

Books: Sticker-shock, anyone?

If not, we'll call in the order!

Images removed due to copyright restrictions. Please see the covers of:

Green, Martin A. *Solar Cells: Operating Principles, Technology, and System Applications*. Englewood Cliffs, NJ: Prentice-Hall, 1982.

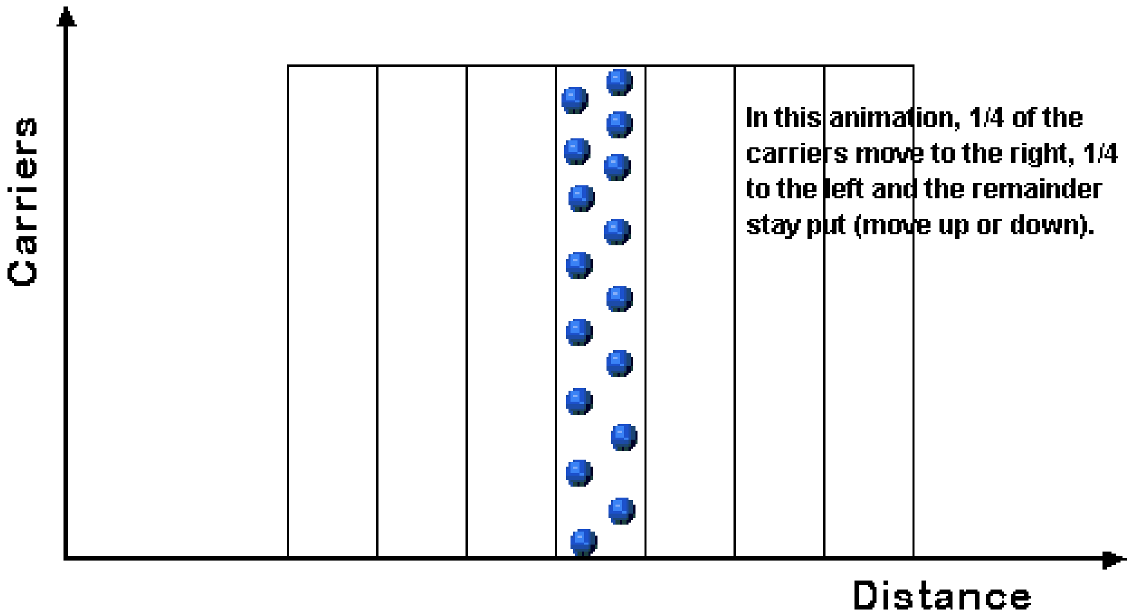
Green, Martin A. *Silicon Solar Cells: Advanced Principles and Practice*. Sydney, Australia: Centre for Photovoltaic Devices and Systems, 1995.

Wenham, Stuart A., et al. *Applied Photovoltaics*. Sterling, VA: Earthscan, 2007.

Outline

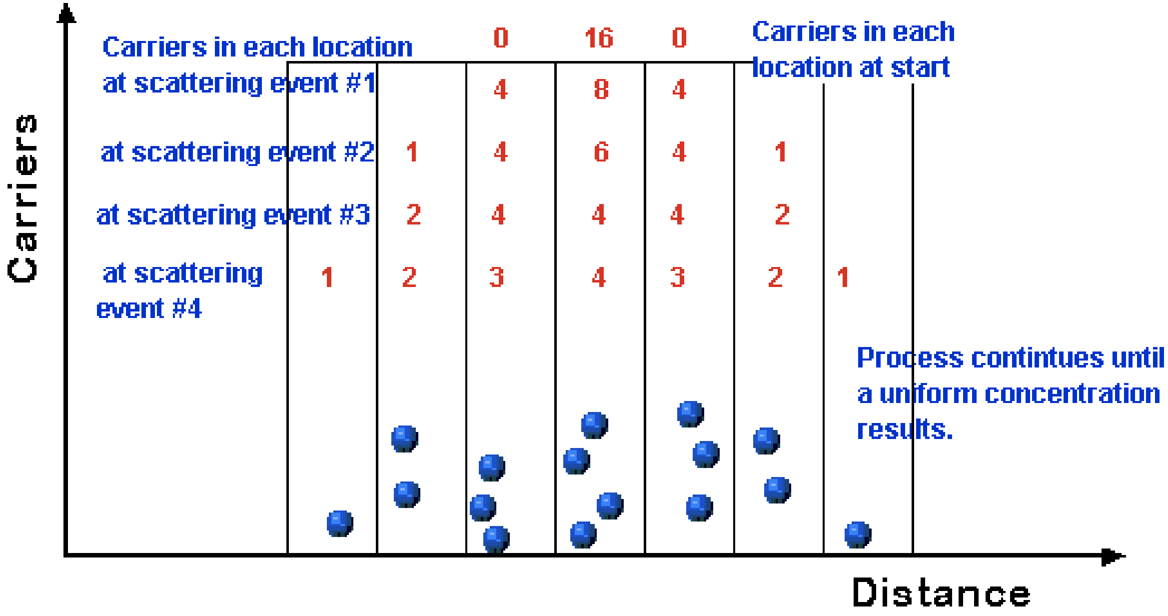
- Review: pn-junctions
- Minority carrier current
- Ideal diode equation

Review: Diffusion



In this animation, 1/4 of the carriers move to the right, 1/4 to the left and the remainder stay put (move up or down).

Courtesy Christiana Honsberg and Stuart Bowden. Used with permission.



