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

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).

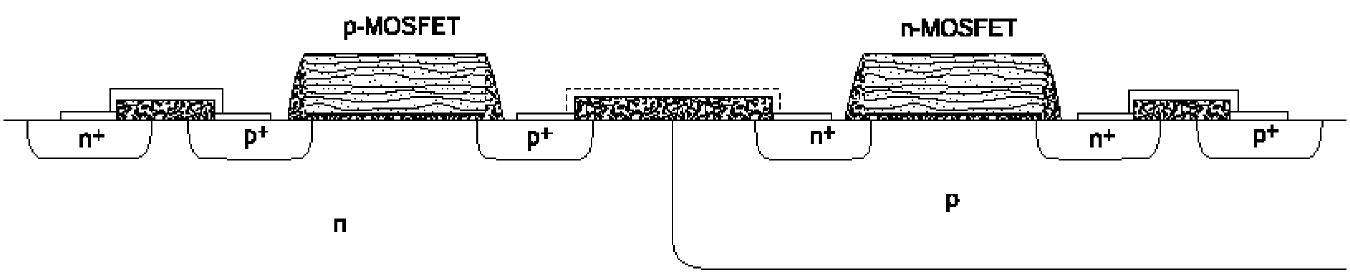
1. Introduction

- 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!

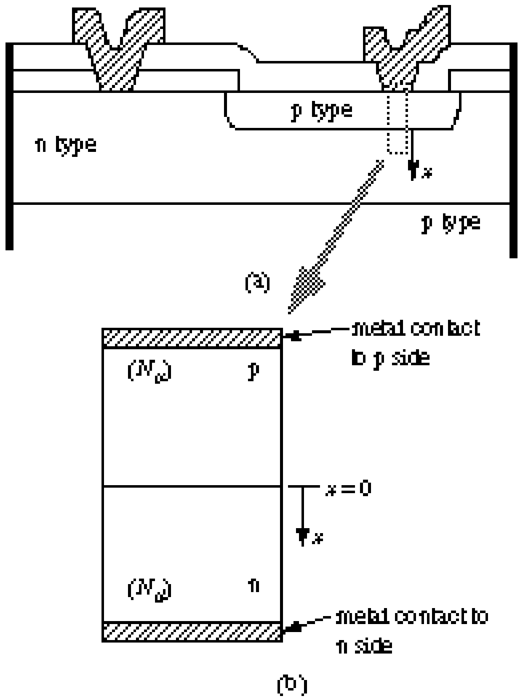
Example: CMOS cross-section



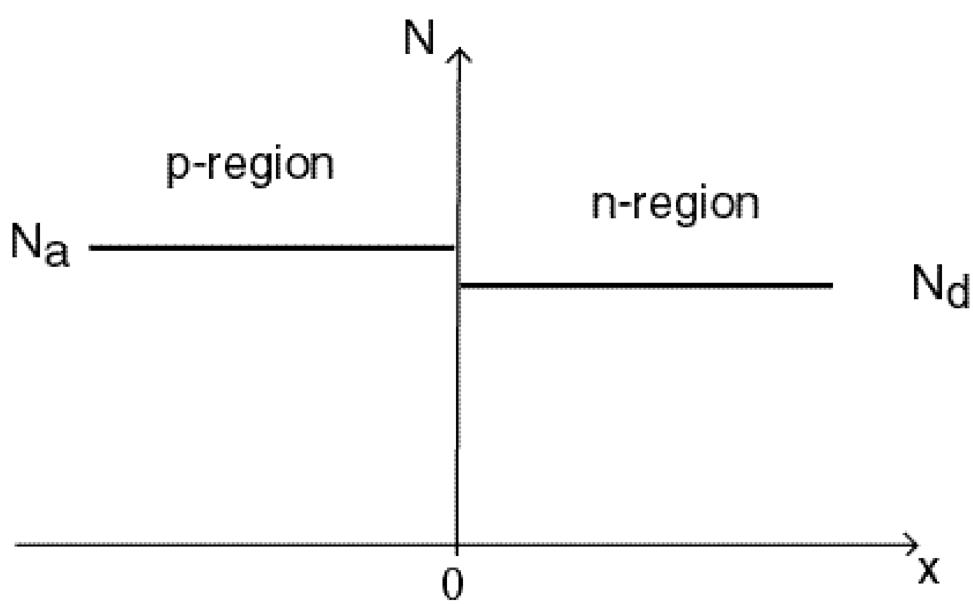
Understanding the pn junction is essential to understanding transistor operation

2. Electrostatics of p-n junction in equilibrium

Focus on intrinsic region:

