Lecture 5 - PN Junction and MOS Electrostatics (II)

pn Junction in Thermal Equilibrium

September 22, 2005

Contents:

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

Reading assignment:

Howe and Sodini, Ch. 3, §§3.3-3.4

Key questions

- What happens if the doping distribution in a semiconductor abruptly changes from n-type to p-type?
- Is there a simple description of the electrostatics of a pn junction?

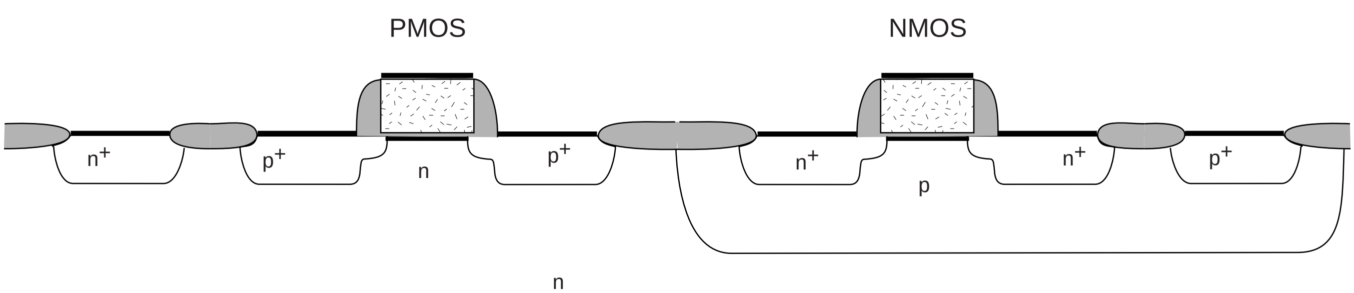
1. Introduction to pn junction

- 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!

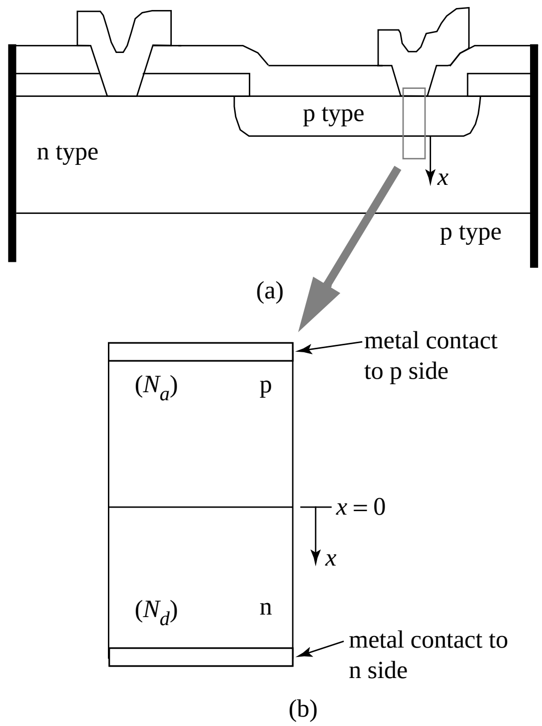
Example: CMOS cross section



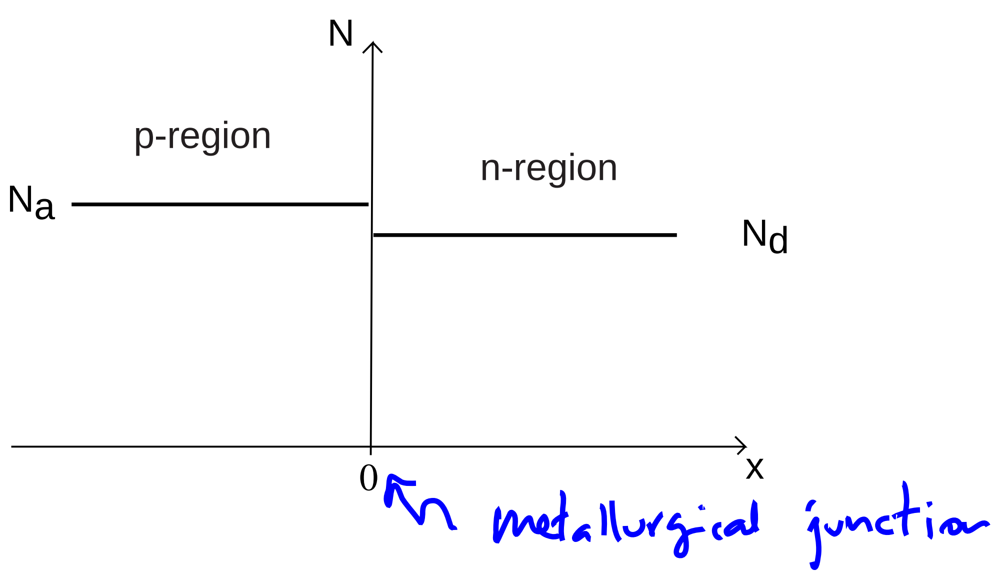
Understanding p-n junction is essential to understanding transistor operation.