Carriers in each location at start

Carriers in each location at scattering event #1

at scattering event #2

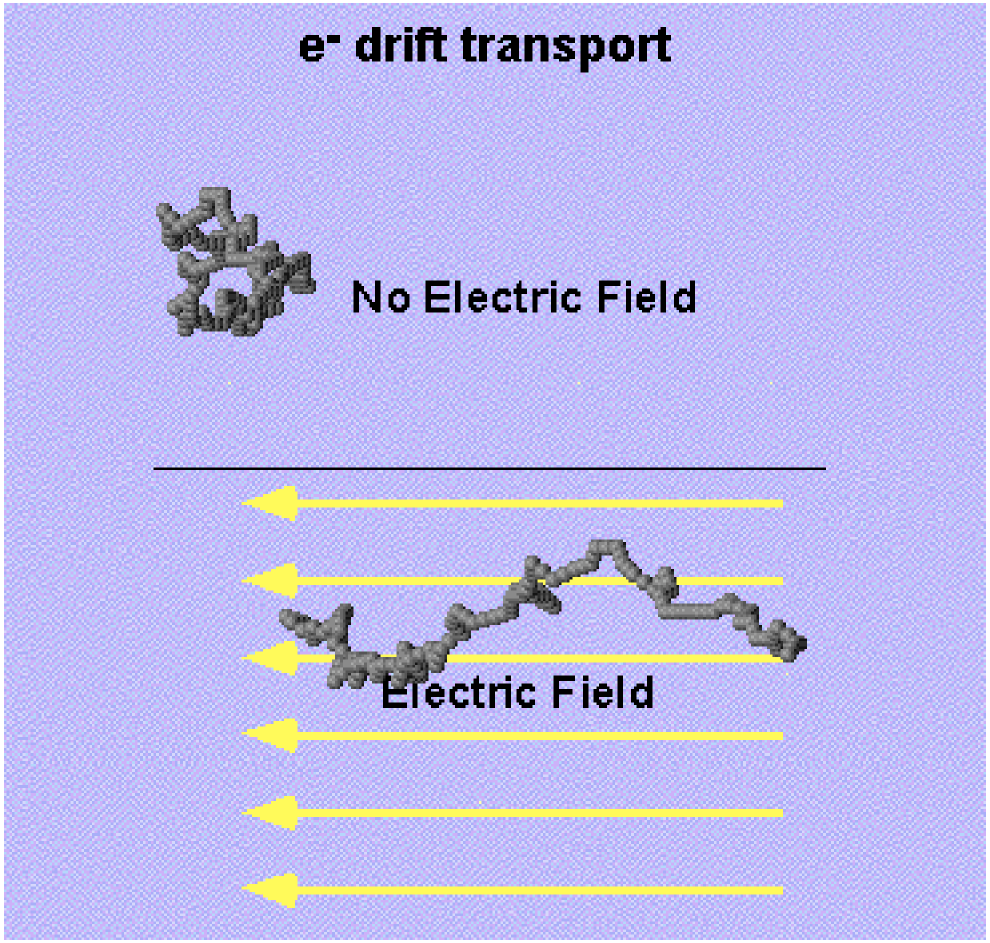
at scattering event #3

at scattering event #4

Process contintues until a uniform concentration results.

From PVCDROM

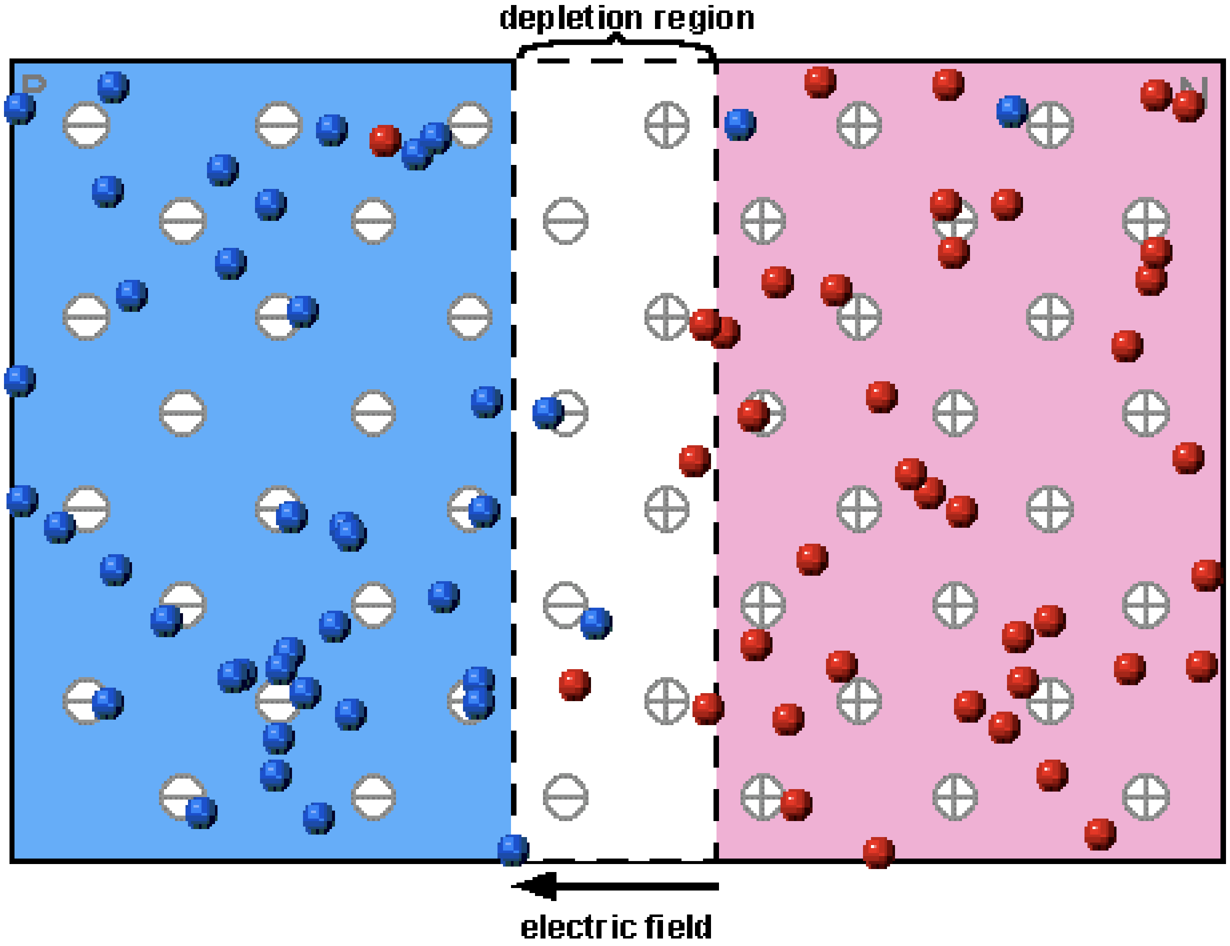
Review: Drift Current



From PVCDROM

Courtesy Christiana Honsberg and Stuart Bowden. Used with permission.

Review: pn-junction



Courtesy Christiana Honsberg and Stuart Bowden. Used with permission.

Eventually, the accumulation of like charges [(h^+ + P^+) or (e^- + B^-)] balances out the diffusion, and steady state condition is reached.

Nicer figure at Wikipedia!

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http://en.wikipedia.org/wiki/File:Pn-junction-equilibrium-graphs.png

http://en.wikipedia.org/wiki/P-n_junction

Pn-junction under bias

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http://www.ecse.rpi.edu/~schubert/Light-Emitting-Diodes-dot-org/chap04/F04-01%20PN%20junction%20energies.jpg.

http://www.ecse.rpi.edu/~schubert/Light-Emitting-Diodes-dot-org/chap04/chap04.htm

Bias Across a pn-Junction

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http://www.ecse.rpi.edu/~schubert/Light-Emitting-Diodes-dot-org/chap04/F04-01%20PN%20junction%20energies.jpg.

$$\begin{aligned} q\psi_{\mathrm{o}} &= E_{\mathrm{g}} - E_1 - E_2 \\ &= E_{\mathrm{g}} - kT\ln\left(\frac{N_{\mathrm{V}}}{N_{\mathrm{A}}}\right) - kT\ln\left(\frac{N_{\mathrm{C}}}{N_{\mathrm{D}}}\right) \\ &= E_{\mathrm{g}} - kT\ln\left(\frac{N_{\mathrm{C}}N_{\mathrm{V}}}{N_{\mathrm{A}}N_{\mathrm{D}}}\right) \end{aligned}$$

$$\psi_{\mathrm{o}} = \frac{kT}{q}\ln\left(\frac{N_{\mathrm{A}}N_{\mathrm{D}}}{n_i^2}\right)$$

Built-in pn-junction potential a function of dopant concentrations.