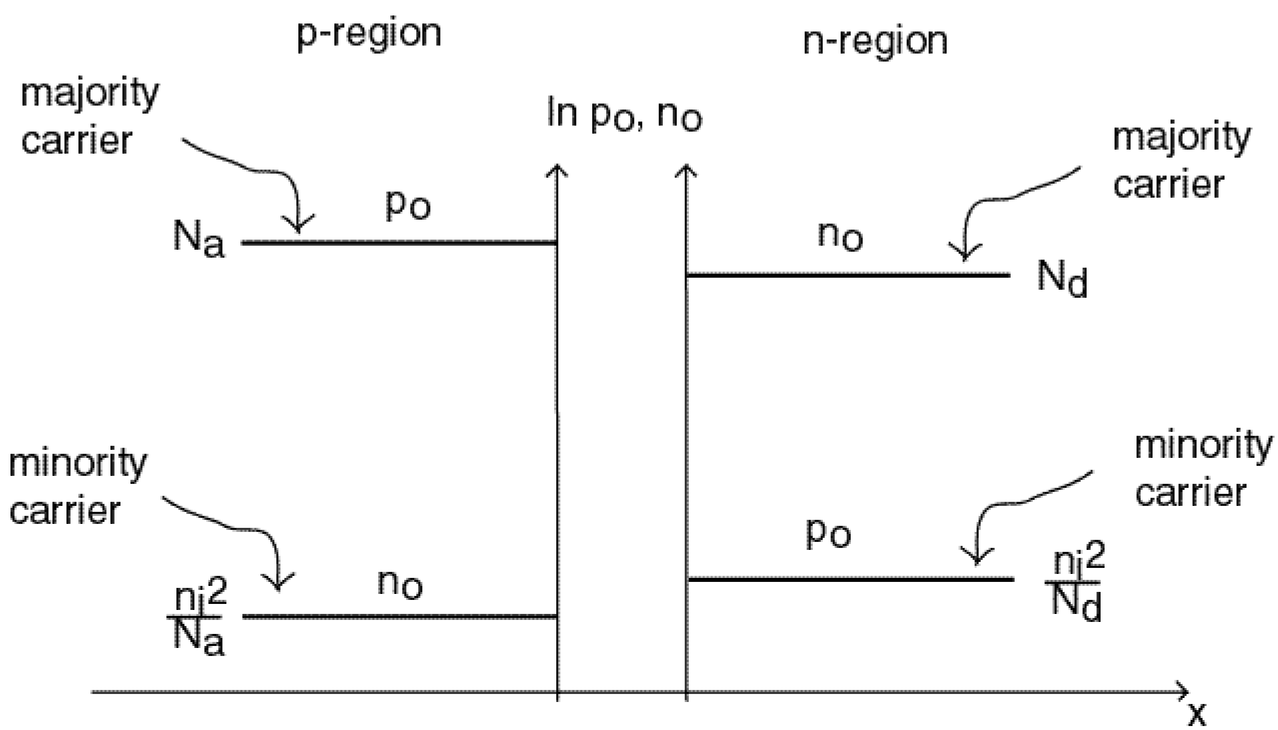


Doping distribution of an **abrupt** p-n junction



What is the carrier concentration distribution in thermal equilibrium?