2. Electrostatics of p-n junction in equilibrium

Focus on intrinsic region:

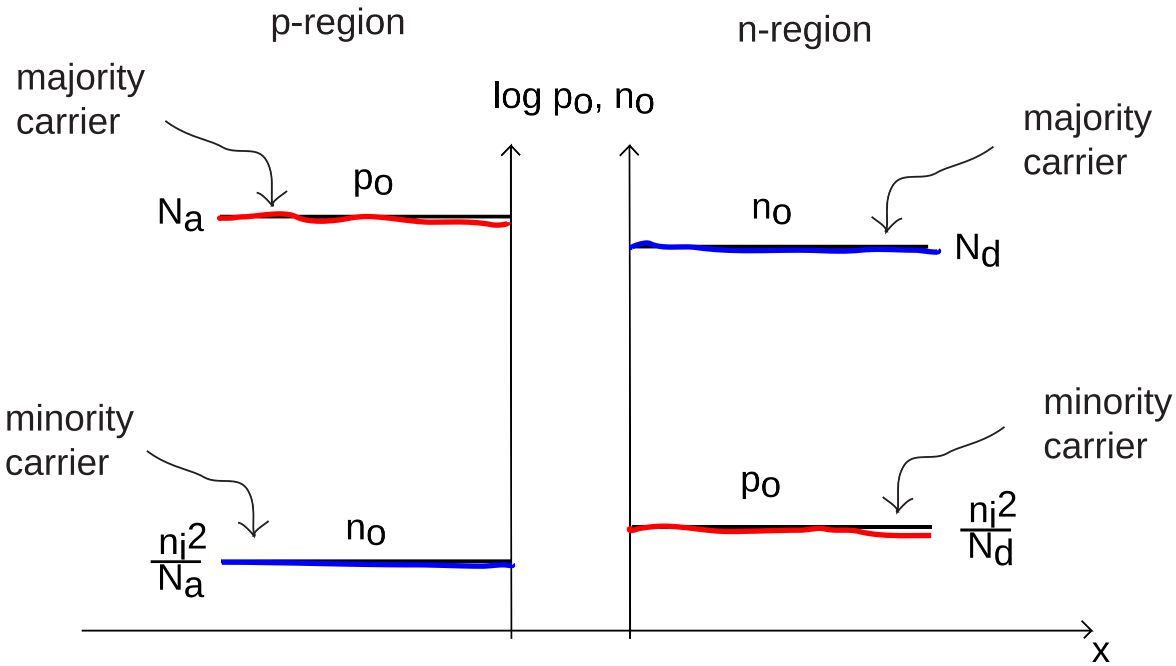


Doping distribution of abrupt p-n junction:



What is the carrier concentration distribution in thermal equilibrium?

