Lecture 13 - p-n Junction

March 7, 2007

Contents:

1. Ideal p-n junction in equilibrium
2. Ideal p-n junction out of equilibrium

Reading assignment:

del Alamo, Ch. 7, §§7.1, 7.2 (7.2.1, 7.2.2)

Announcements:

Quiz 1: **March 13**, 7:30-9:30 PM; lec-tures #1-12 (up to SCR-type transport). Open book. *Calculator required.*

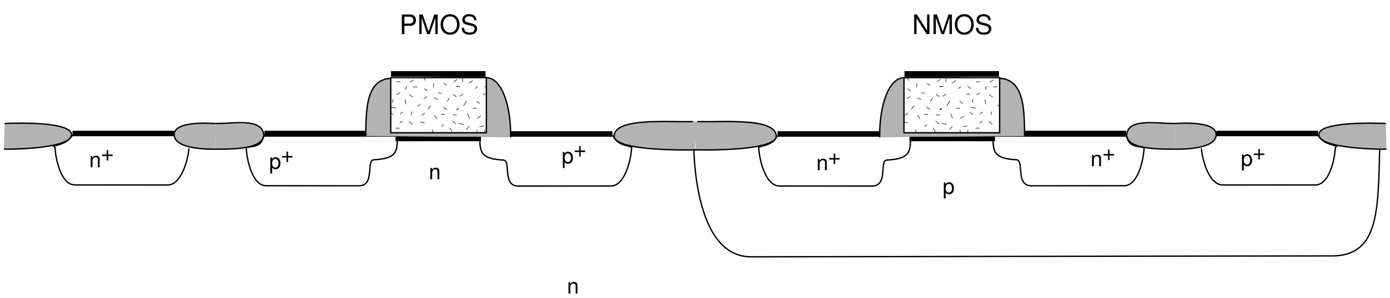
Final Exam scheduled: **May 23**, 1:30-3:30 PM.

Key questions

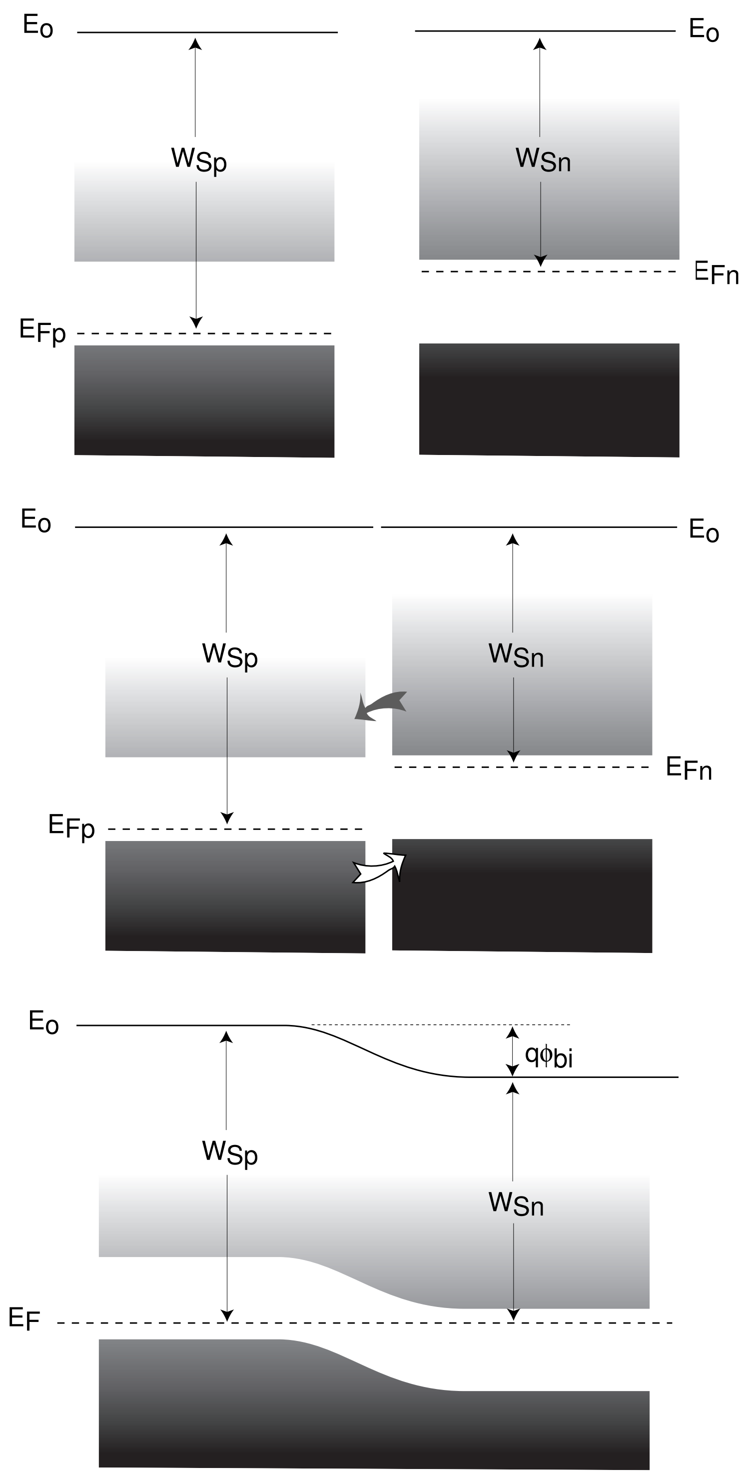
- What happens if you bring into intimate contact an n-type region and a p-type region?
- What happens to the electrostatics of a p-n junction if one applies a bias accross?