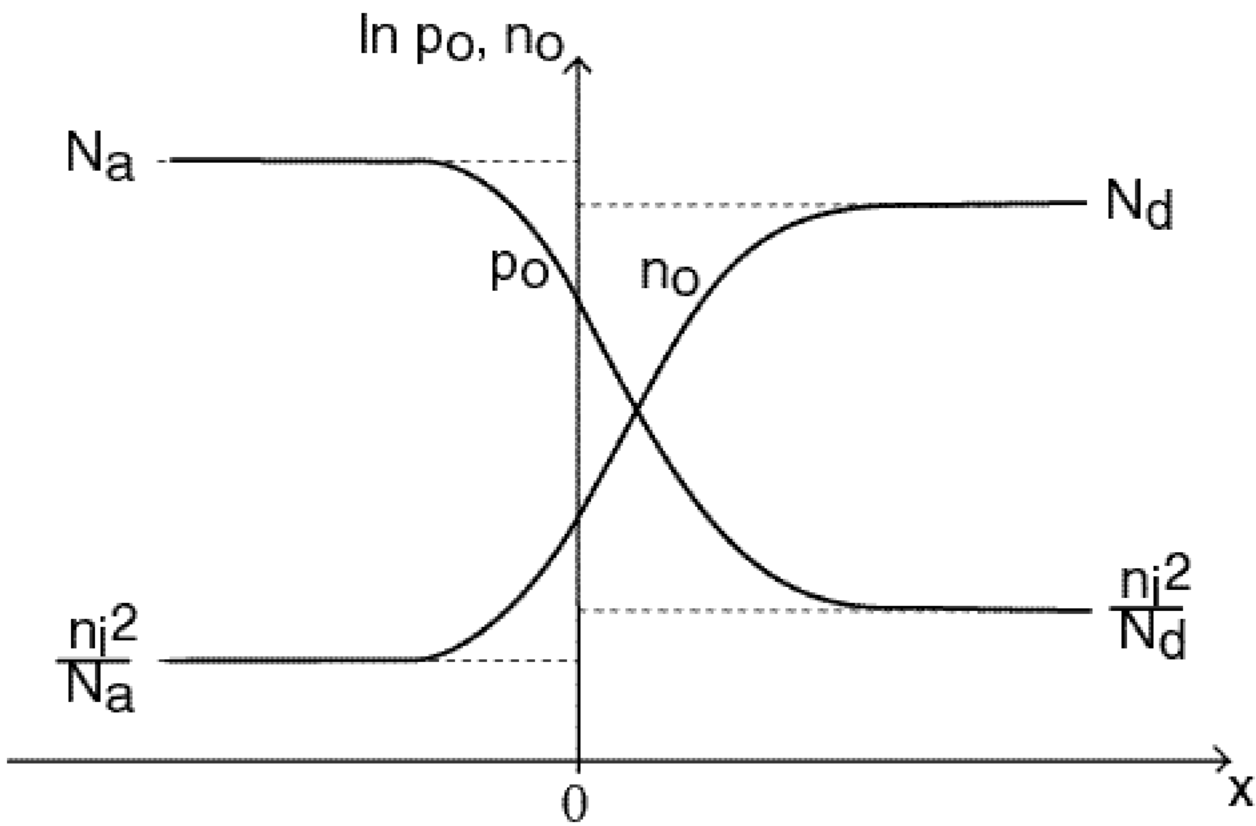
First think of the two sides separately:



Now bring the two sides together. What happens?

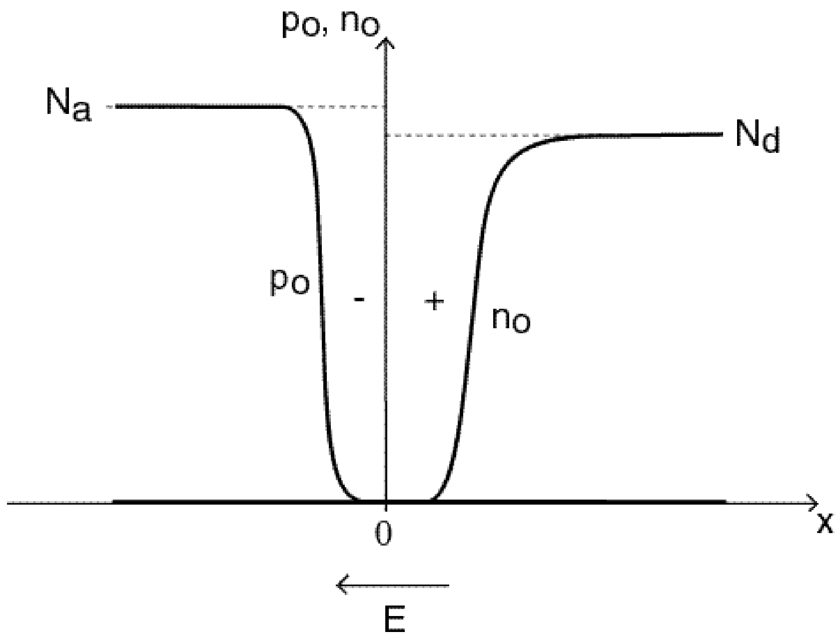
Diffusion of electrons and holes from the majority carrier side to the minority carrier side until drift balances diffusion.

Resulting carrier concentration profile in thermal equilibrium:

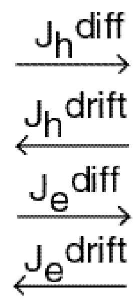


- Far away from the metallurgical junction: nothing happens
  - Two ***quasi-neutral regions***
- Around the metallurgical junction: diffusion of carriers must counter-balance drift
  - ***Space-charge region***

On a linear scale:



Thermal equilibrium: balance between drift and diffusion



We can divide semiconductor into three regions

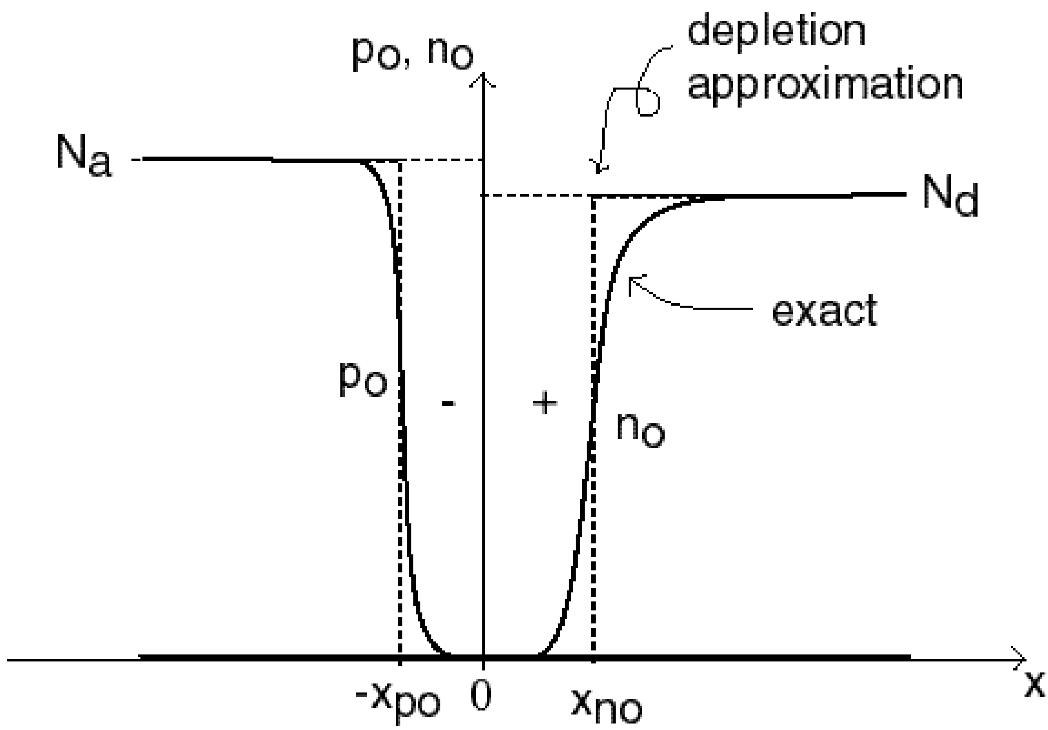
- Two quasi-neutral n- and p-regions (QNR's)
- One space-charge region (SCR)

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**)



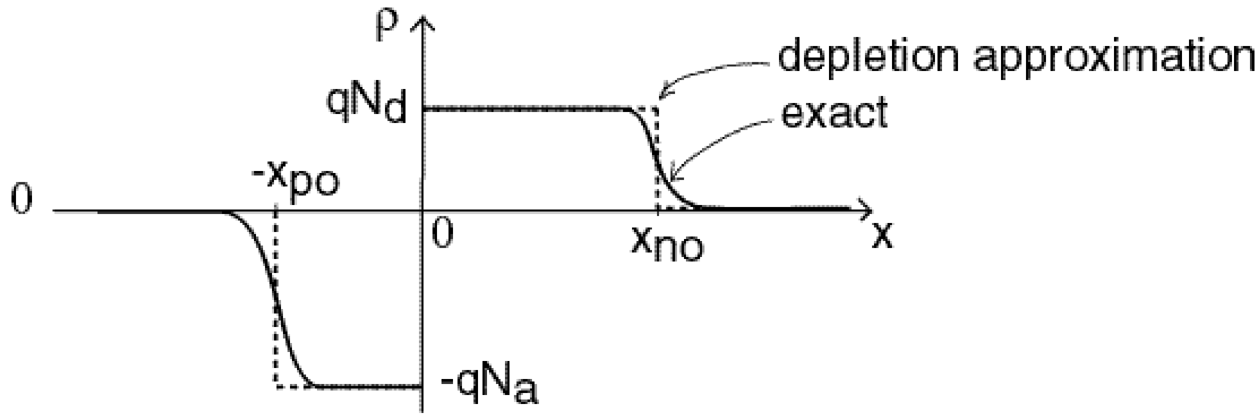
$$x < -x_{po}; \qquad p_o(x) = N_a, \quad n_o(x) = \frac{n_i^2}{N_a}$$