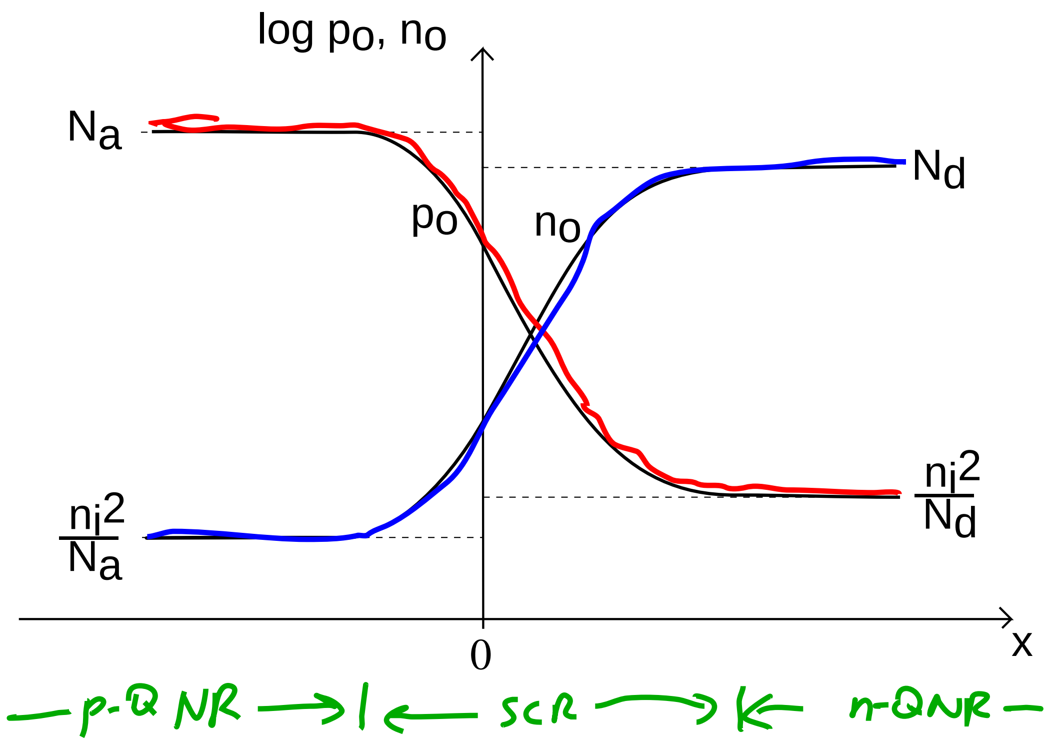
First think of two sides separately:



Now bring them together. What happens?

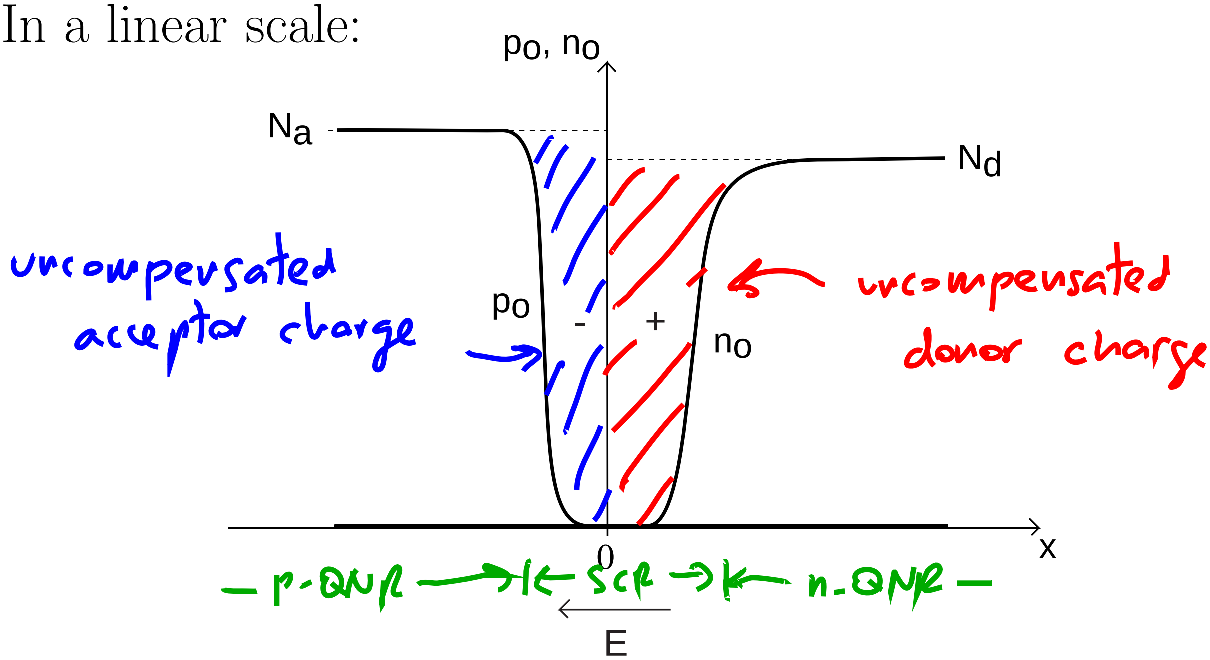
Diffusion of electrons and holes from majority carrier side to minority carrier side until drift balances diffusion.