Motivation: pn junctions everywhere!

Example: CMOS



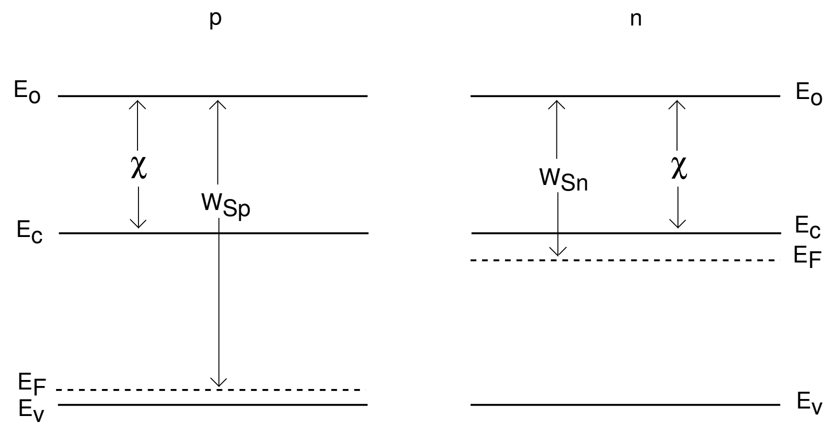
1. Ideal p-n junction in equilibrium

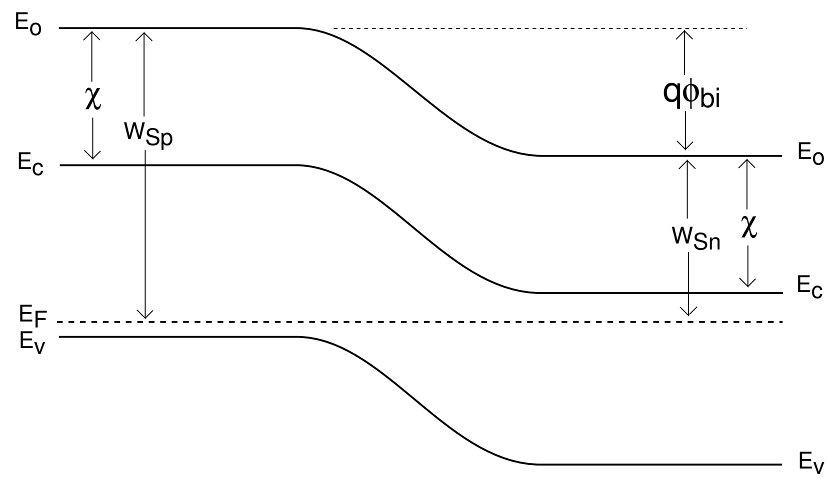


a) two semiconductors far apart

b) two semiconductors just before contact

c) two semiconductors in intimate contact

