Lecture 5

PN Junction and MOS Electrostatics(II)

PN JUNCTION IN THERMAL EQUILIBRIUM

Outline

1. Introduction
2. Electrostatics of pn junction in thermal equilibrium
3. The depletion approximation
4. Contact potentials

Reading Assignment:
Howe and Sodini, Chapter 3, Sections 3.3-3.6

1. Introduction

- pn junction
  - p-region and n-region in intimate contact

Why is the p-n junction worth studying?

It is present in virtually every semiconductor device!

Example: CMOS cross-section

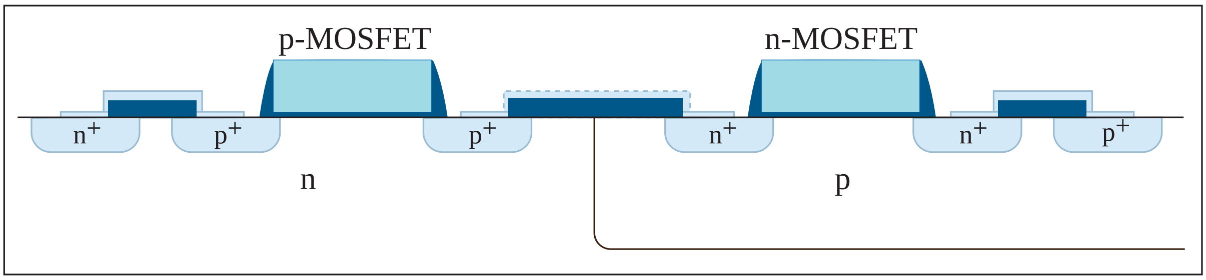
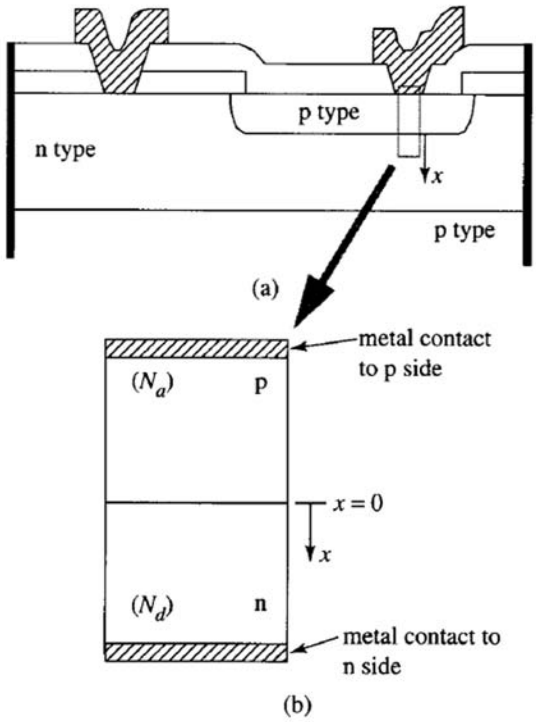


Figure by MIT OpenCourseWare.

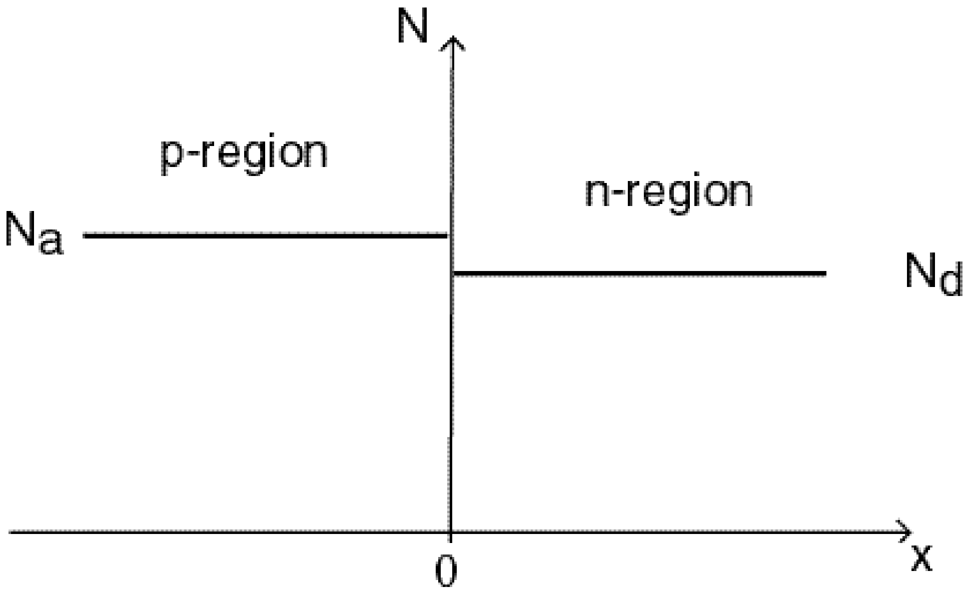
Understanding the pn junction is essential to understanding transistor operation

2. Electrostatics of p-n junction in equilibrium

Focus on intrinsic region:

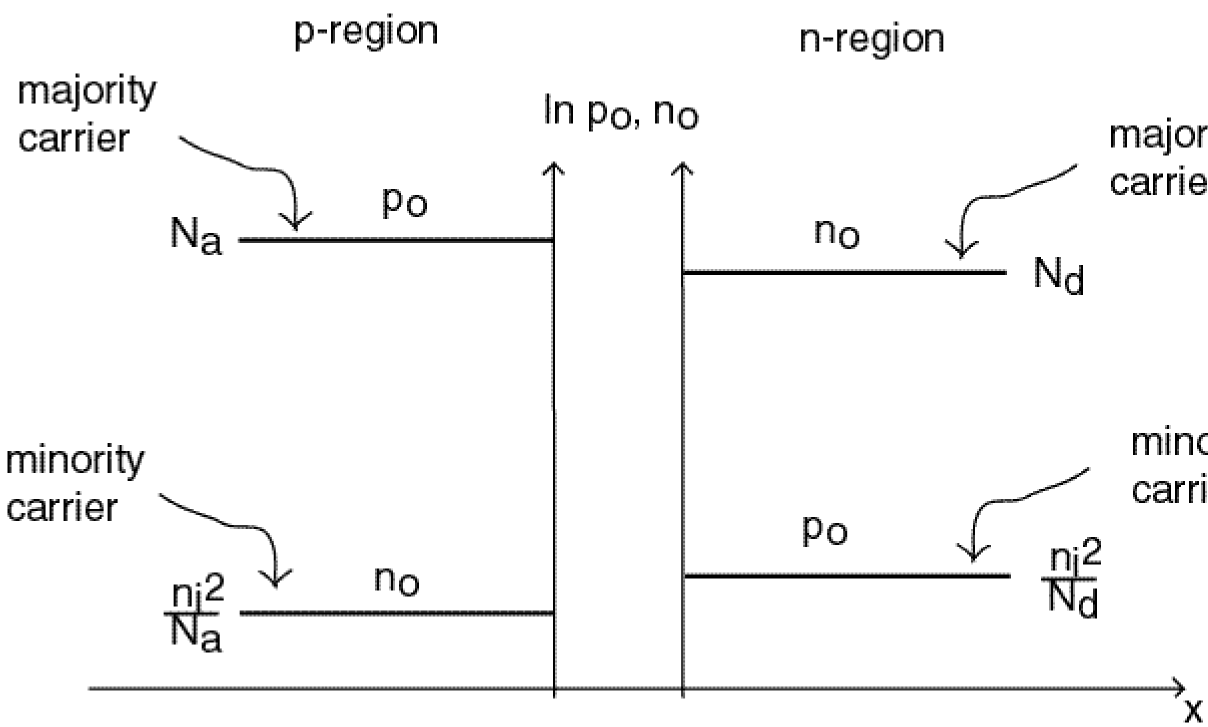


Doping distribution of an **abrupt** p-n junction



What is the carrier concentration distribution in thermal equilibrium?

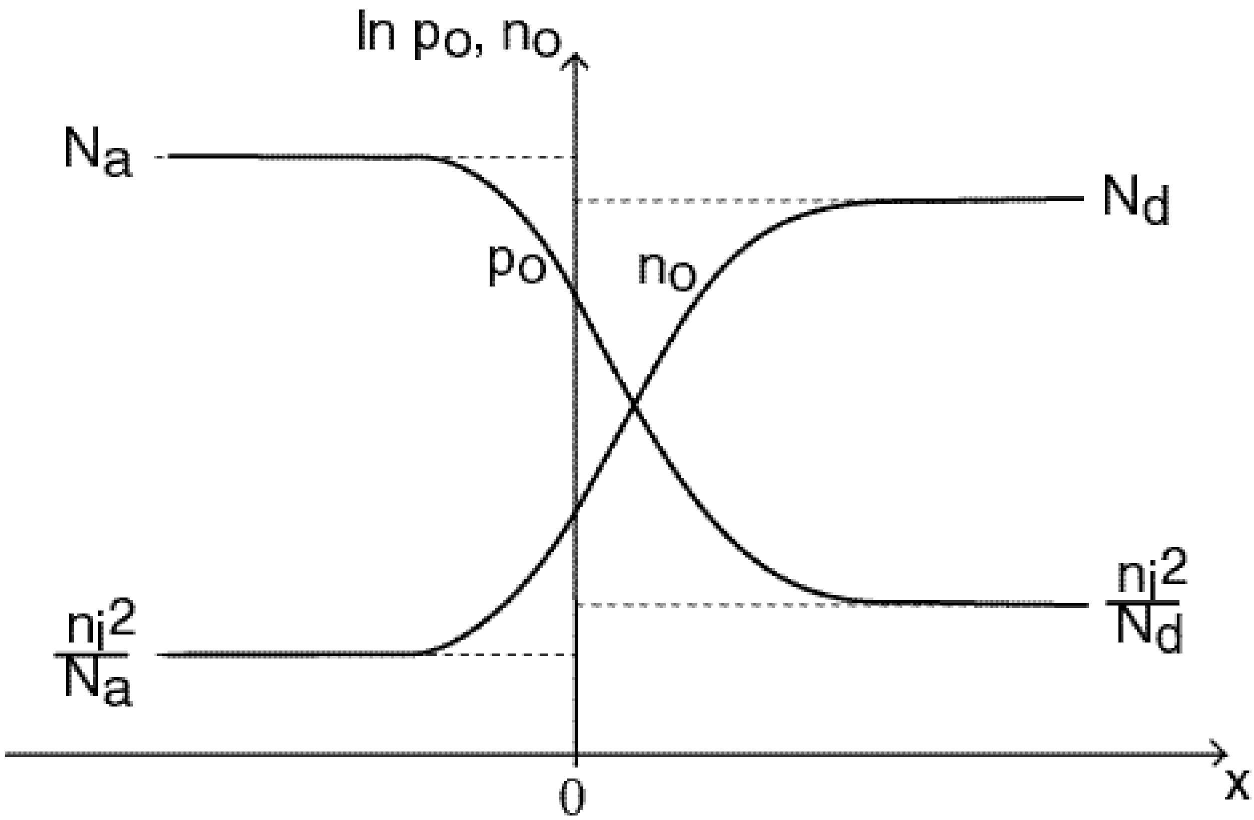
First think of the two sides separately:



Now bring the two sides together.