Bias Across a pn-Junction

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http://www.ecse.rpi.edu/~schubert/Light-Emitting-Diodes-dot-org/chap04/F04-01%20PN%20junction%20energies.jpg.

$$q\psi_{\mathrm{o}} = E_{\mathrm{g}} - E_1 - E_2$$

$$= E_{\mathrm{g}} - kT\ln\left(\frac{N_{\mathrm{V}}}{N_{\mathrm{A}}}\right) - kT\ln\left(\frac{N_{\mathrm{C}}}{N_{\mathrm{D}}}\right)$$

$$= E_{\mathrm{g}} - kT\ln\left(\frac{N_{\mathrm{C}}N_{\mathrm{V}}}{N_{\mathrm{A}}N_{\mathrm{D}}}\right)$$

$$\psi_{\mathrm{o}} = \frac{kT}{q}\ln\left(\frac{N_{\mathrm{A}}N_{\mathrm{D}}}{n_i^2}\right)$$

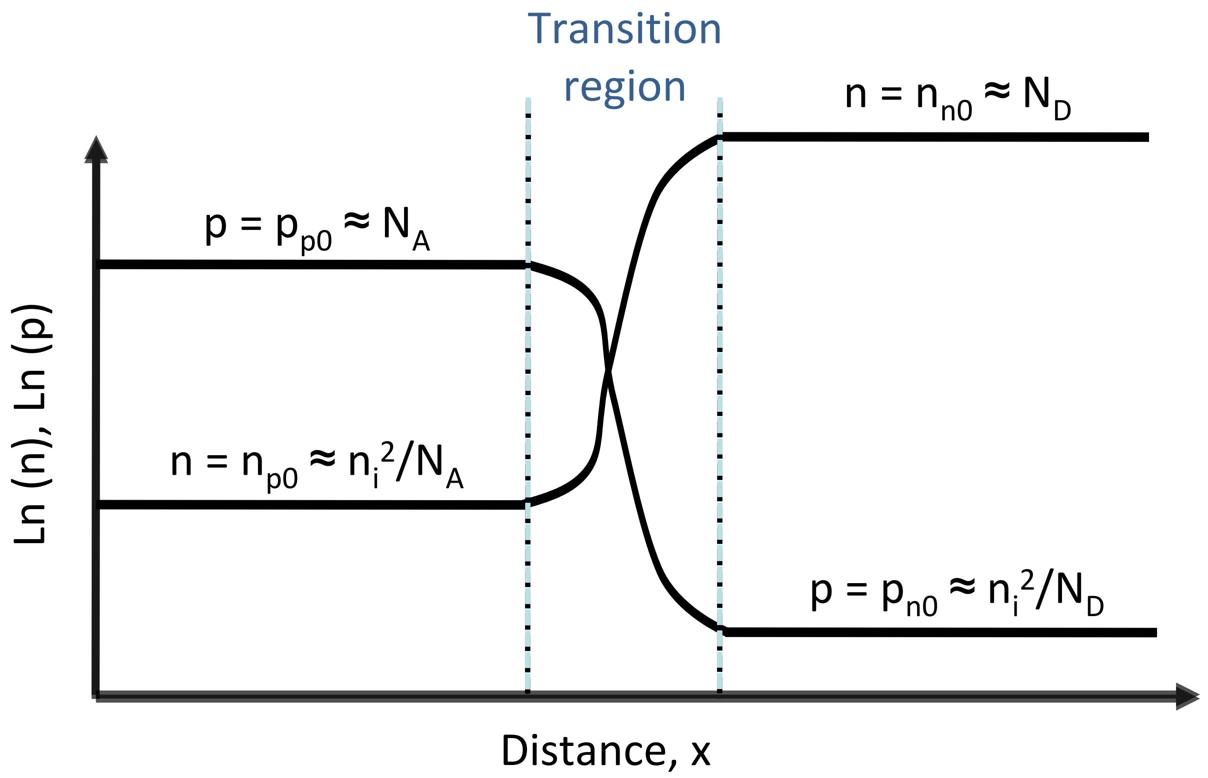
Built-in pn-junction potential a function of dopant concentrations.

Bias Across a pn-Junction

The potential across a biased pn-junction device is

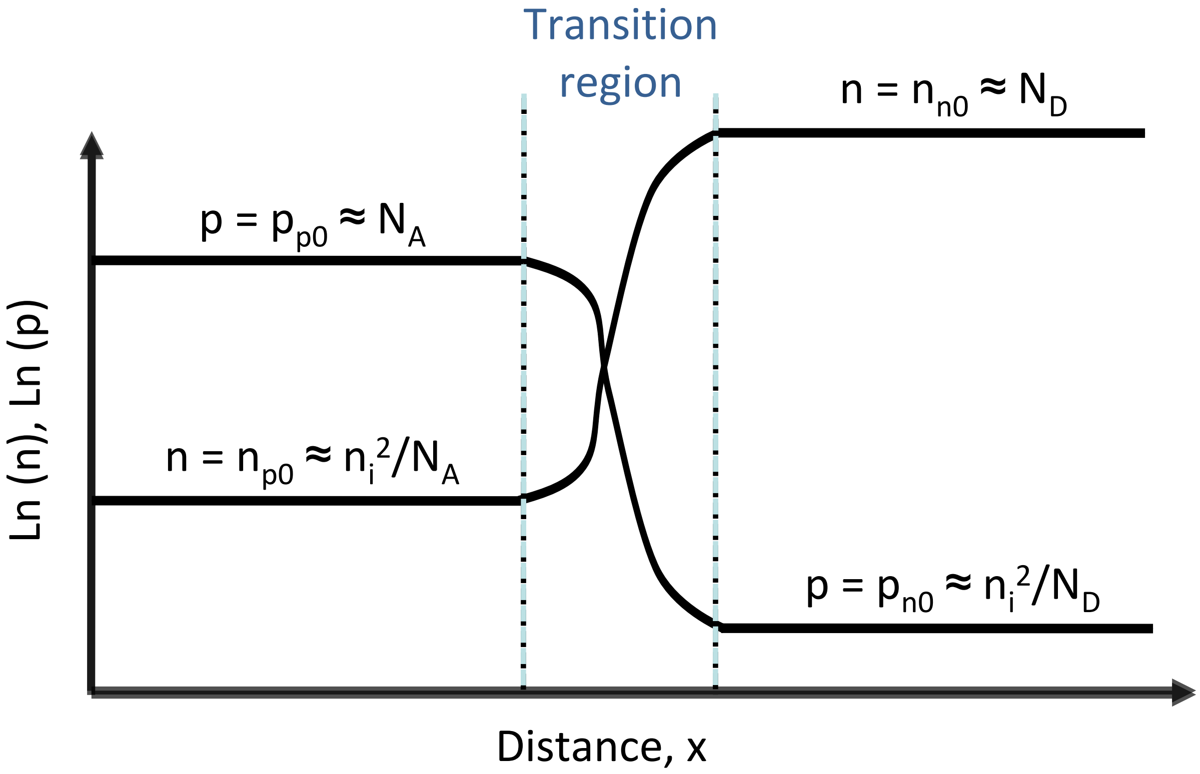
$$\psi_{\mathrm{o}} - V_{\mathrm{A}} = \frac{kT}{q}\ln\left(\frac{N_{\mathrm{A}}N_{\mathrm{D}}}{n_i^2}\right) - V_{\mathrm{A}}$$