Resulting carrier profile in thermal equilibrium:

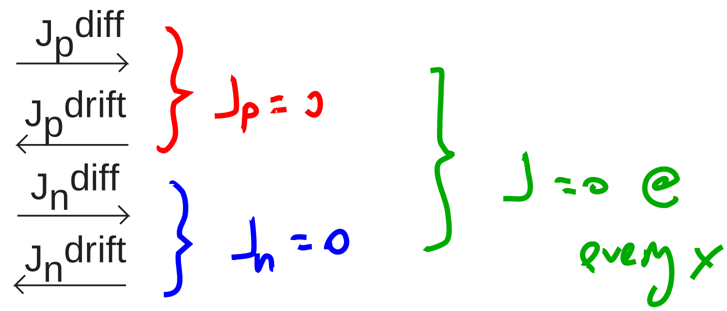


- Far away from metallurgical junction: nothing happens
  - two *quasi-neutral regions*
- Around metallurgical junction: carrier drift must cancel diffusion
  - *space-charge region*

In a linear scale:



Thermal equilibrium: balance between drift and diffusion



Can divide semiconductor in three regions:

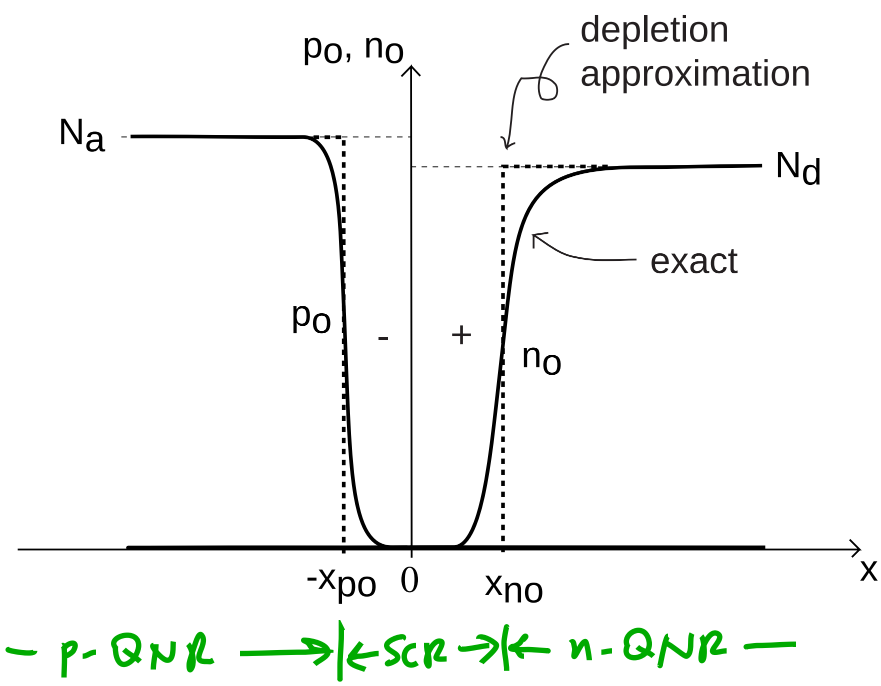
- two quasi-neutral n- and p-regions (QNR's)
- one space charge region (SCR)

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

Solve electrostatics using simple, powerful approximation.