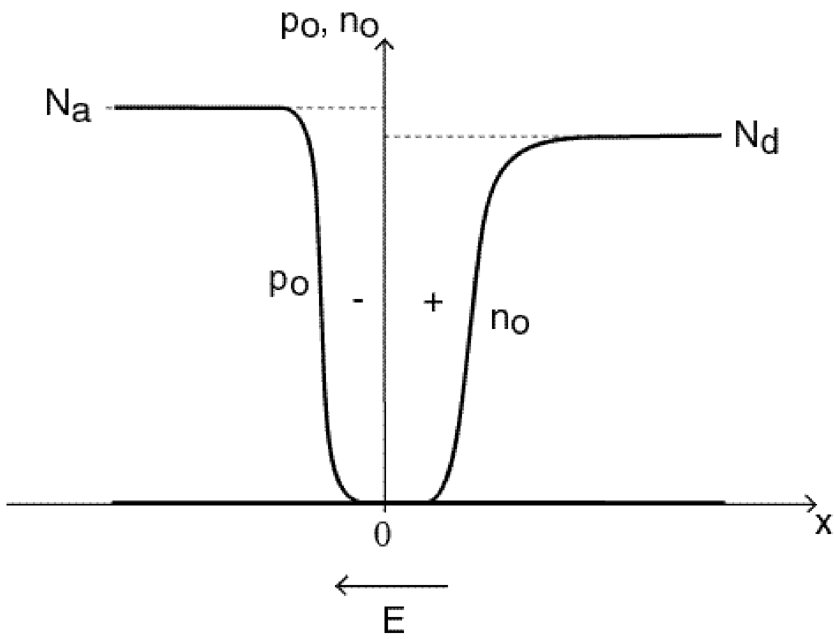
What happens?

Resulting carrier concentration profile in thermal equilibrium:



- Far away from the metallurgical junction: nothing happens
  - Two ***quasi-neutral regions***
- Around the metallurgical junction: diffusion of carriers must counter-balance drift
  - ***Space-charge region***

On a linear scale:



Thermal equilibrium: balance between drift and diffusion

$$J_n(x) = J_n^{drift}(x) + J_n^{diff}(x) = 0$$

$$J_p(x) = J_p^{drift}(x) + J_p^{diff}(x) = 0$$

We can divide semiconductor into three regions

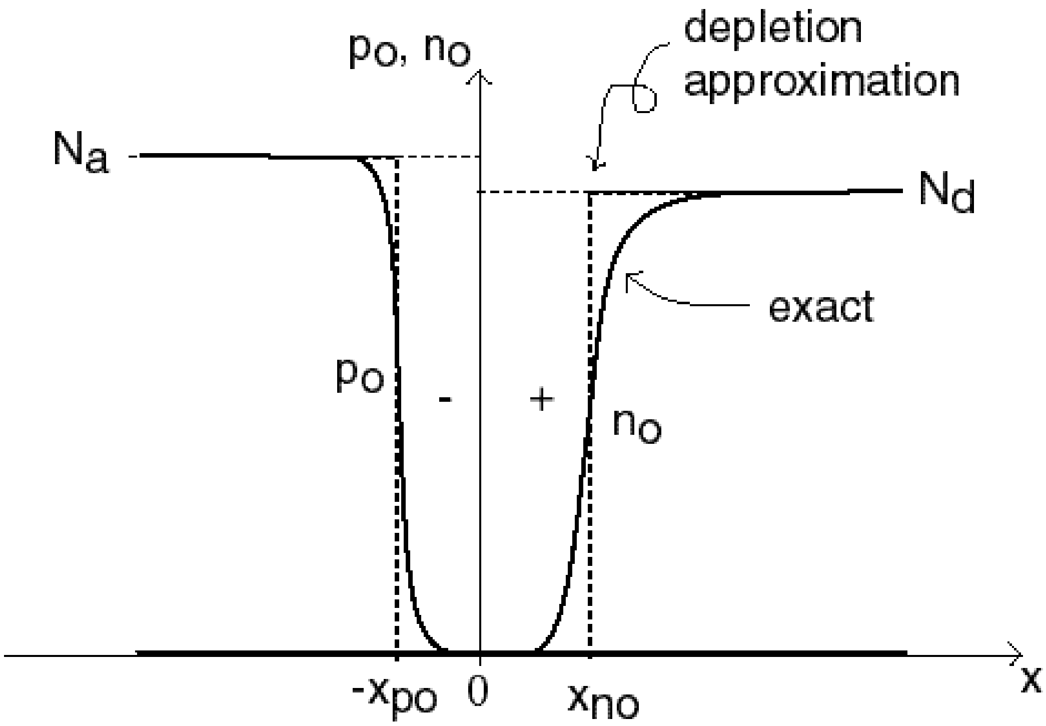
- Two quasi-neutral n- and p-regions (QNR's)
- One space-charge region (SCR)

Now, we want to know $n_o(x)$, $p_o(x)$, $\rho(x)$, $E(x)$ and $\phi(x)$.