Carrier Concentrations Across a pn-Junction



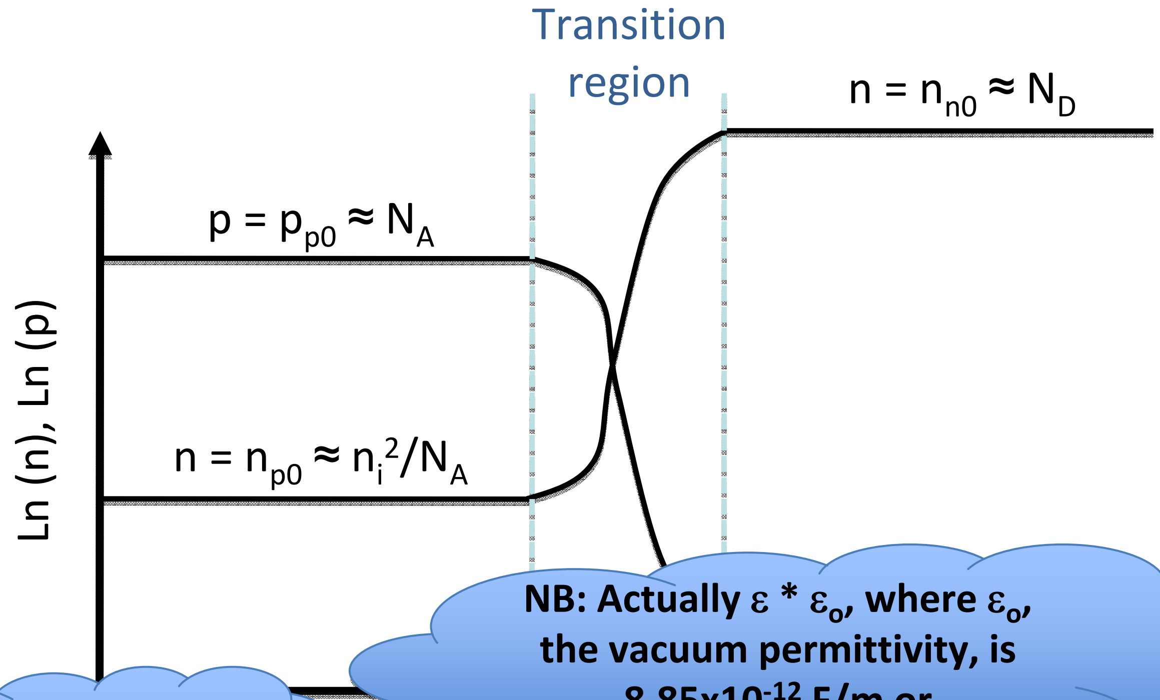
Approximation 1: Device can be split into two types of region: quasi-neutral regions (space-charge density is assumed zero) and the depletion region (where carrier concentrations are small, and ionized dopants contribute to fixed charge).

Width of space charge region



$$W = l_n + l_p = \sqrt{\frac{2\varepsilon}{q}(\psi_o - V_a)\cdot\left(\frac{1}{N_A}+\frac{1}{N_D}\right)}$$

Width of space charge region

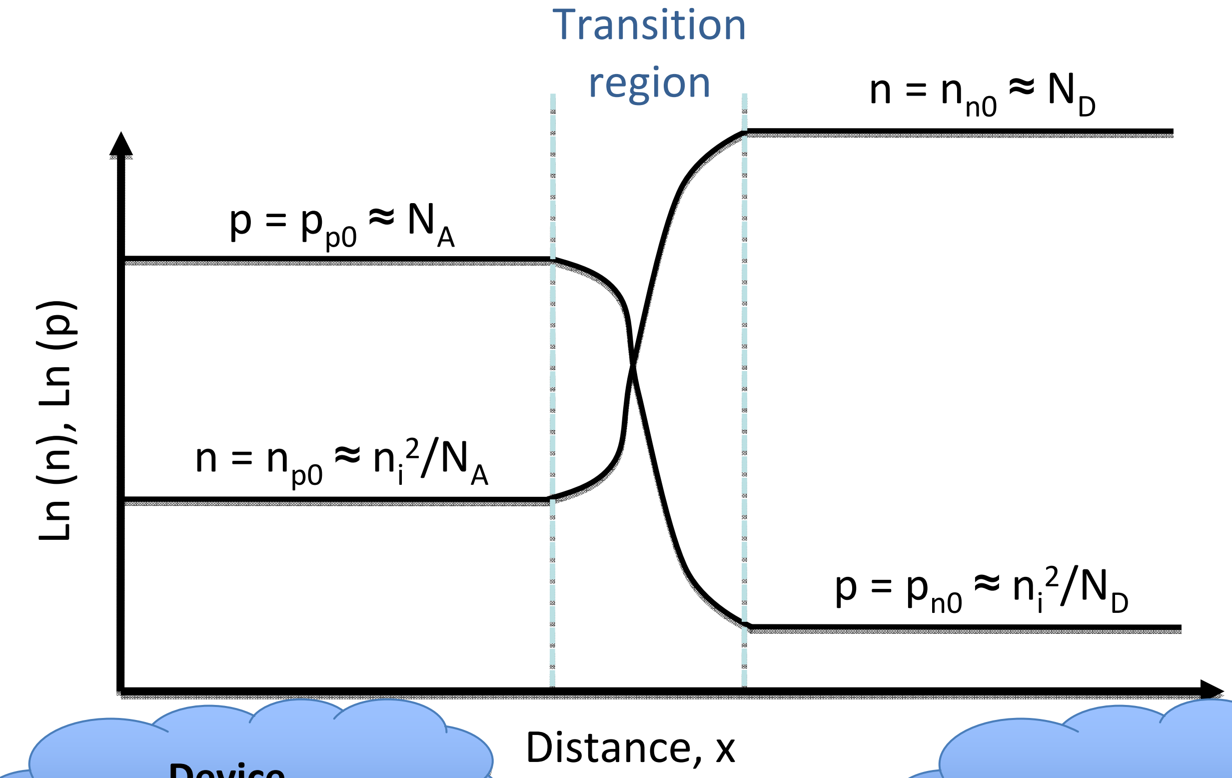


NB: Actually $\varepsilon * \varepsilon_o$, where ε_o, the vacuum permittivity, is $8.85\text{x}10^{-12}$ F/m or $5.53\text{x}10^{7}$ e/(V*m)

Width of the space-charge region

$$W = l_n + l_p = \sqrt{\frac{2\varepsilon}{q}(\psi_o - V_a)\cdot\left(\frac{1}{N_A} + \frac{1}{N_D}\right)}$$