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

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

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

Space Charge Density

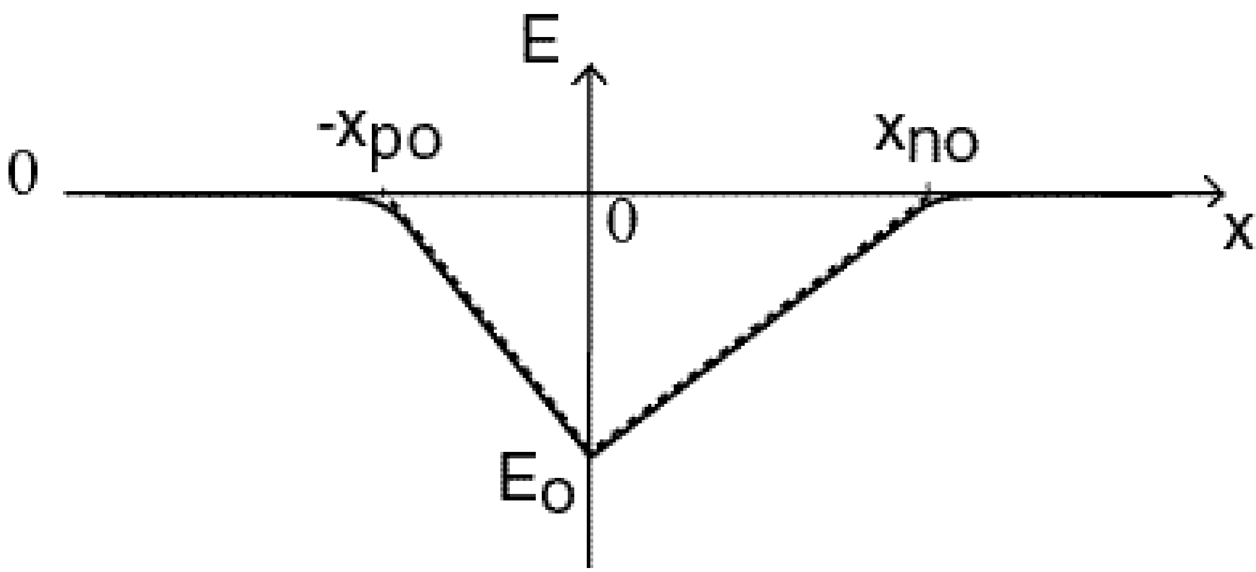


$$\rho(\mathbf{x}) = 0; \qquad \mathbf{x} < -\mathbf{x}_{\mathbf{po}}$$
$$= -\mathbf{qN}_{\mathbf{a}}; \qquad -\mathbf{x}_{\mathbf{po}} < \mathbf{x} < 0$$
$$= \mathbf{qN}_{\mathbf{d}}; \qquad 0 < \mathbf{x} < \mathbf{x}_{\mathbf{no}}$$
$$= 0; \qquad \mathbf{x}_{\mathbf{no}} < \mathbf{x}$$

Electric Field

Integrate Gauss's equation

$$\mathbf{E}(\mathbf{x}_2) - \mathbf{E}(\mathbf{x}_1) = \frac{1}{\varepsilon_s} \int_{x_1}^{x_2} \rho(\mathbf{x})\, \mathbf{dx}$$



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

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

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

$$0 < \mathbf{x} < \mathbf{x}_{no}; \qquad \mathbf{E}(\mathbf{x}) = \frac{\mathbf{qN_d}}{\varepsilon_s} \left(\mathbf{x} - \mathbf{x}_{no} \right)$$

$$\mathbf{x}_{no} < \mathbf{x}; \qquad \mathbf{E}(\mathbf{x}) = 0$$

Electrostatic Potential

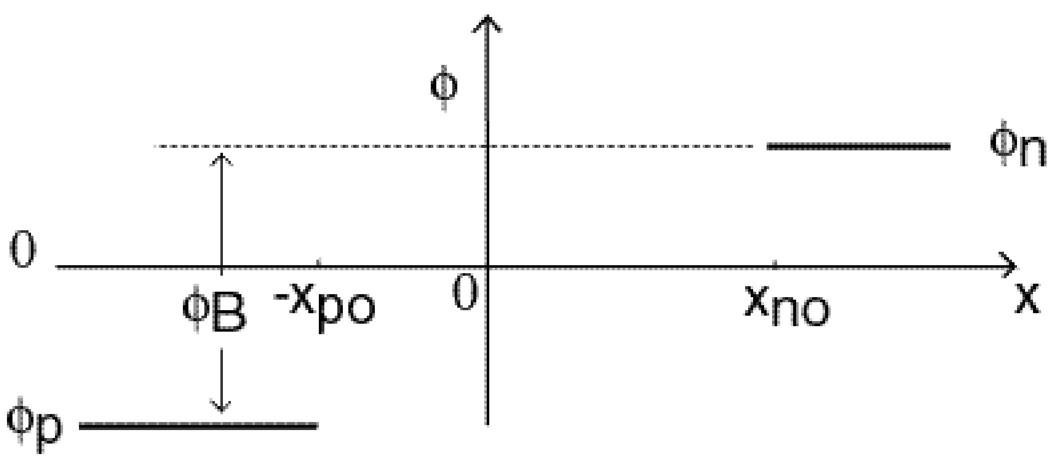
(with $\phi=0$ @ $n_o=p_o=n_i$)