We need to solve Poisson's equation using a simple but powerful approximation

3. The Depletion Approximation

- Assume the QNR's are perfectly **charge neutral**
- Assume the SCR is **depleted** of carriers
  - *depletion region*
- Transition between SCR and QNR's sharp at
  - $-x_{po}$ and x_{no} (**must calculate where to place these**)



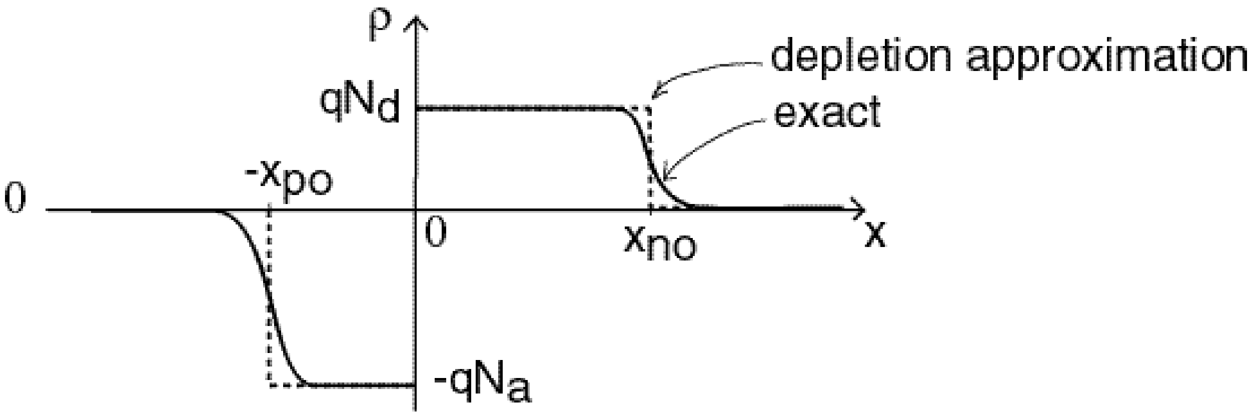
$$x < -x_{po}; \qquad p_o(x) = N_a, \quad n_o(x) = \frac{n_i^2}{N_a}$$

$$-x_{po} < x < 0; \qquad p_o(x), \quad n_o(x) << N_a$$

$$0 < x < x_{no}; \qquad n_o(x), \quad p_o(x) << N_d$$

$$x > x_{no}; \qquad n_o(x) = N_d, \quad p_o(x) = \frac{n_i^2}{N_d}$$

Space Charge Density



$$\rho(x) = 0; \qquad x < -x_{po}$$

$$= -qN_a; \qquad -x_{po} < x < 0$$

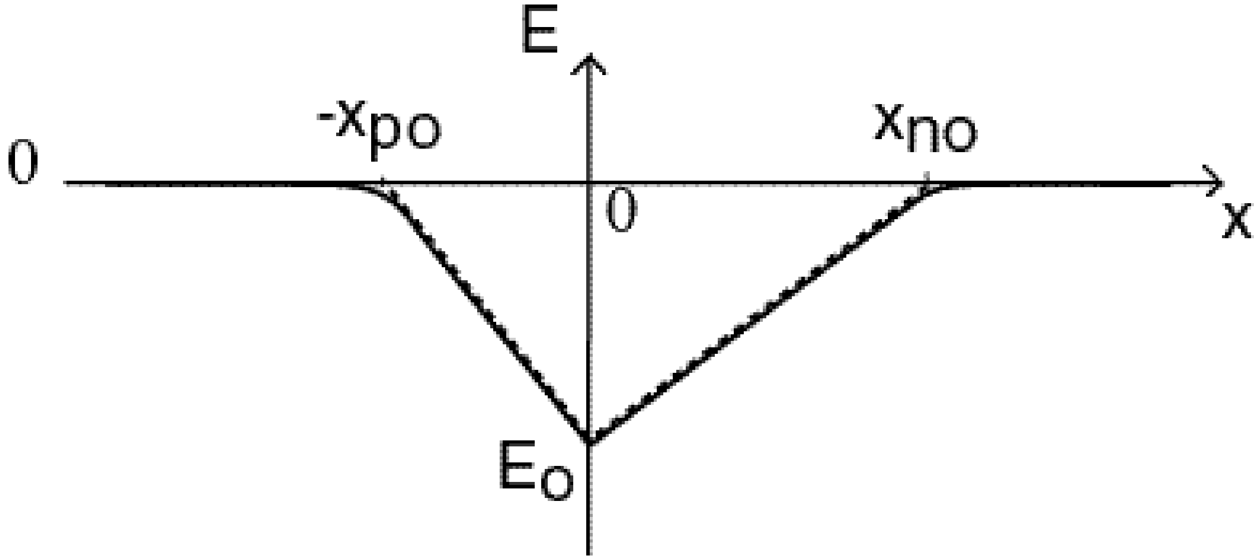
$$= \quad qN_d; \qquad 0 < x < x_{no}$$

$$= 0; \qquad x > x_{no}$$

Electric Field

Integrate Poisson's equation

$$E(x_2) - E(x_1) = \frac{1}{\varepsilon_s} \int_{x_1}^{x_2} \rho(x)\, dx$$



$x < -x_{po};$ $\qquad E(x) = 0$

$$-x_{po} < x < 0; \qquad E(x) - E(-x_{po}) = \frac{1}{\varepsilon_s} \int_{-x_{po}}^{x} -qN_a \, dx'$$

$$= \left[-\frac{qN_a}{\varepsilon_s} x \right]_{-x_{po}}^{x} = \frac{-qN_a}{\varepsilon_s} \left(x + x_{po} \right)$$