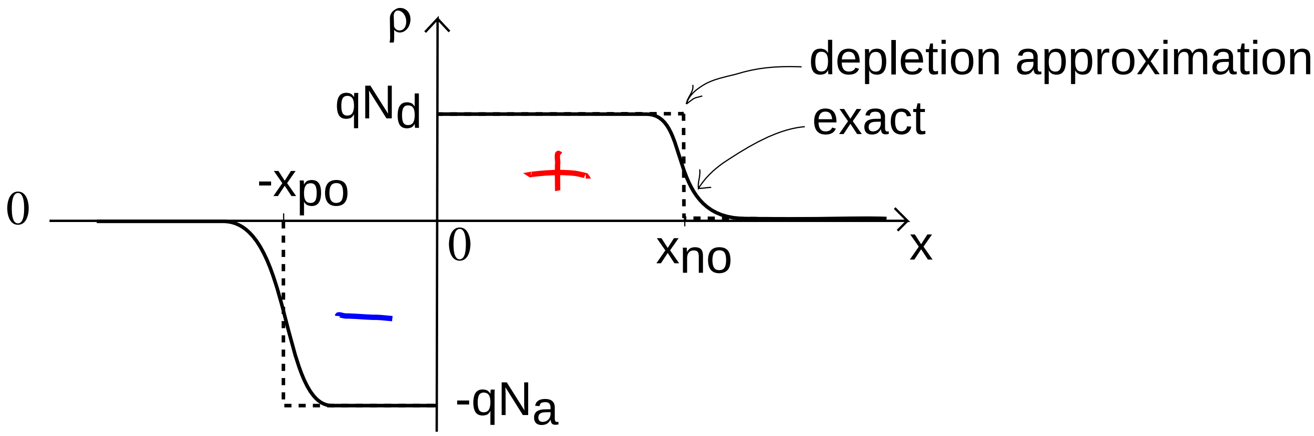
3. The depletion approximation

- Assume QNR's perfectly charge neutral
- assume SCR depleted of carriers (*depletion region*)
- transition between SCR and QNR's sharp
  (must calculate where to place $-x_{po}$ and x_{no})



- $x < -x_{po}$ $\quad p_o(x) = N_a, \; n_o(x) = \frac{n_i^2}{N_a}$
- $-x_{po} < x < 0$ $\quad p_o(x), \; n_o(x) \ll N_a$
- $0 < x < x_{no}$ $\quad n_o(x), \; p_o(x) \ll N_d$
- $x_{no} < x$ $\quad n_o(x) = N_d, \; p_o(x) = \frac{n_i^2}{N_d}$

- **Space charge density**

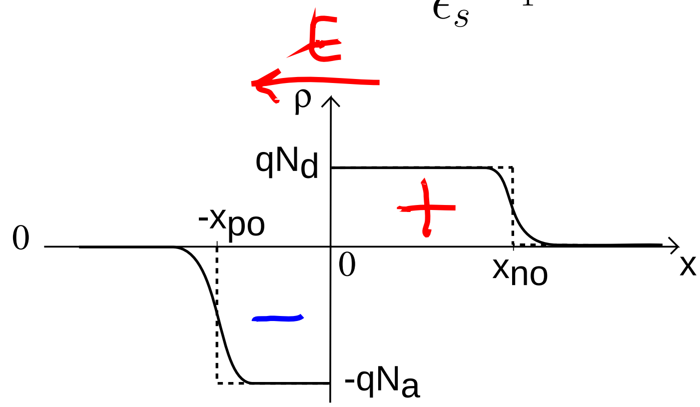


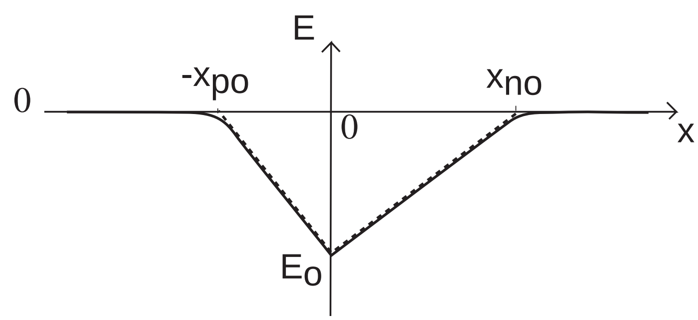
$$
\begin{aligned}
\rho(x) &= 0 && x < -x_{po} \\
&= -qN_a && -x_{po} < x < 0 \\
&= qN_d && 0 < x < x_{no} \\
&= 0 && x_{no} < x
\end{aligned}
$$

• Electric field

Integrate Gauss' equation:

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





- $x < -x_{po}$ $\quad E(x) = 0$
- $-x_{po} < x < 0$ $\quad E(x) - E(-x_{po}) = \frac{1}{\epsilon_s} \int_{-x_{po}}^{x} -qN_a dx$
  $= \frac{-qN_a}{\epsilon_s} x|_{-x_{po}}^{x} = \frac{-qN_a}{\epsilon_s}(x + x_{po})$
- $0 < x < x_{no}$ $\quad E(x) = \frac{qN_d}{\epsilon_s}(x - x_{no})$
- $x_{no} < x$ $\quad E(x) = 0$

- **Electrostatic potential**
  (with $\phi = 0$ @ $n_o = p_o = n_i$):