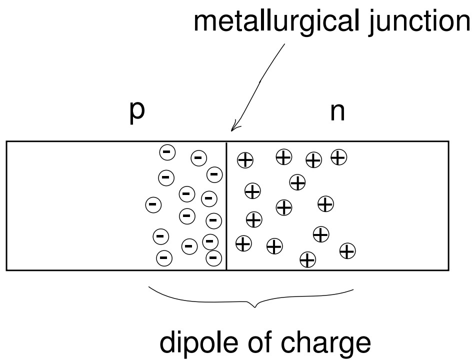


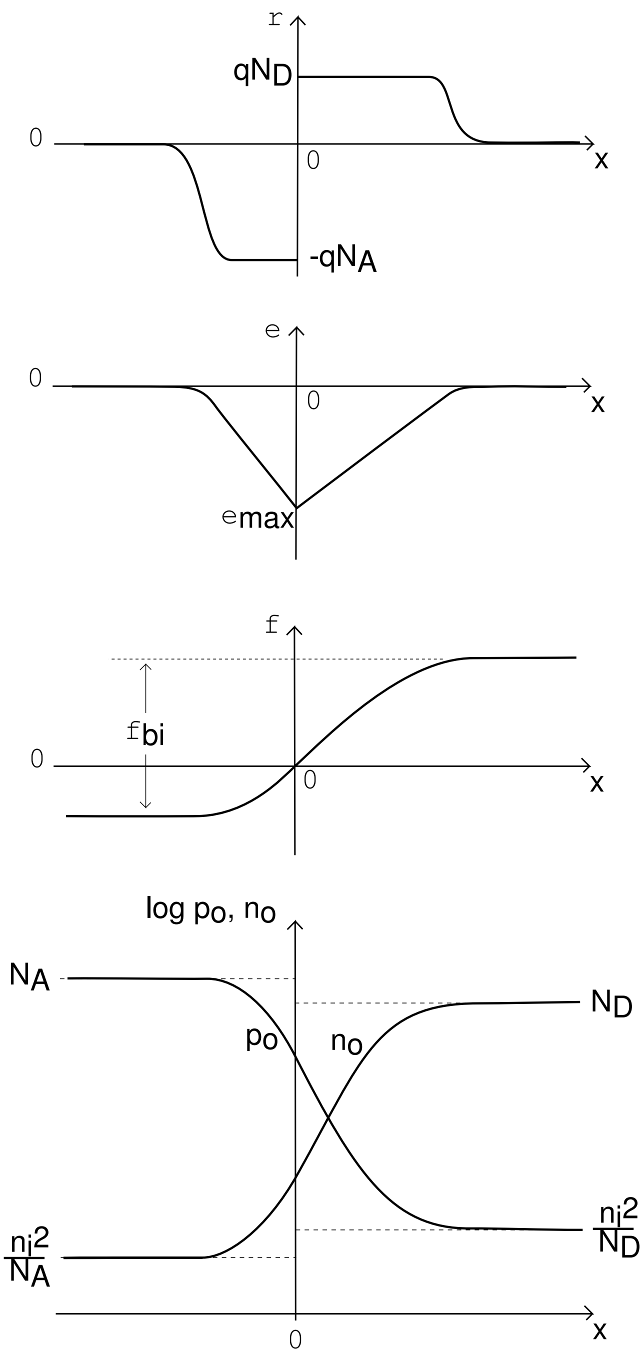


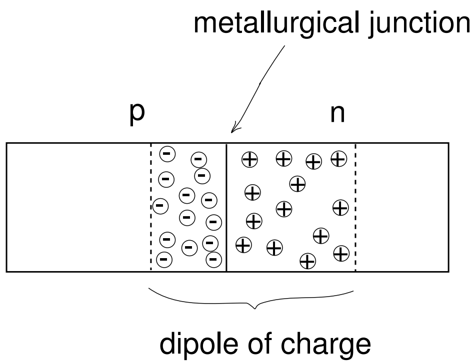
$$
\begin{aligned}
q\phi_{bi} &= W_{Sp} - W_{Sn} = (E_C - E_F)|_{x \ll 0} - (E_C - E_F)|_{x \gg 0} \\
&= kT \ln \frac{n_o(x \gg 0)}{n_o(x \ll 0)}
\end{aligned}
$$

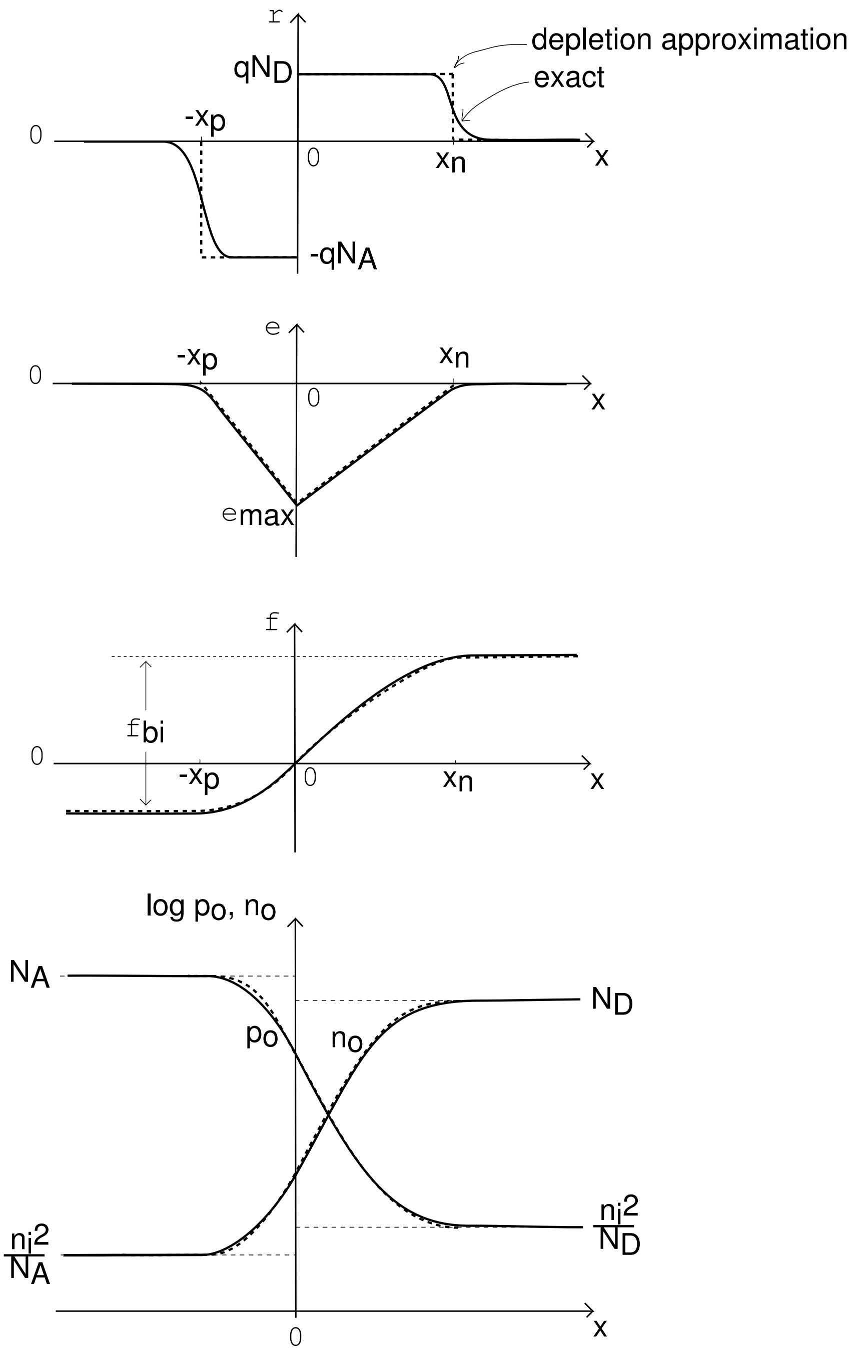
Then:

$$\phi_{bi} = \frac{kT}{q} \ln \frac{N_D N_A}{n_i^2}$$


metallurgical junction
p
n
dipole of charge


r
qND
0
0
x
-qNA
e
0
0
x
emax
f
fbi
0
0
x
log po, no
NA
ND
po
no
ni2/NA
ni2/ND
0
x


metallurgical junction
p
n
dipole of charge


r
depletion approximation
exact
qND
-xp
0
0
xn
x
-qNA
e
-xp
xn
0
0
x
emax
f
fbi
0
-xp
0
xn
x
log po, no
NA
ND
po
no
ni2/NA
ni2/ND
0
x

Do *depletion approximation*:

□ Volume charge density:

$$\begin{aligned}
\rho(x) &\simeq 0 && \text{in p-QNR: } x < -x_p \\
\rho(x) &\simeq -qN_A && \text{in SCR: } -x_p < x < 0 \\
\rho(x) &\simeq qN_D && \text{in SCR: } 0 < x < x_n \\
\rho(x) &\simeq 0 && \text{in n-QNR: } x_n < x
\end{aligned}$$

□ Electric field:

$$\begin{aligned}
\mathcal{E}(x) &\simeq 0 && \text{in p-QNR: } x \leq -x_p \\
\mathcal{E}(x) &\simeq -\frac{qN_A}{\epsilon}(x + x_p) && \text{in SCR: } -x_p \leq x \leq 0 \\
\mathcal{E}(x) &\simeq \frac{qN_D}{\epsilon}(x - x_n) && \text{in SCR: } 0 \leq x \leq x_n \\
\mathcal{E}(x) &\simeq 0 && \text{in n-QNR: } x_n \leq x
\end{aligned}$$

□ Electrostatic potential [select $\phi(x = 0) = 0$]:

$$\begin{aligned}
\phi(x) &\simeq -\frac{qN_A x_p^2}{2\epsilon} && \text{in p-QNR: } x \leq -x_p \\
\phi(x) &\simeq \frac{qN_A}{2\epsilon}(x^2 + 2x_p x) && \text{in SCR: } -x_p \leq x \leq 0 \\
\phi(x) &\simeq -\frac{qN_D}{2\epsilon}(x^2 - 2x_n x) && \text{in SCR: } 0 \leq x \leq x_n \\
\phi(x) &\simeq \frac{qN_D x_n^2}{2\epsilon} && \text{in n-QNR: } x_n \leq x
\end{aligned}$$

Two unknowns: x_n and x_p.

- demand overall charge neutrality:

$$qN_A x_p = qN_D x_n$$

- potential difference across structure must be ϕ_{bi}:

$$\phi(x_n) - \phi(-x_p) = \frac{qN_D x_n^2}{2\epsilon} + \frac{qN_A x_p^2}{2\epsilon} = \phi_{bi}$$

Solve for x_n and x_p:

$$x_n = \sqrt{\frac{2\epsilon N_A \phi_{bi}}{qN_D(N_D + N_A)}} \qquad x_p = \sqrt{\frac{2\epsilon N_D \phi_{bi}}{qN_A(N_D + N_A)}}$$