$$0 < x < x_{no}; \qquad E(x) = \frac{qN_d}{\varepsilon_s} (x - x_{no})$$

$x > x_{no};$ $\qquad E(x) = 0$

Electrostatic Potential

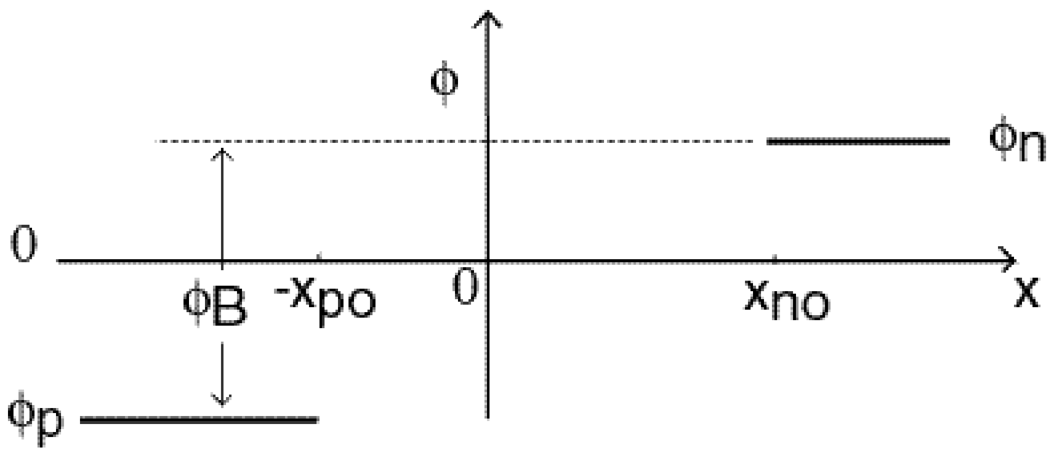
(with $\phi=0$ @ $n_o=p_o=n_i$)

$$\phi = \frac{kT}{q} \bullet \ln \frac{n_o}{n_i} \qquad \phi = -\frac{kT}{q} \bullet \ln \frac{p_o}{n_i}$$

In QNRs, n_o and p_o are known $\Rightarrow$ can determine ϕ

in p-QNR: $p_o=N_a \Rightarrow \phi_p = -\frac{kT}{q} \bullet \ln \frac{N_a}{n_i}$

in n-QNR: $n_o=N_d \Rightarrow \phi_n = \frac{kT}{q} \bullet \ln \frac{N_d}{n_i}$



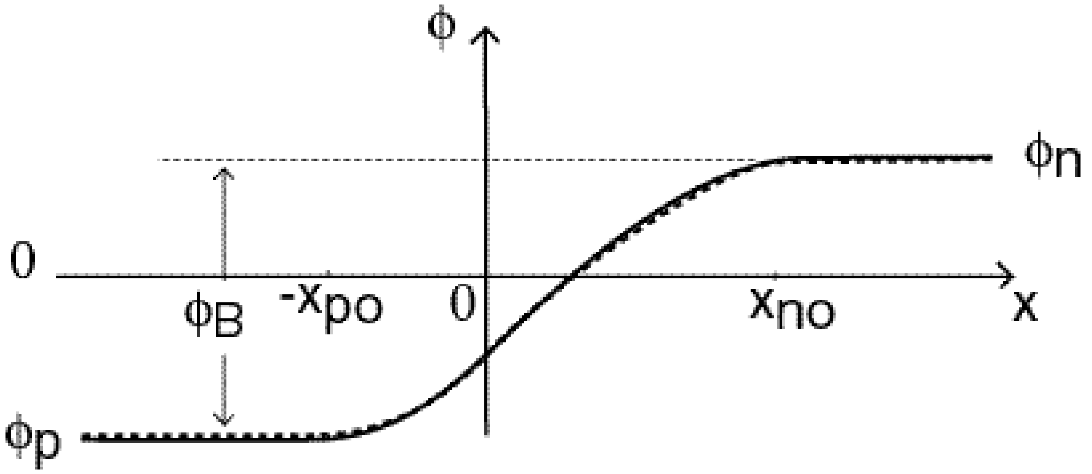
Built-in potential:

$$\phi_B = \phi_n - \phi_p = \frac{kT}{q} \bullet \ln \frac{N_d N_a}{n_i^2}$$

This expression is always correct in TE!
We did not use depletion approximation.

To obtain ϕ(x) in between, integrate E(x)

$$\phi(x_2) - \phi(x_1) = -\int_{x_1}^{x_2} E(x')\,dx'$$



$x < -x_{po};$ $\qquad \phi(x) = \phi_p$

$-x_{po} < x < 0;$ $\qquad \phi(x) - \phi(-x_{po}) = -\int_{-x_{po}}^{x} -\frac{qN_a}{\varepsilon_s}\left(x' + x_{po}\right)dx'$

$$= \frac{qN_a}{2\varepsilon_s}\left(x + x_{po}\right)^2$$

$$\phi(x) = \phi_p + \frac{qN_a}{2\varepsilon_s}\left(x + x_{po}\right)^2$$

$0 < x < x_{no};$ $\qquad \phi(x) = \phi_n - \frac{qN_d}{2\varepsilon_s}\left(x - x_{no}\right)^2$

$x > x_{no};$ $\qquad \phi(x) = \phi_n$

Almost done ….