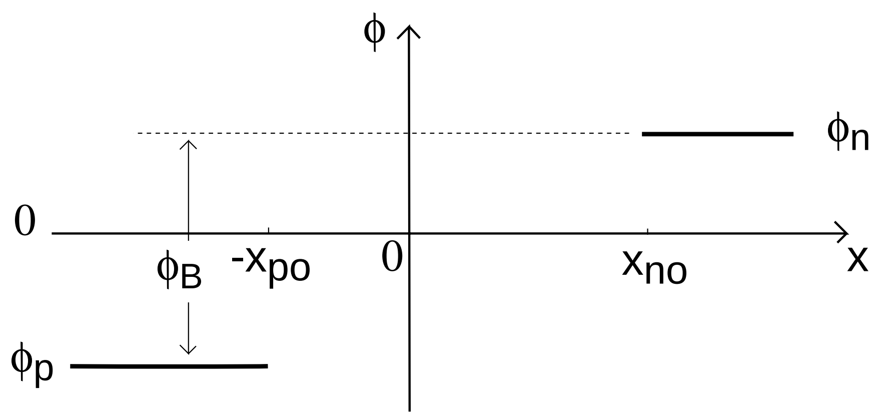
$$\phi = \frac{kT}{q} \ln \frac{n_o}{n_i} \qquad \phi = -\frac{kT}{q} \ln \frac{p_o}{n_i}$$

← Boltzmann relations

In QNR's, n_o, p_o known $\Rightarrow$ can determine ϕ:

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

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



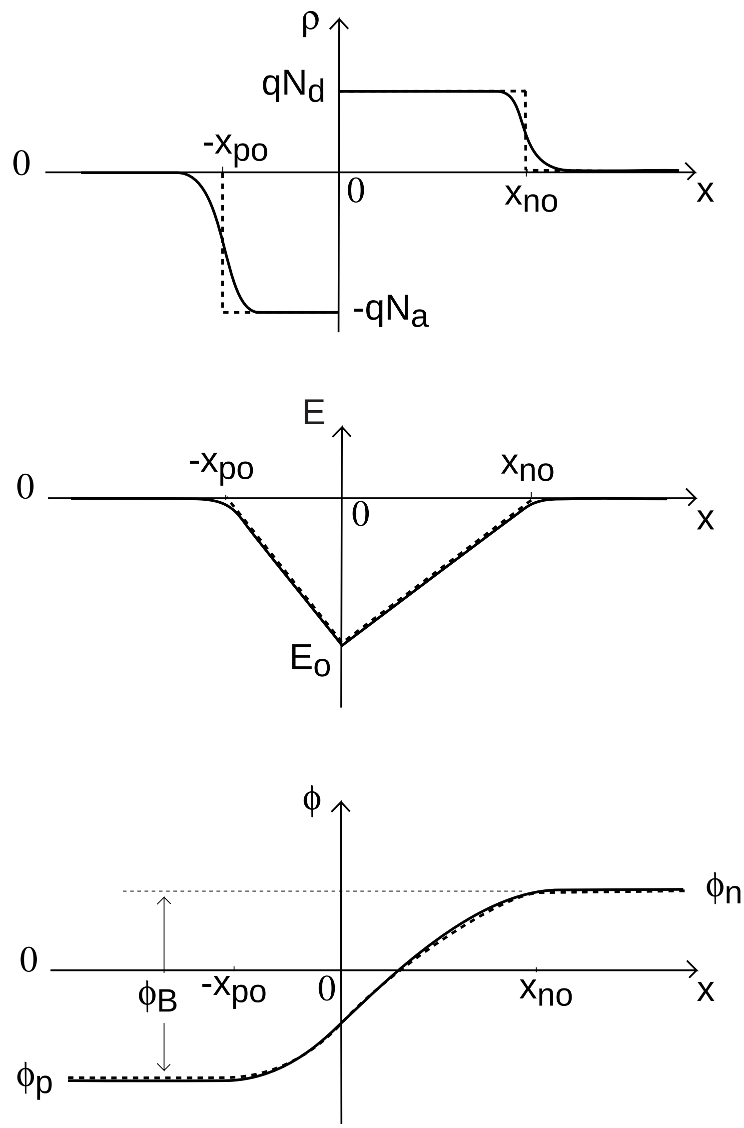
Built-in potential:

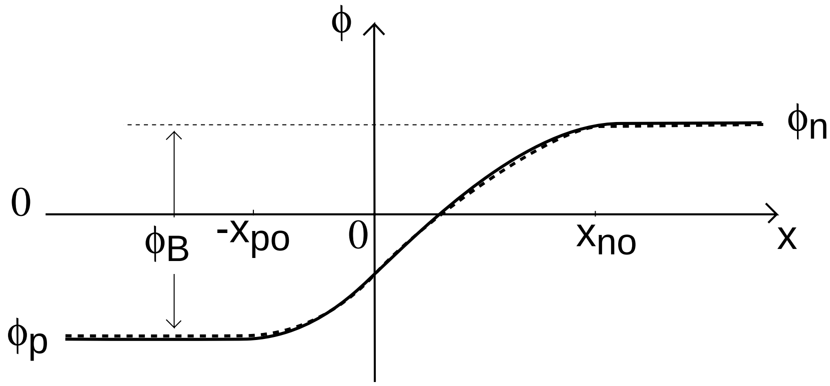
$$\boxed{\phi_B = \phi_n - \phi_p = \frac{kT}{q} \ln \frac{N_a N_d}{n_i^2}}$$

General expression: did not use depletion approximation.