Capacitance

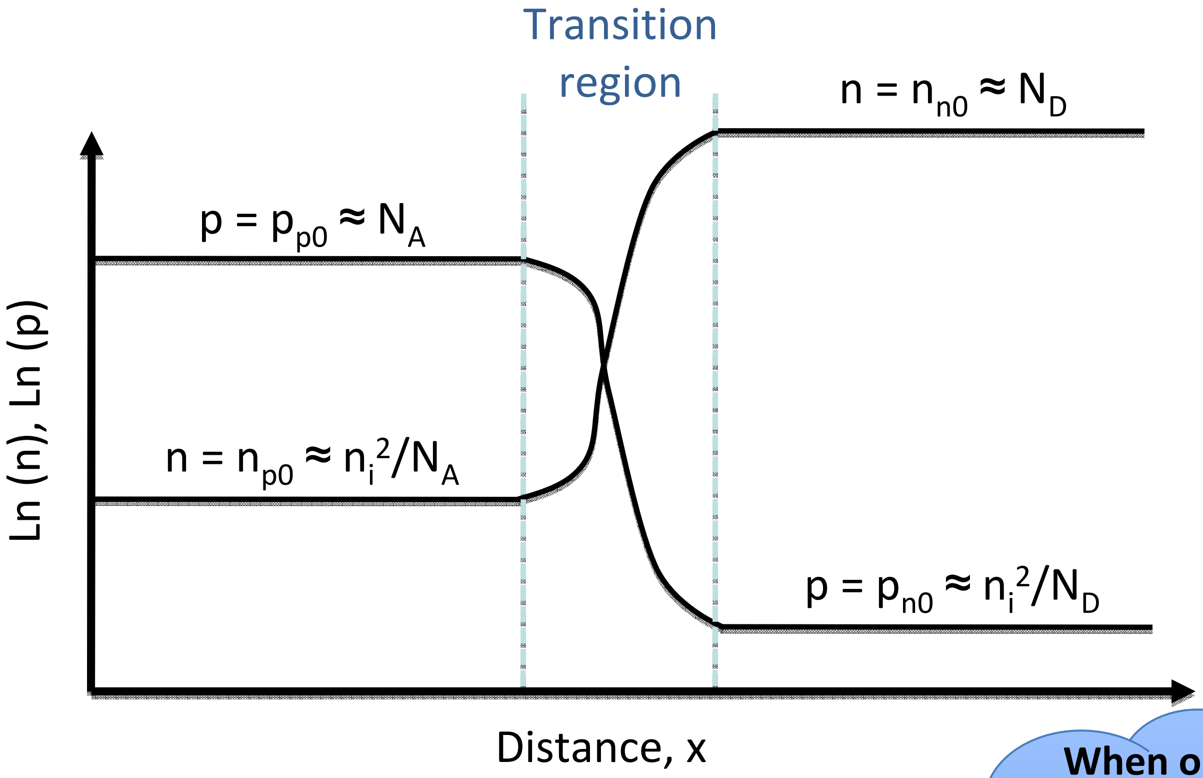


Device capacitance

pn-junction area

$$C = \frac{\varepsilon A}{W}$$

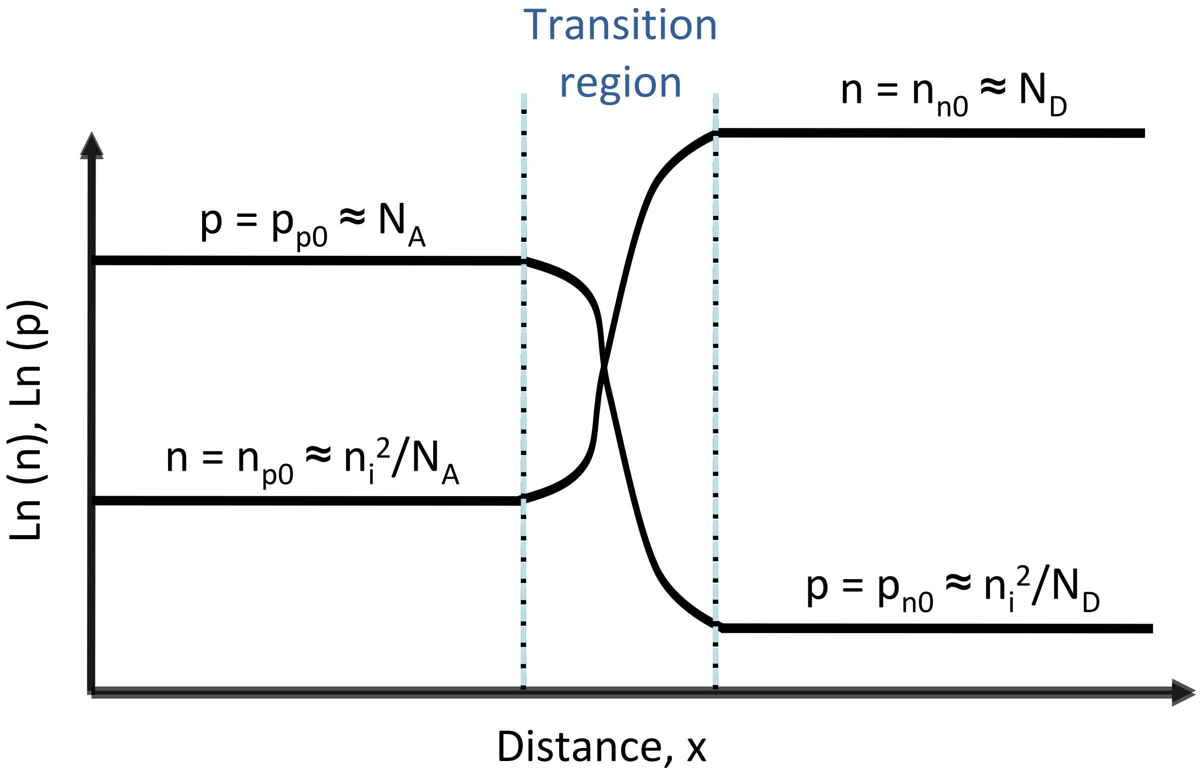
Capacitance



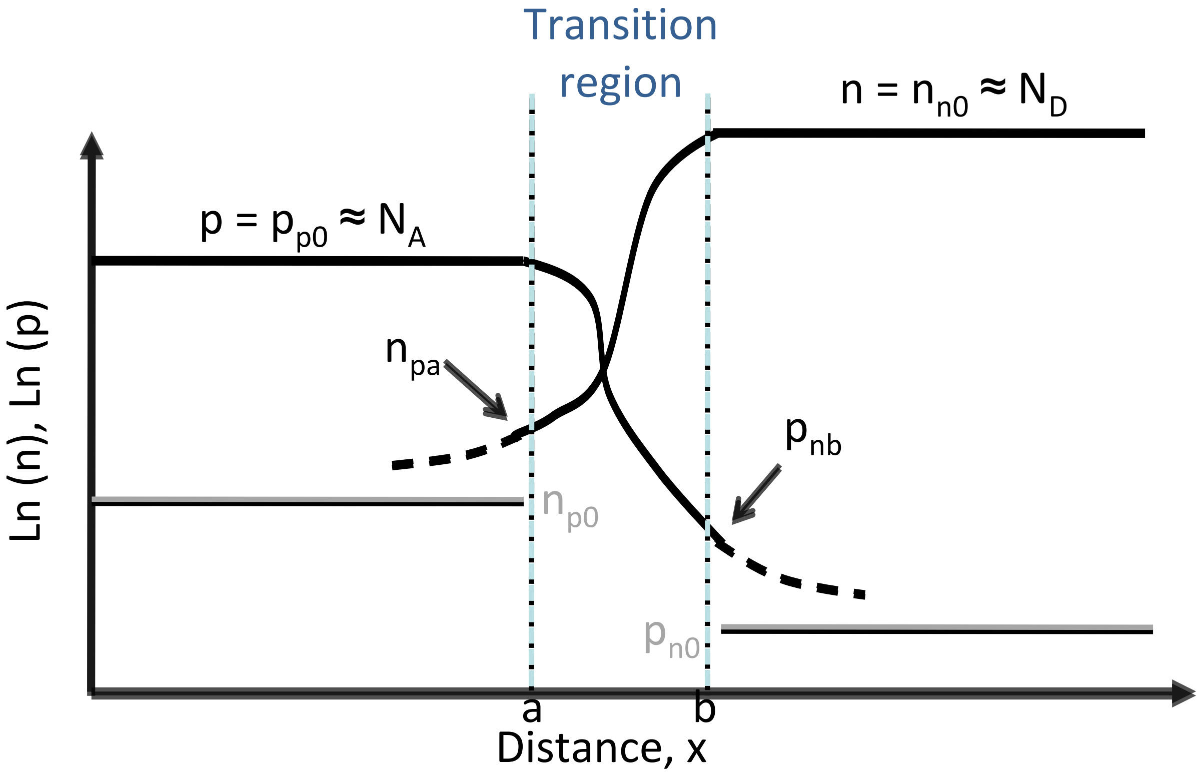
$$\frac{C}{A} = \sqrt{\frac{q\varepsilon N}{2(\psi_o - V_a)}}$$