Still do not know x_{no} and x_{po} $\Rightarrow$ need two more equations

1. Require overall charge neutrality:

$$qN_a x_{po} = qN_d x_{no}$$

2. Require $\phi(x)$ to be continuous at x=0;

$$\phi_p + \frac{qN_a}{2\varepsilon_s} x_{po}^2 = \phi_n - \frac{qN_d}{2\varepsilon_s} x_{no}^2$$

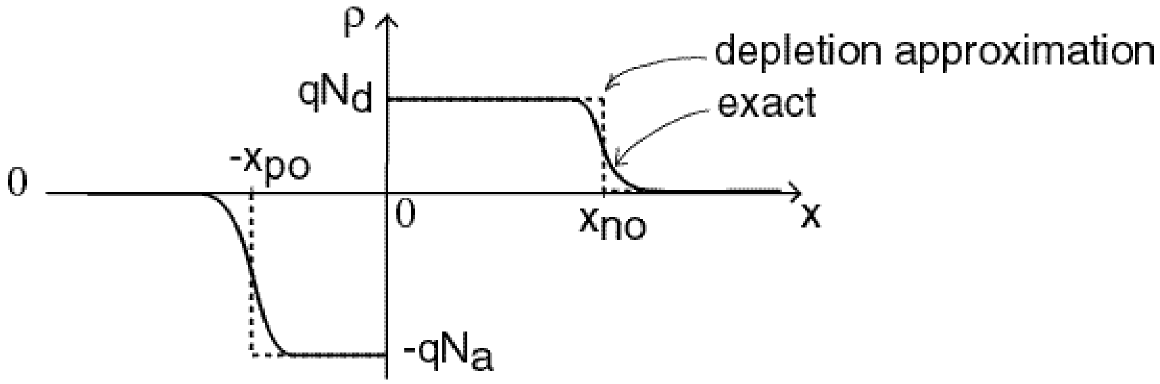
Two equations with two unknowns — obtain solution:

$$x_{no} = \sqrt{\frac{2\varepsilon_s \phi_B N_a}{q(N_a + N_d)N_d}} \qquad x_{po} = \sqrt{\frac{2\varepsilon_s \phi_B N_d}{q(N_a + N_d)N_a}}$$

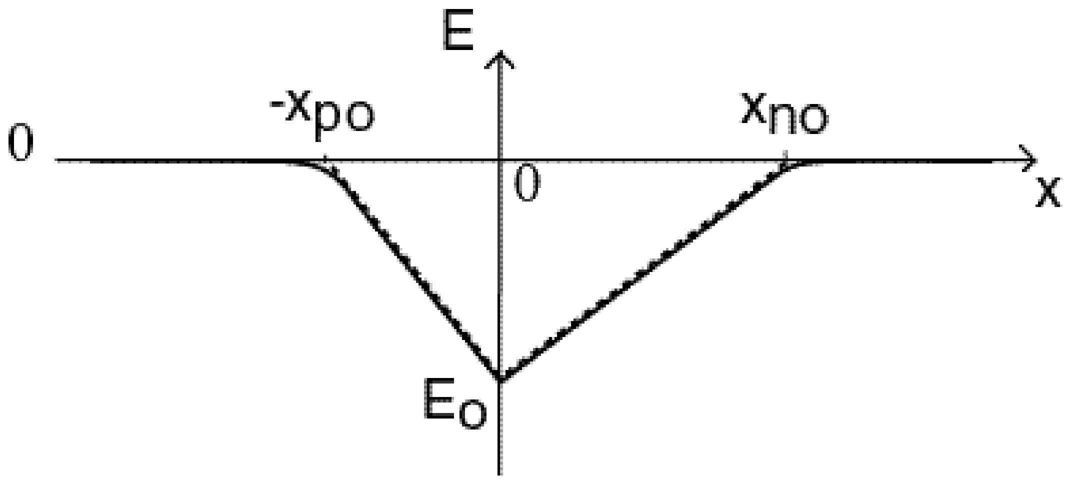
Now problem is completely solved!

Solution Summary

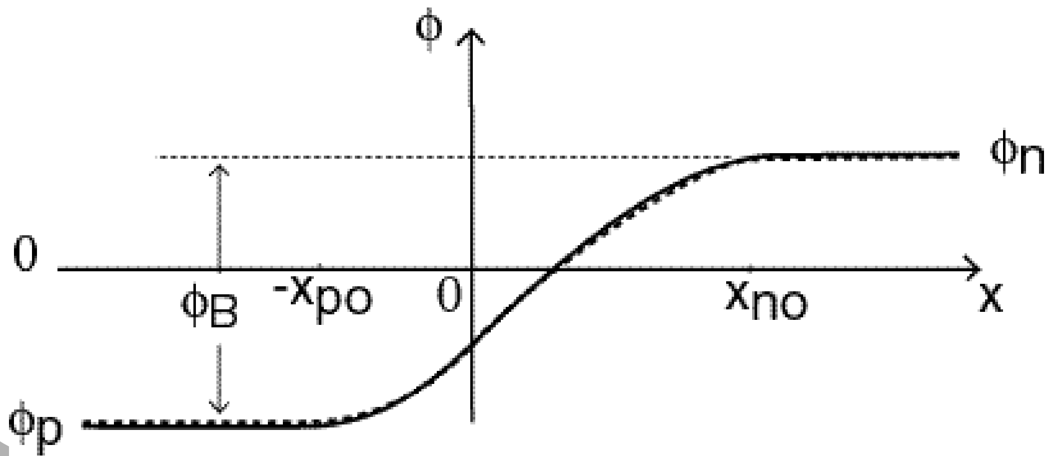
Space Charge Density



Electrostatic Field



Electrostatic Potential



Other results:

Width of the space charge region:

$$\mathbf{x_{do}} = \mathbf{x_{po}} + \mathbf{x_{no}} = \sqrt{\frac{2\varepsilon_s \phi_B (\mathbf{N_a} + \mathbf{N_d})}{\mathbf{q N_a N_d}}}$$

Field at the metallurgical junction:

$$|\mathbf{E_o}| = \sqrt{\frac{\mathbf{2q}\phi_B \mathbf{N_a N_d}}{\varepsilon_s (\mathbf{N_a} + \mathbf{N_d})}}$$

Three Special Cases

- Symmetric junction: $N_a = N_d$

$$\mathbf{x_{po} = x_{no}}$$

- Asymmetric junction: $N_a > N_d$

$$\mathbf{x_{po} < x_{no}}$$

- Strongly asymmetric junction
  - p^+n junction: $N_a >> N_d$

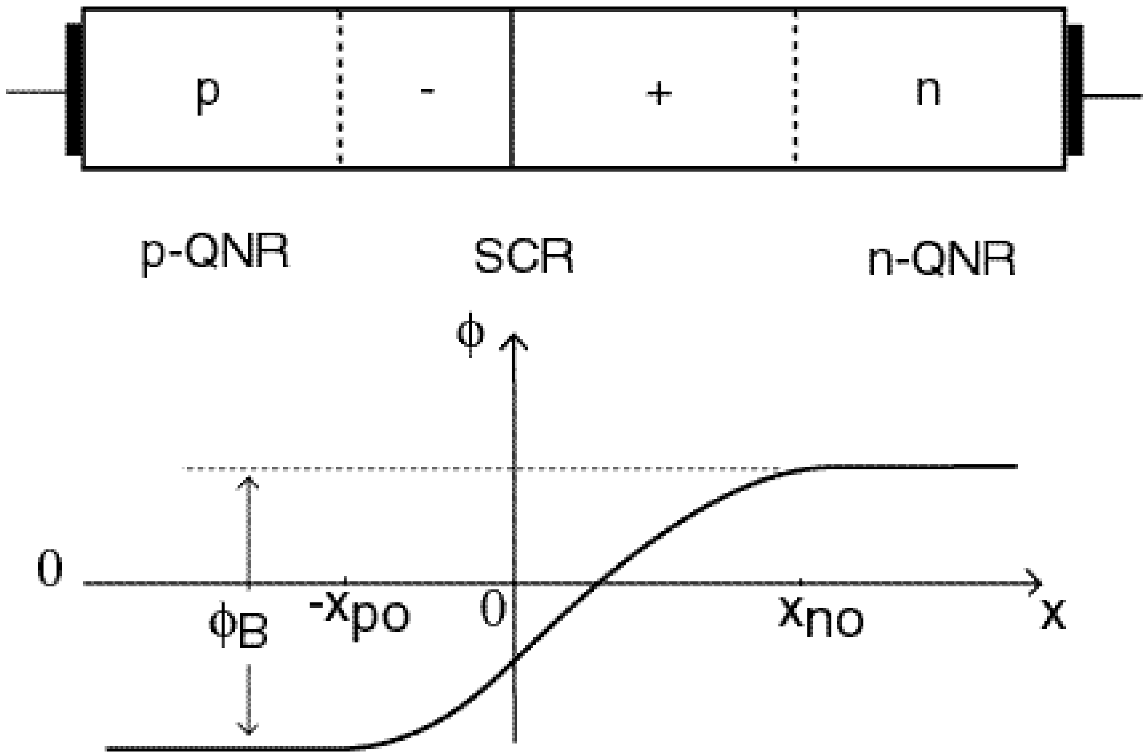
$$x_{po} << x_{no} \approx x_{do} \approx \sqrt{\frac{2\varepsilon_s \phi_B}{qN_d}}$$

$$|E_o| \approx \sqrt{\frac{2q\phi_B N_d}{\varepsilon_s}}$$

The lightly-doped side controls the electrostatics of the pn junction

4. Contact Potential

Potential distribution in thermal equilibrium so far:



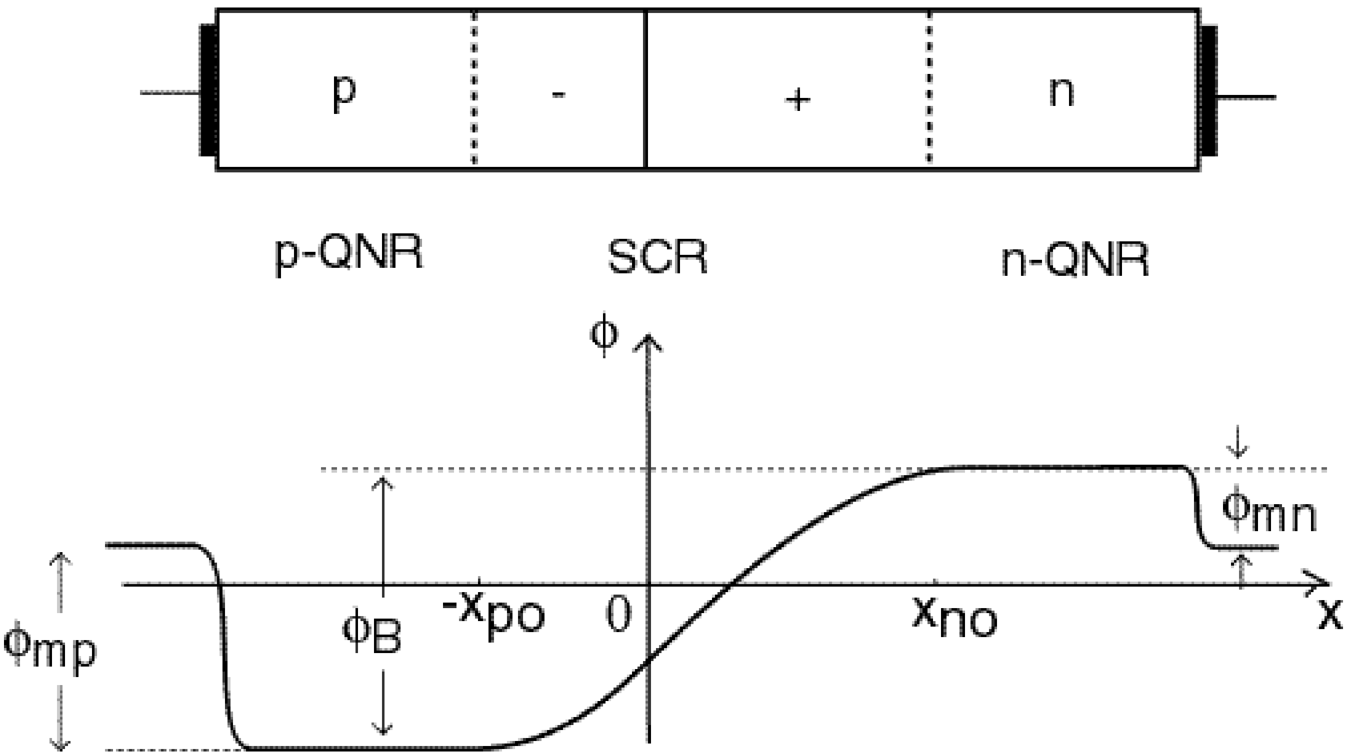
Question 1: *If I apply a voltmeter across the pn junction diode, do I measure ϕ_B?*

☐ yes ☐ no ☐ it depends

Question 2: *If I short terminals of pn junction diode, does current flow on the outside circuit?*

☐ yes ☐ no ☐ sometimes

We are missing *contact potential* at the metal-semiconductor contacts:



Metal-semiconductor contacts: junction of dissimilar materials

$\Rightarrow$ built-in potentials at contacts ϕ_{mn} and ϕ_{mp}.

Potential difference across structure must be zero

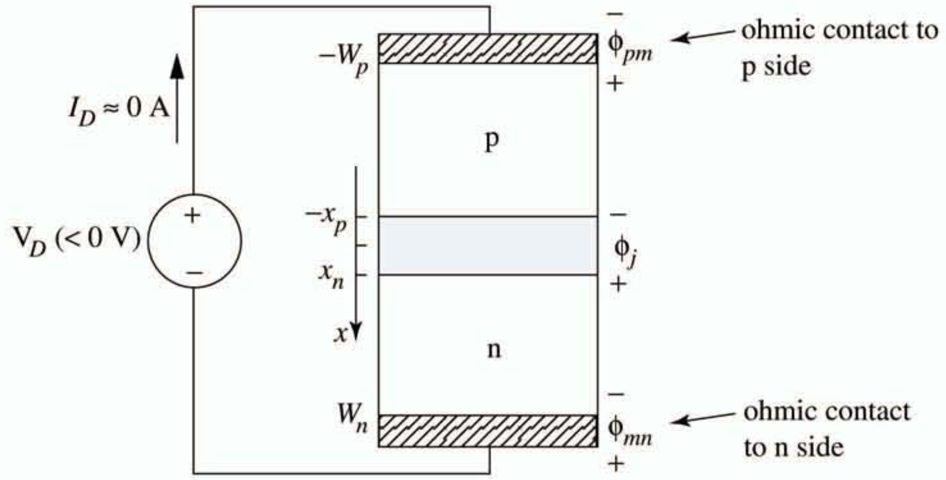
$\Rightarrow$ Cannot measure ϕ_B.

$$\phi_B = |\phi_{mn}| + |\phi_{mp}|$$

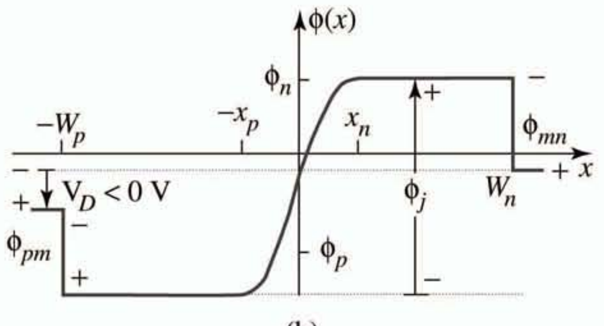
5. PN Junction-Reverse Bias

Assume: No Current Flows

$$\phi_j = \phi_B - V_D$$



(a)



(b)

Same Analysis applies:

Substitute

$$x_{do} = x_{po} + x_{no} = \sqrt{\frac{2\varepsilon_s(\phi_B - V_D)(N_a + N_d)}{qN_aN_d}}$$

What did we learn today?

Summary of Key Concepts

- Electrostatics of pn junction in equilibrium
  - A ***space-charge region*** surrounded by two ***quasi-neutral regions*** formed.
- To first order, carrier concentrations in space-charge region are much smaller than the doping level
  - $\Rightarrow$ can use ***Depletion Approximation***
- From contact to contact, there is no potential build-up across the pn junction diode
  - Contact potential(s).