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

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



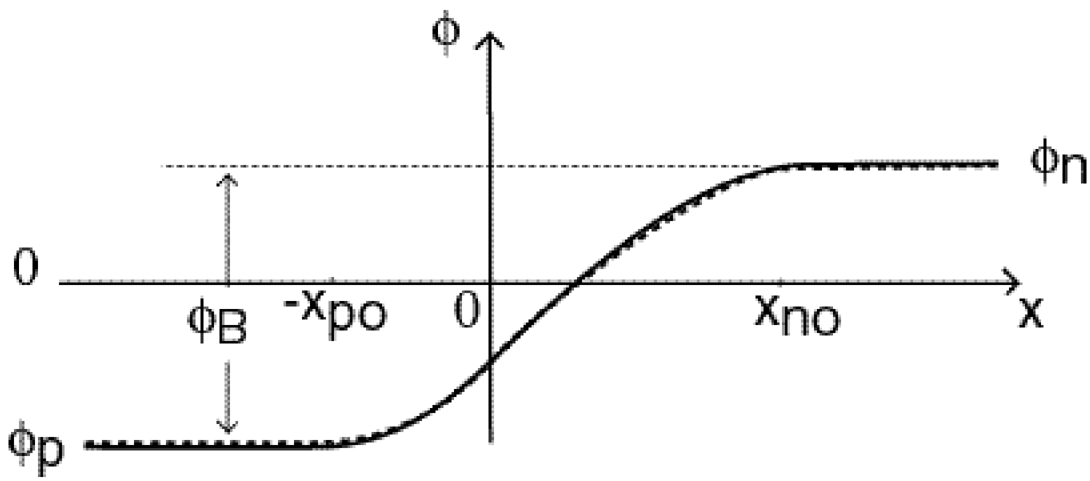
Built-in potential:

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

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

To obtain $\phi(x)$ in between, integrate E(x)

$$\phi(\mathbf{x}_2) - \phi(\mathbf{x}_1) = -\int_{\mathbf{x}_1}^{\mathbf{x}_2} \mathbf{E}(\mathbf{x}')\,\mathbf{dx}'$$



$$\mathbf{x} < -\mathbf{x}_{\mathbf{po}}; \qquad \phi(\mathbf{x}) = \phi_{\mathbf{p}}$$

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

$$= \frac{\mathbf{qN_a}}{2\varepsilon_{\mathbf{s}}}\left(\mathbf{x} + \mathbf{x}_{\mathbf{po}}\right)^2$$

$$\phi(\mathbf{x}) = \phi_{\mathbf{p}} + \frac{\mathbf{qN_a}}{2\varepsilon_{\mathbf{s}}}\left(\mathbf{x} + \mathbf{x}_{\mathbf{po}}\right)^2$$

$$0 < \mathbf{x} < \mathbf{x}_{\mathbf{no}}; \qquad \phi(\mathbf{x}) = \phi_{\mathbf{n}} - \frac{\mathbf{qN_d}}{2\varepsilon_{\mathbf{s}}}\left(\mathbf{x} - \mathbf{x}_{\mathbf{no}}\right)^2$$

$$\mathbf{x}_{\mathbf{no}} < \mathbf{x}; \qquad \phi(\mathbf{x}) = \phi_{\mathbf{n}}$$

Almost done ….

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

1. Require overall charge neutrality:

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

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!

Other results:

Width of the space charge region:

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

Field at the metallurgical junction:

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

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: $N_a >> N_d$

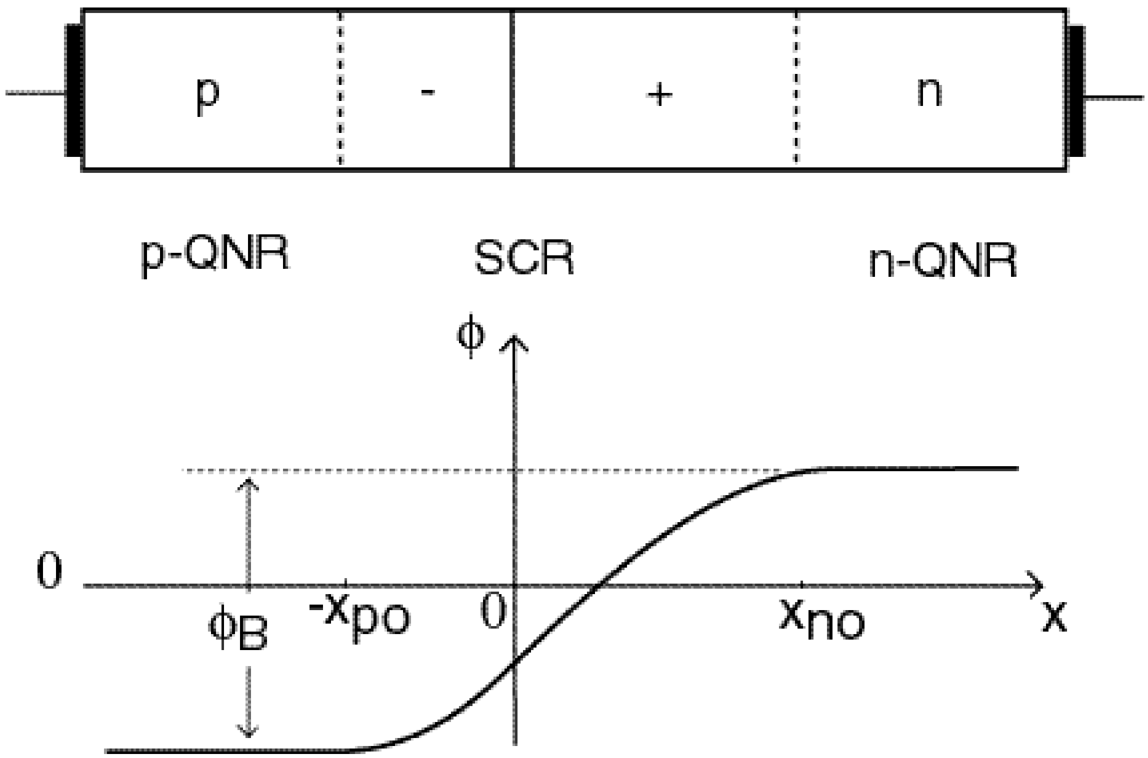
$$\mathbf{x_{po} << x_{no} \approx x_{do} \approx \sqrt{\frac{2\varepsilon_s \phi_B}{qN_d}}}$$

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

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

4. Contact Potential

Potential distribution in thermal equilibrium so far:



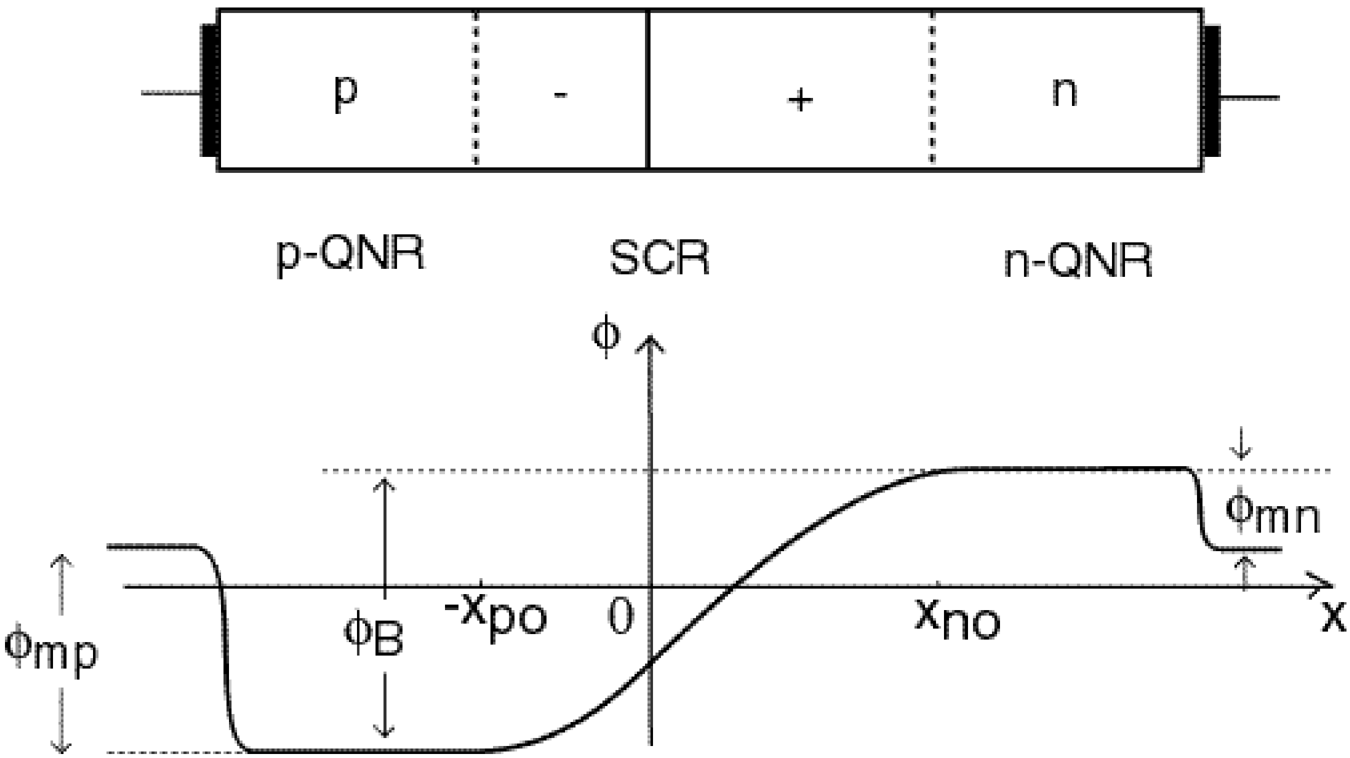
Question 1: *If I apply a voltmeter across the pn junction diode, do I measure* ϕ_B?