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

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





- $x < -x_{po}$ $\quad\phi(x) = \phi_p$
- $-x_{po} < x < 0$ $\quad\phi(x) - \phi(-x_{po})$ ϕ_p

$$= -\int_{-x_{po}}^{x} -\frac{qN_a}{\epsilon_s}(x + x_{po})dx$$
$$= \frac{qN_a}{2\epsilon_s}(x + x_{po})^2$$

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

- $0 < x < x_{no}$ $\quad\phi(x) = \phi_n - \frac{qN_d}{2\epsilon_s}(x - x_{no})^2$
- $x_{no} < x$ $\quad\phi(x) = \phi_n$

Almost done...

Still don't 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 $\phi(x)$ continuous at $x = 0$:

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

Two equations with two unknowns. Solution:

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

Now problem completely solved.

Other results:

Total width of space charge region:

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

Field at metallurgical junction:

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

Three cases:

- Symmetric junction: $N_a = N_d \Rightarrow x_{po} = x_{no}$
- Asymmetric junction: $N_a > N_d \Rightarrow x_{po} < x_{no}$
- Strongly asymmetric junction:
  i.e. p$^+$n junction: $N_a \gg N_d$

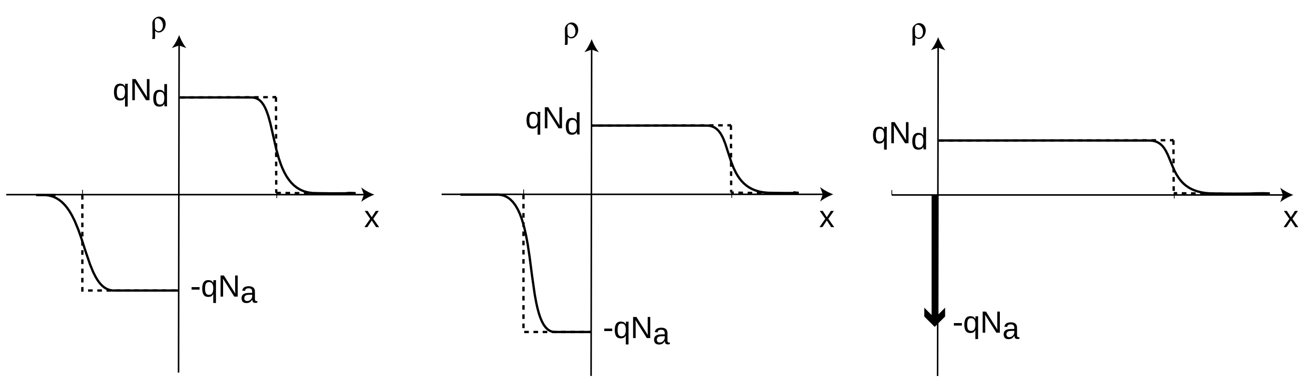
$$x_{po} \ll x_{no} \simeq x_{do} \simeq \sqrt{\frac{2\epsilon_s \phi_B}{qN_d}} \propto \frac{1}{\sqrt{N_d}}$$