Total SCR width:

$$x_{SCR} = \sqrt{\frac{2\epsilon(N_D + N_A)\phi_{bi}}{qN_A N_D}}$$

Maximum electric field:

$$|\mathcal{E}_{max}| = \sqrt{\frac{2qN_A N_D \phi_{bi}}{\epsilon(N_D + N_A)}}$$

- symmetric junction: $N_A = N_D$:

$$x_p = x_n$$

$$|\phi(-x_p)| = \phi(x_n)$$

- asymmetric junction: *i.e.* $N_A > N_D$:

$$x_p < x_n$$

$$|\phi(-x_p)| < \phi(x_n)$$

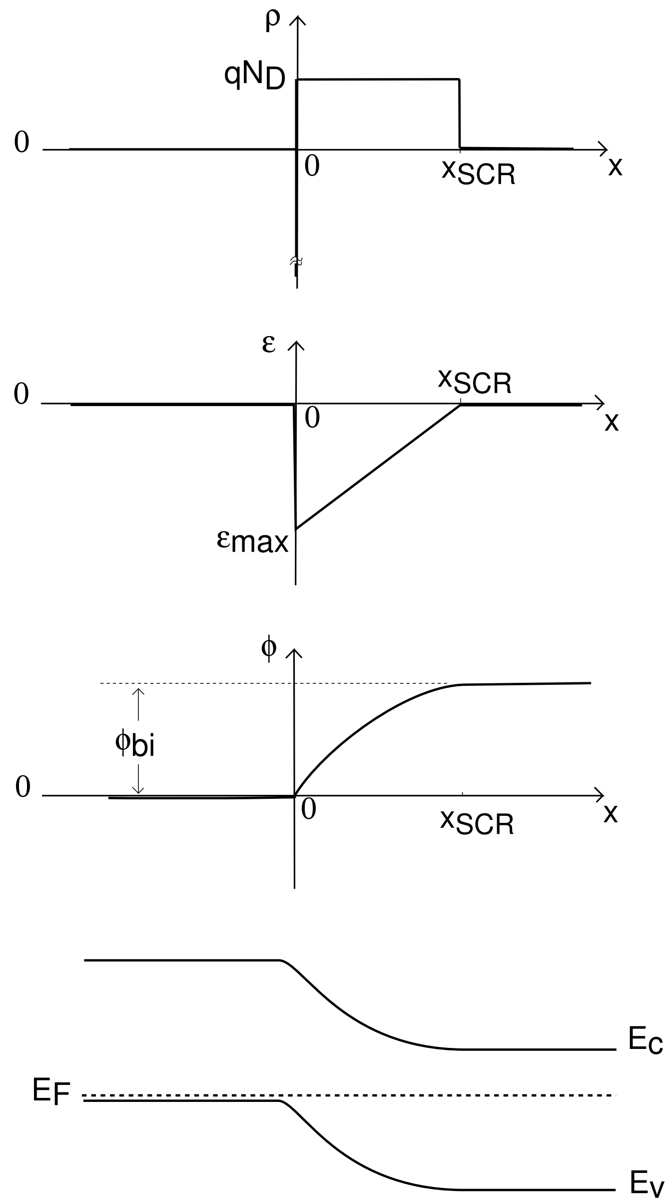
- strongly asymmetric junction: *i.e.* p$^+$-n junction $N_A \gg N_D$:

$$x_p \ll x_n \simeq x_{SCR} \simeq \sqrt{\frac{2\epsilon\phi_{bi}}{qN_D}}$$

$$|\mathcal{E}_{max}| \simeq \sqrt{\frac{2qN_D\phi_{bi}}{\epsilon}}$$

the lowly-doped side controls everything

$$|\phi(-x_p)| \ll \phi(x_n) \simeq \phi_{bi}$$


ρ
qN_D
0
0
x_SCR
x
ε
0
x_SCR
0
x
εmax
φ
φbi
0
0
x_SCR
x
Ec
EF
Ev

2. Ideal p-n junction out of equilibrium

Apply voltage across:

- forward bias: p-region positive with respect to n-region
- reverse bias: p-region negative with respect to n-region