When one side of the pn-junction is heavily doped, the capacitance reduces to this expression

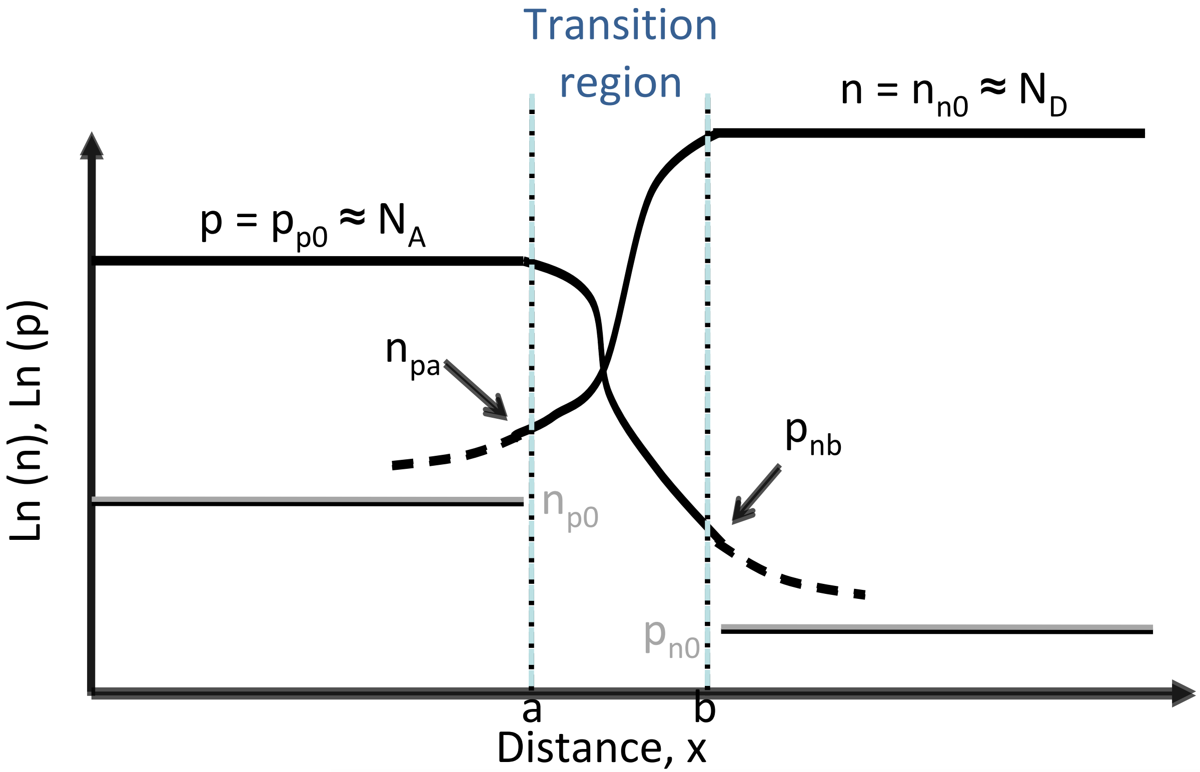
Pn-junction under zero bias



Pn-junction under **forward** bias



Pn-junction under forward bias

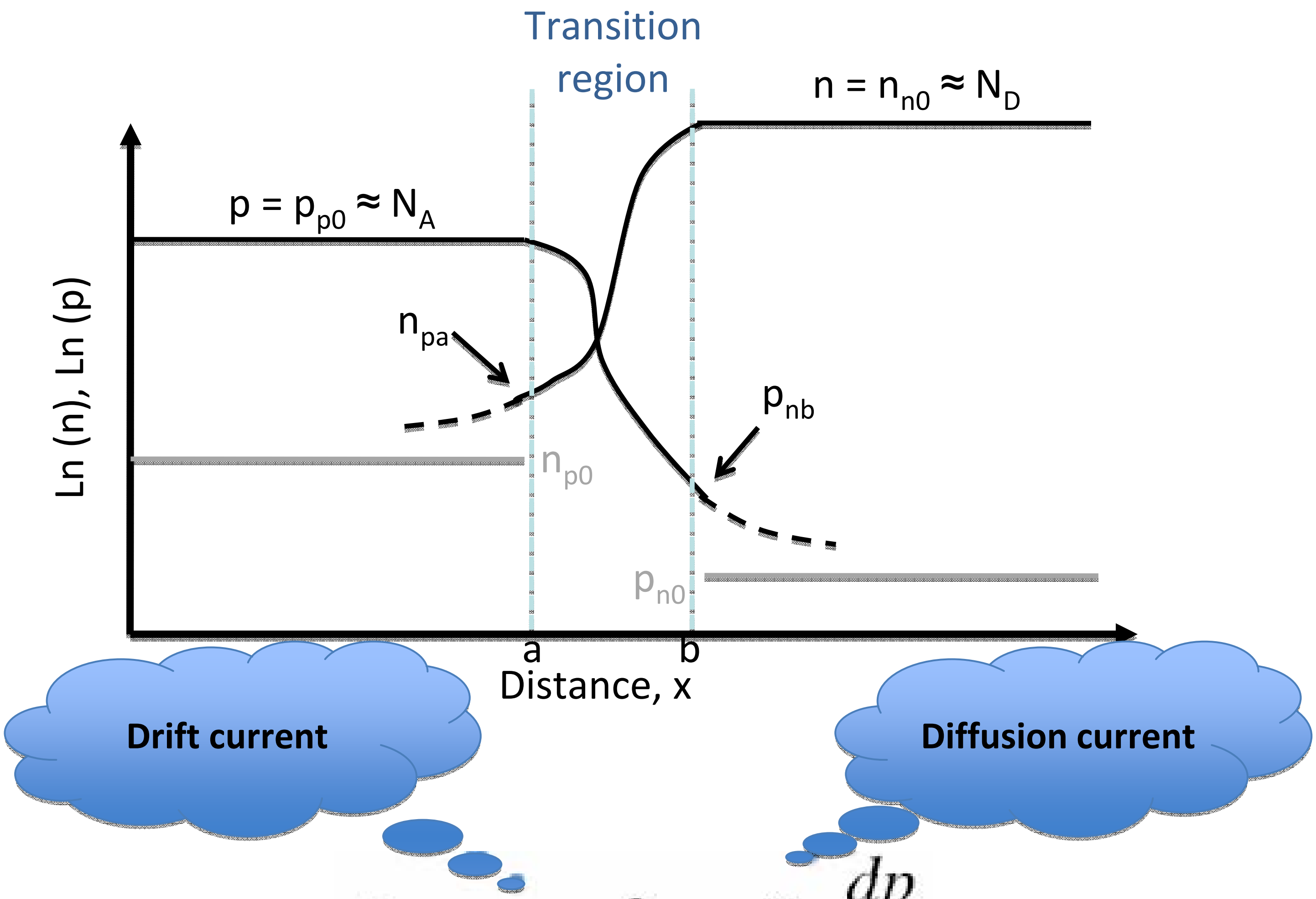


At zero bias:

$$p_{nb} = p_{n0} = p_{p0} \cdot \exp\left(-\frac{q\psi_\circ}{kT}\right) \approx \frac{n_i^2}{N_\mathrm{D}}$$

$$n_{pa} = n_{p0} = n_{n0} \cdot \exp\left(-\frac{q\psi_\circ}{kT}\right) \approx \frac{n_i^2}{N_\mathrm{A}}$$