$N_d \uparrow \Rightarrow x_{do} \downarrow$

$$|E_o| \simeq \sqrt{\frac{2q\phi_B N_d}{\epsilon_s}} \propto \sqrt{N_d}$$

$N_d \uparrow \Rightarrow |E_o| \uparrow$

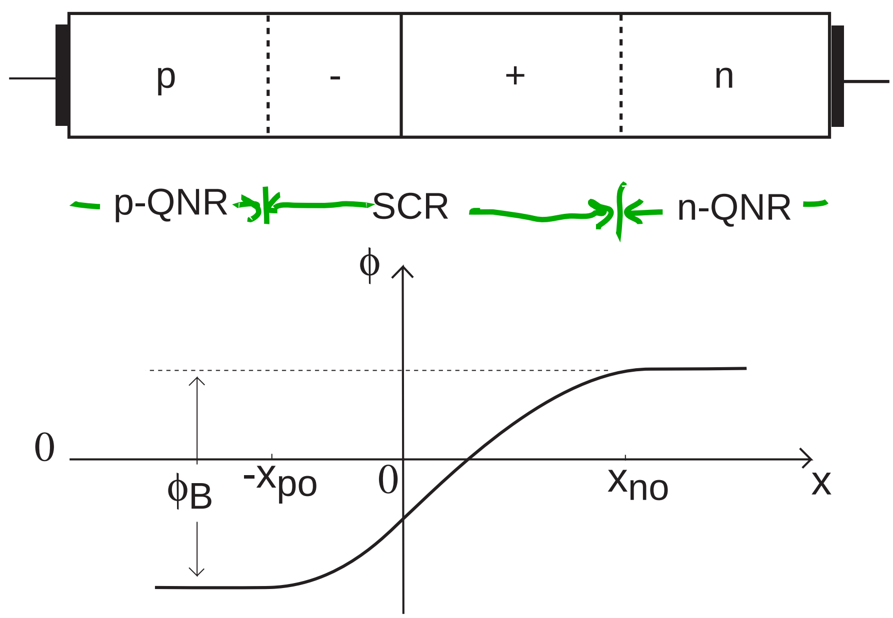
The lowly-doped side controls the electrostatics of the pn junction.



symmetric asymmetric strongly asymmetric

4. Contact potentials

Potential distribution in thermal equilibrium so far:



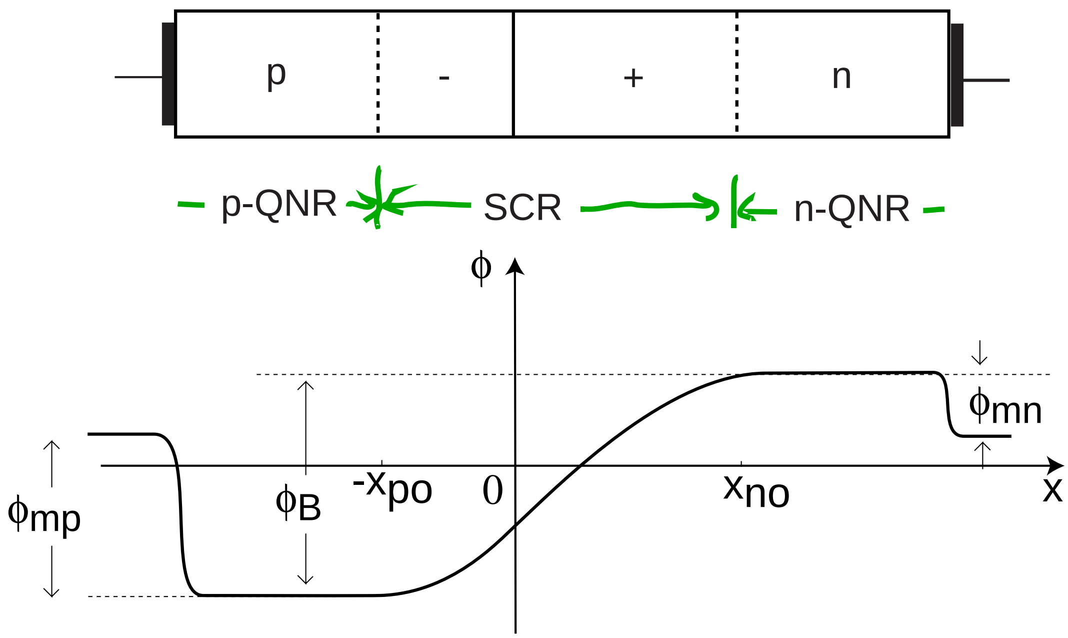
Question 1: *If I apply a voltmeter across diode, do I measure ϕ_B?*

☐ yes ☐ no ☐ it depends

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

☐ yes ☐ no ☐ sometimes

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



Metal-semiconductor contacts: junctions of dissimilar materials

$\Rightarrow$ built-in potentials: ϕ_{mn}, ϕ_{mp}

Potential difference across structure must be zero

$\Rightarrow$ cannot measure ϕ_B!

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

Key conclusions

- Electrostatics of pn junction in equilibrium:
  - a *space-charge region*
  - surrounded by two *quasi-neutral regions*

  ⇒ built-in potential across p-n junction

- To first order, carrier concentrations in space-charge region are much smaller than doping level

  ⇒ *depletion approximation.*

- Contact potential at metal-semiconductor junctions: ⇒ from contact to contact, there is no potential build-up across pn junction