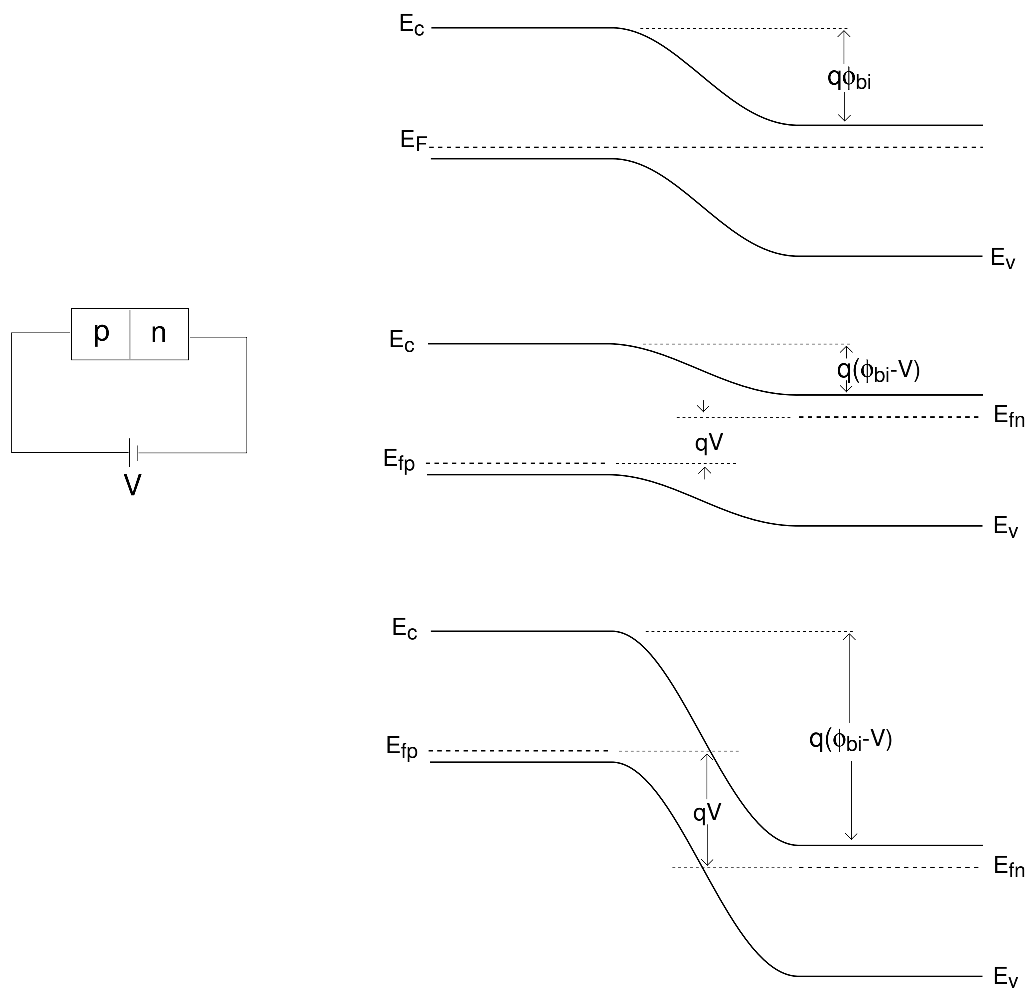
Voltage can drop in five distinct regions:

- ohmic contact to n-region
- quasi-neutral n-region
- space-charge region
- quasi-neutral p-region
- ohmic contact to p-region

□ Electrostatics

Battery grabs on majority carrier Fermi levels [will see when we discuss ohmic contacts].

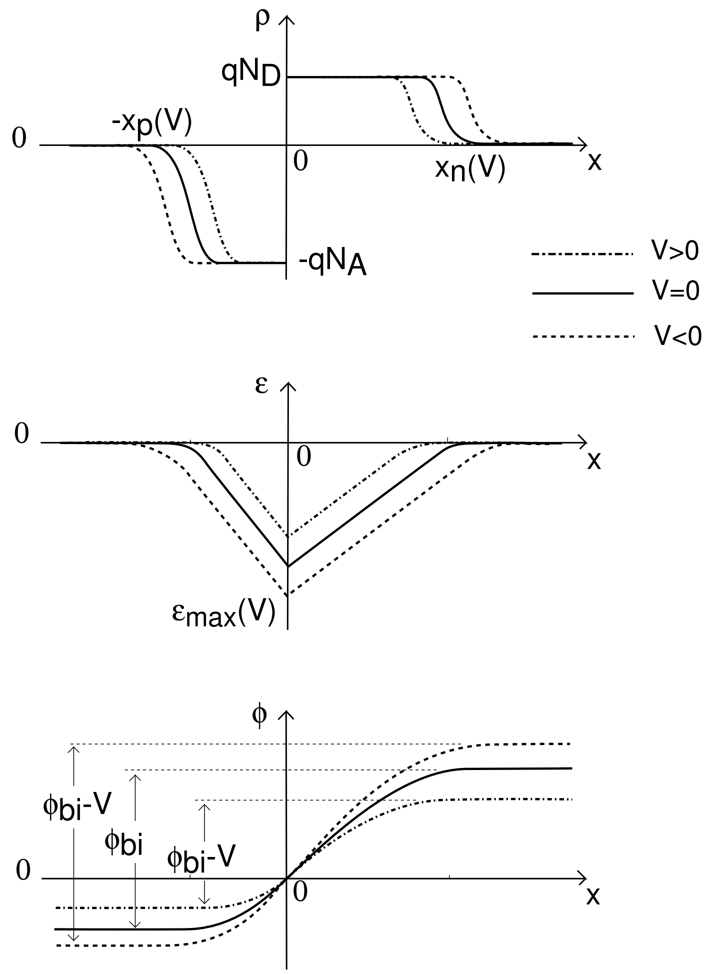
Application of voltage splits Fermi levels:



In forward and reverse bias:

$$\phi_{bi} \rightarrow \phi_{bi} - V$$

Qualitatively, electrostatics unchanged out of equilibrium, but SCR widens and shrinks, as needed:



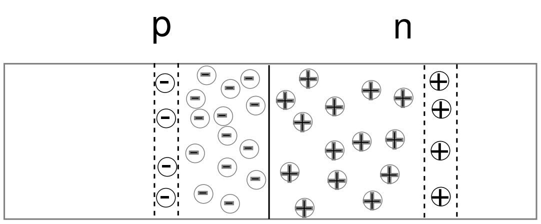
→ use equilibrium equations:

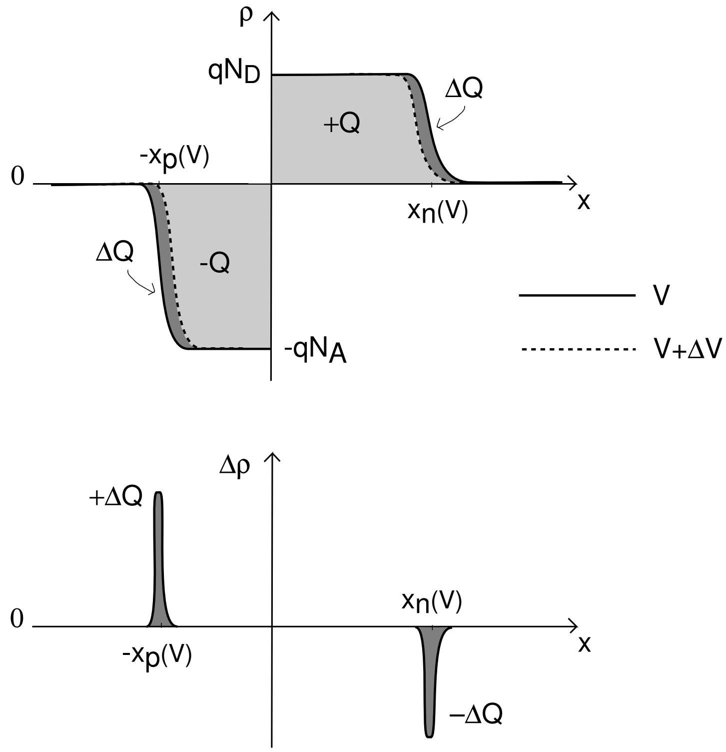
$$x_{SCR}(V) = \sqrt{\frac{2\epsilon(N_D + N_A)(\phi_{bi} - V)}{qN_AN_D}} = x_{SCR}(V=0)\sqrt{1 - \frac{V}{\phi_{bi}}}$$

$$|\mathcal{E}_{max}(V)| = \sqrt{\frac{2qN_AN_D(\phi_{bi} - V)}{\epsilon(N_D + N_A)}} = |\mathcal{E}_{max}(V=0)|\sqrt{1 - \frac{V}{\phi_{bi}}}$$

□ Depletion capacitance

Think differentially:





$$C(V) = \frac{\epsilon}{x_{SCR}(V)}$$

Then:

$$C(V) = \sqrt{\frac{\epsilon q N_A N_D}{2(N_D + N_A)(\phi_{bi} - V)}} = \frac{C(V=0)}{\sqrt{1 - \frac{V}{\phi_{bi}}}}$$

$$C(V) = \sqrt{\frac{\epsilon q N_A N_D}{2(N_D + N_A)(\phi_{bi} - V)}} = \frac{C(V=0)}{\sqrt{1 - \frac{V}{\phi_{bi}}}}$$

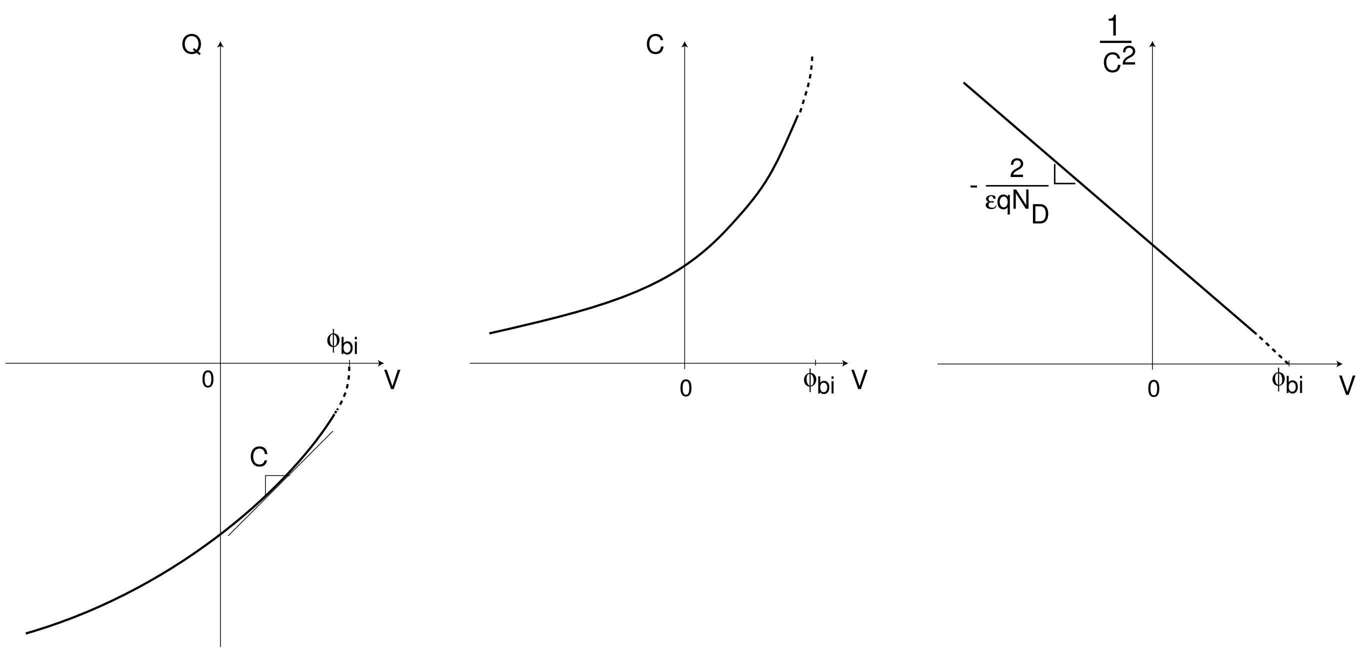
For p$^+$-n junction:

$$C(V) = \sqrt{\frac{\epsilon q N_D}{2(\phi_{bi} - V)}}$$

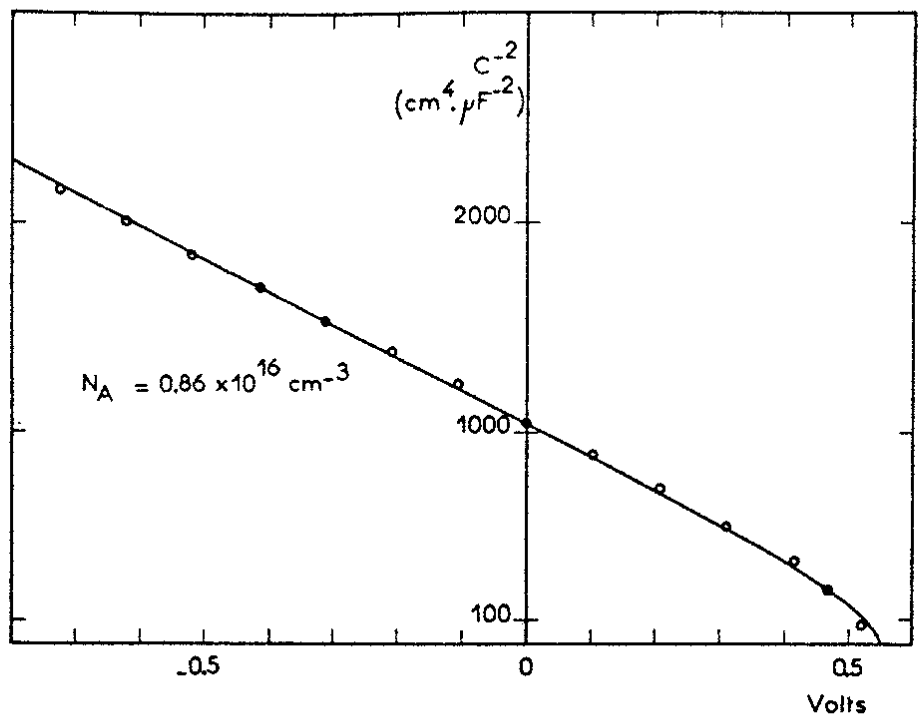
Capacitance dominated by lowly-doped side

Technique to extract ϕ_{bi} and N_{low}:

$$\frac{1}{C^2} = \frac{2(\phi_{bi} - V)}{\epsilon q N_D}$$



Experimental verification:



Fortini, A., A. Hairie, and M. Gomina. "Analysis and Capacitive Measurement of the Built-in-field Parameter in Highly Doped Emitters." *IEEE Transactions on Electron Devices* 29, no. 10 (1982): 1604-1610. Copyright 1982 IEEE. Used with permission.

Key conclusions

- Built-in potential of p-n junction:

$$\phi_{bi} = \frac{kT}{q} \ln \frac{N_D N_A}{n_i^2}$$

- *Depletion approximation*: two quasi-neutral regions separated by a space-charge region.
- In strongly asymmetric junction electrostatics dominated by region with lowest doping level; *i.e.* for p^+-n junction:

$$x_{SCR} \simeq \sqrt{\frac{2\epsilon\phi_{bi}}{qN_D}} \qquad |\mathcal{E}_{max}| \simeq \sqrt{\frac{2qN_D\phi_{bi}}{\epsilon}}$$

- Electrostatics out of equilibrium same as in TE if $\phi_{bi} \Rightarrow \phi_{bi} - V$.
- Depletion capacitance due to SCR width modulation:

$$C(V) = \frac{\epsilon}{x_{SCR}(V)}$$