Current flow through the depletion region



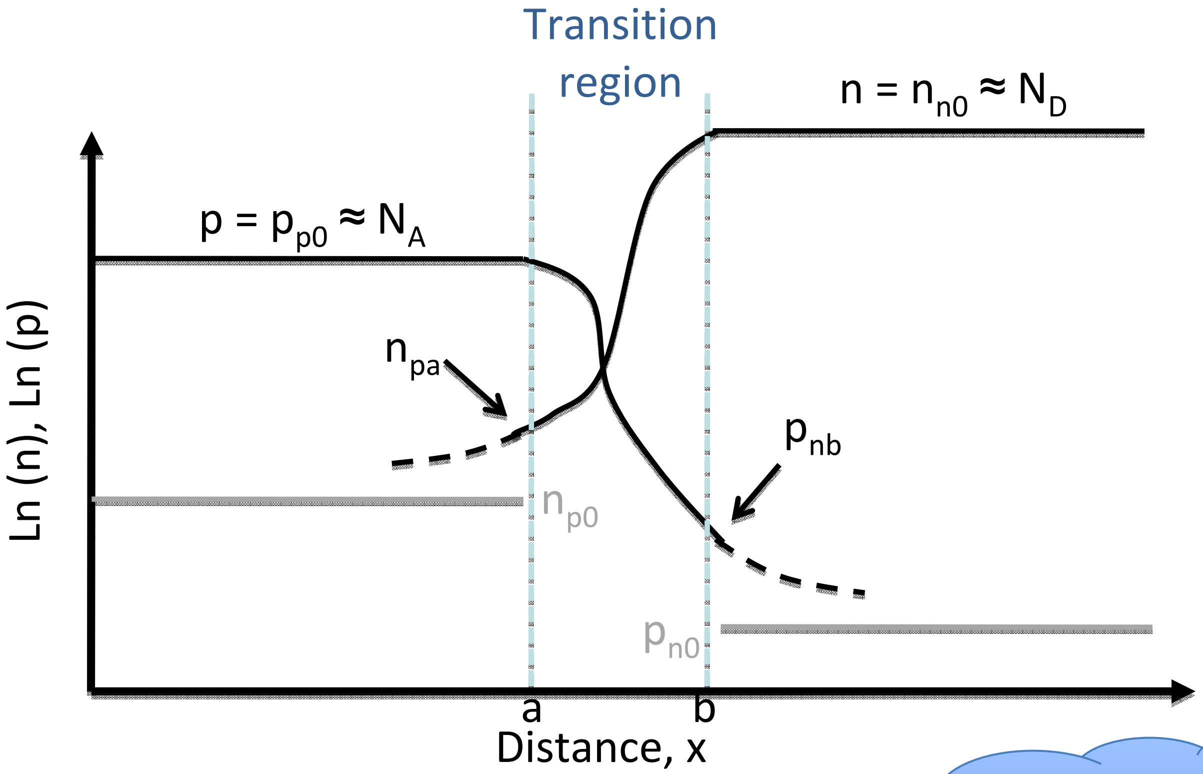
Drift current

Diffusion current

For <u>holes</u>:

$$J_h = q\mu_h p\xi - qD_h \frac{dp}{dx}$$

Current flow through the depletion region

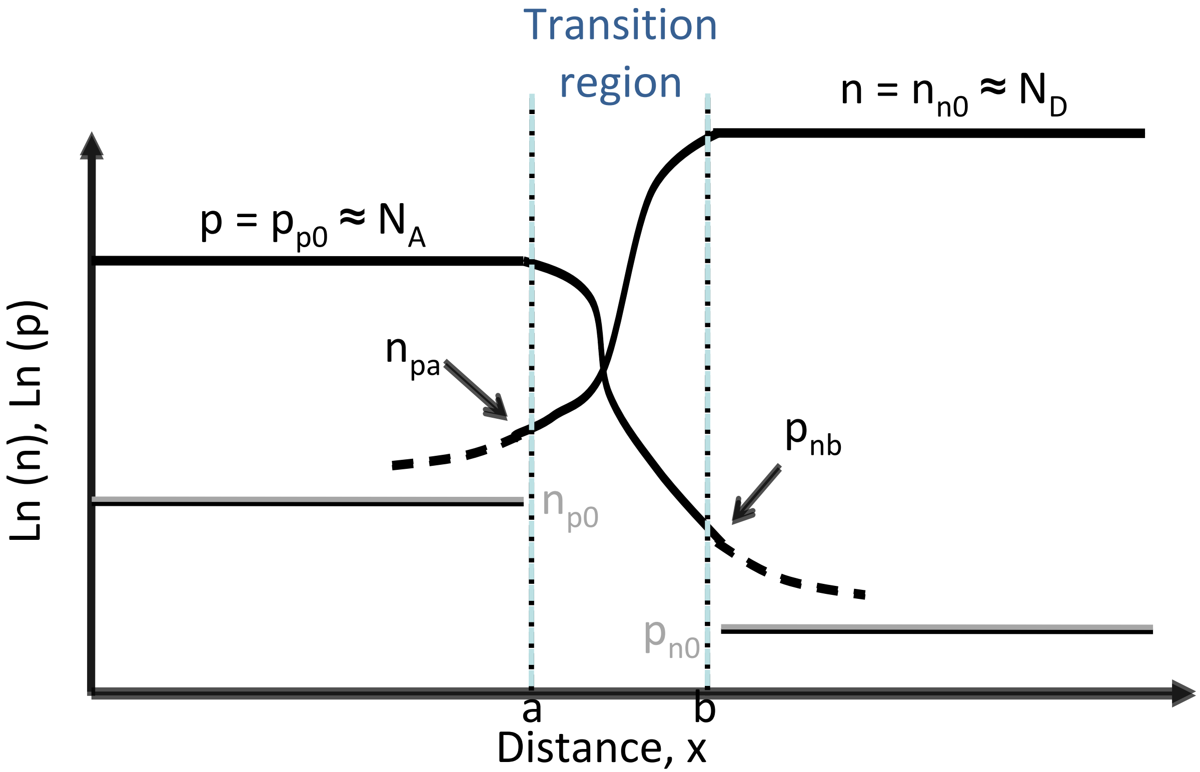


Approximation 2:
Assume J_h is small!