☐ 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

⇒ built-in potentials at contacts ϕ_{mn} and ϕ_{mp}.

Potential difference across structure must be zero

⇒ Cannot measure ϕ_B.

$$\phi_{\mathbf{B}} = \left|\phi_{\mathbf{mn}}\right| + \left|\phi_{\mathbf{mp}}\right|$$

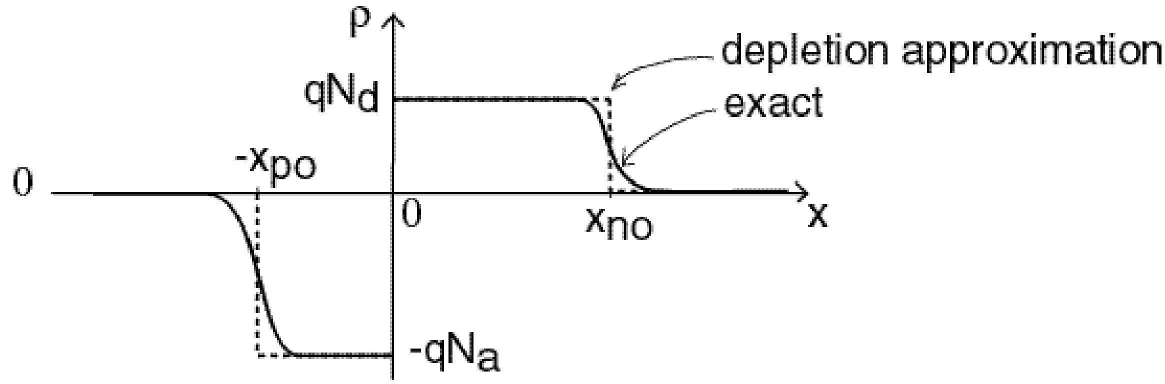
What did we learn today?

Summary of Key Concepts

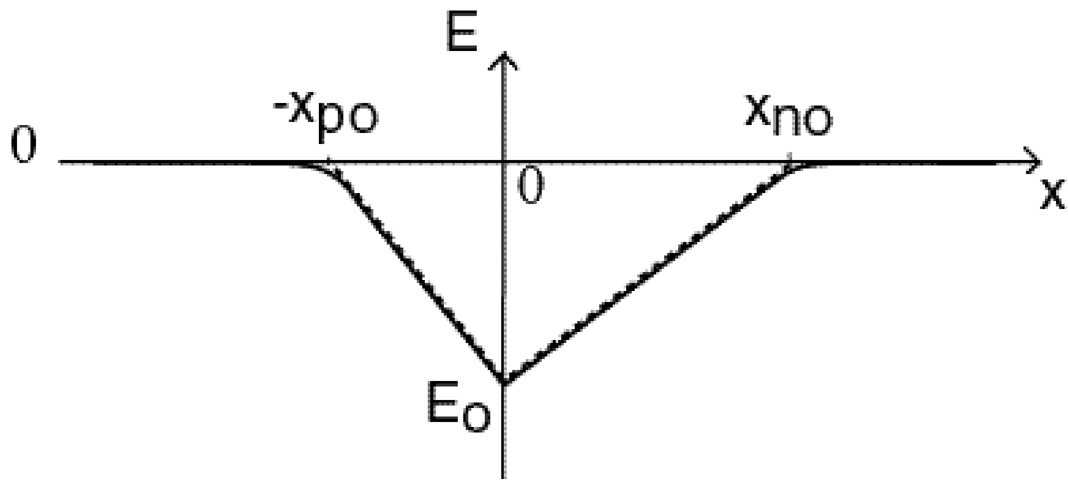
- Electrostatics of pn junction in equilibrium
  - A ***space-charge region*** surrounded by two ***quasi-neutral regions*** formed.
- To first order, carrier concentrations in space-charge region are much smaller than the doping level
  - ⇒ can use ***Depletion Approximation***
- From contact to contact,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

Solution Summary

Space Charge Density



Electrostatic Field



Electrostatic Potential