For holes:

$$\xi \approx \frac{kT}{q}\frac{1}{p}\frac{dp}{dx}$$

Current flow through the depletion region

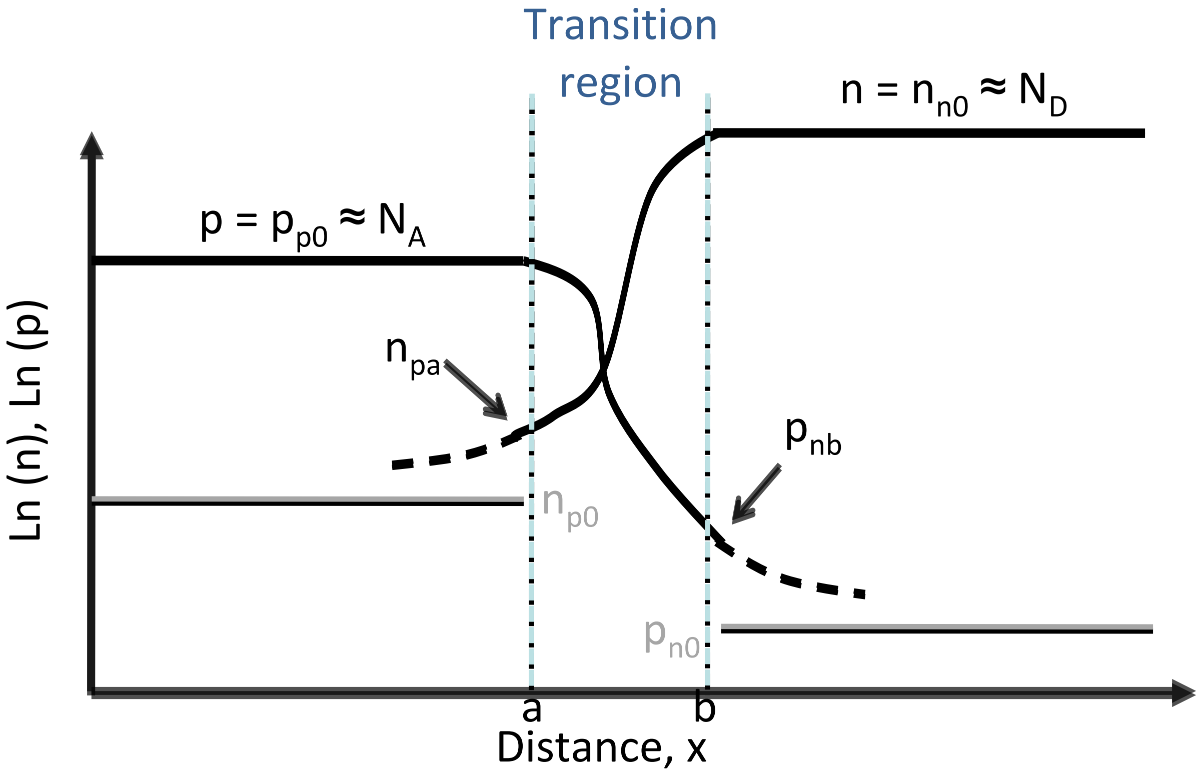


Integrating…

$$\psi_o - V_a = -\frac{kT}{q}\ln(p)\Big|_a^b$$

$$= \frac{kT}{q}\ln\left(\frac{p_{pa}}{p_{nb}}\right)$$

Current flow through the depletion region



Approximation 3: Only cases where minority carriers have a much lower concentration than majority carriers will be considered, i.e., $p_{pa} >> n_{pa}$, $n_{na} >> p_{na}$

$$p_{pa} = N_A + n_{pa}$$

Current densities

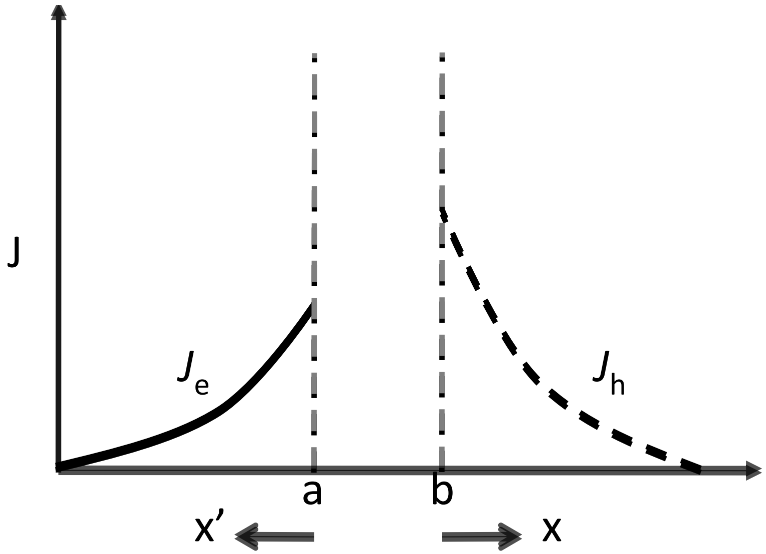
Calculate (diffusive) currents in quasi-neutral region:

$$J_h = -qD_h \frac{dp}{dx}$$

... from previous slide ...

$$J_h(x) = \frac{qD_h p_{n0}}{L_h}\left(e^{qV/kT} - 1\right)e^{-x/L_h}$$

$$J_e(x') = \frac{qD_e n_{n0}}{L_e}\left(e^{qV/kT} - 1\right)e^{-x/L_e}$$



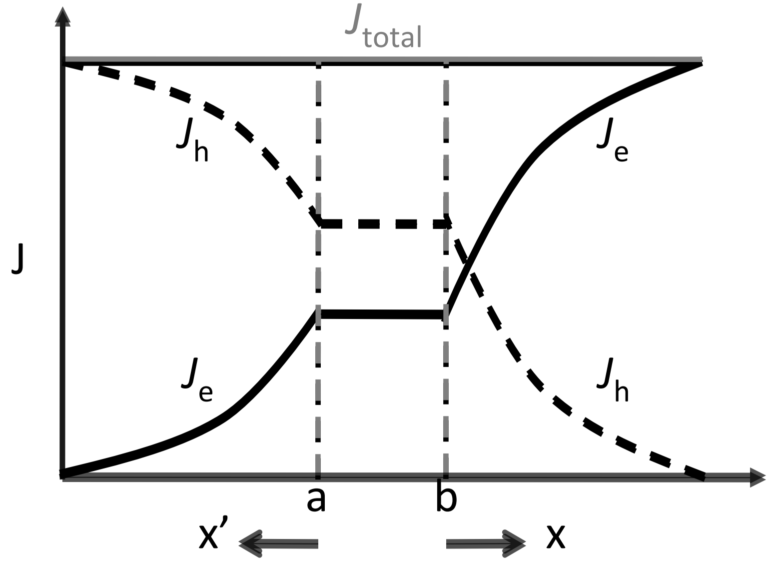
Current densities

$$\frac{1}{q}\frac{dJ_e}{dx} = U - G = -\frac{1}{q}\frac{dJ_h}{dx}$$

Magnitude of the change in current across the depletion region:

$$\delta J_e = \left|\delta J_h\right| = q\int_{-W}^{0}(U-G)\,dx \approx 0$$

Key assumption: W is small compared to L_e *and* L_h*. Therefore, integral is negligible. It follows that the current* J_e *and* J_h *are essentially constant across the depletion region, as shown below.*



Ideal Diode Equation

Since J_e and J_h are known at all points in the depletion region, we can calculate the total current:

$$J_{\text{total}} = J_e\big|_{x'=0} + J_h\big|_{x=0} = \left(\frac{qD_e n_{p0}}{L_e} + \frac{qD_h p_{n0}}{L_h}\right)\left(e^{qV/kT} - 1\right)$$

This leads to the ideal diode law:

$$I = I_o\left(e^{qV/kT} - 1\right), \text{ where}$$

$$I_o = A\left(\frac{qD_e n_i^2}{L_e N_A} + \frac{qD_h n_i^2}{L_h N_D}\right)$$

Next Class

- *Ideal diode equation discussion*
- *Contacts*
- *Review Part 1*