Chapter 5-1. PN-junction electrostatics

In this chapter you will learn about pn junction electrostatics: Charge density, electric field and electrostatic potential existing inside the diode under equilibrium and steady state conditions.

You will also learn about:
Poisson's Equation
Built-In Potential
Depletion Approximation
Step-Junction Solution

PN-junction fabrication

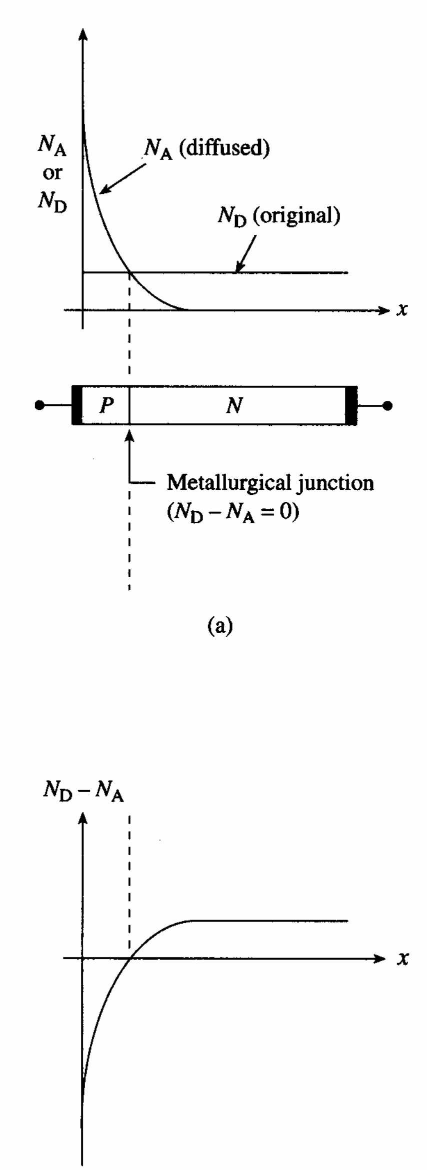


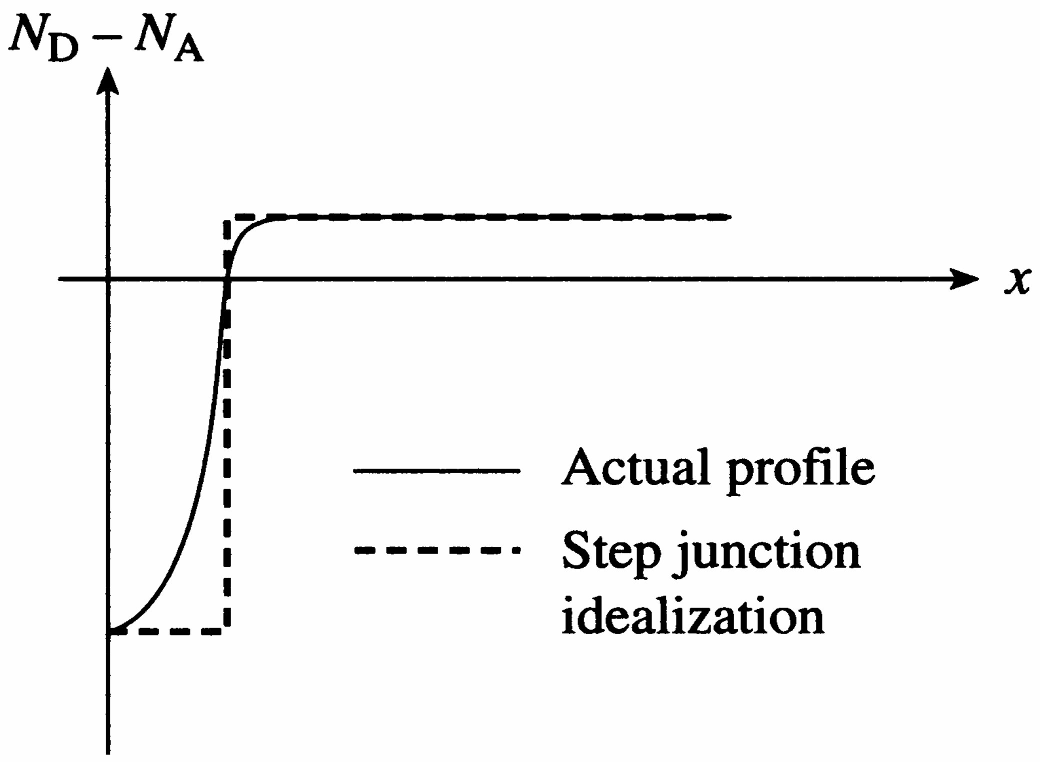
Figure 5.1 (b)

PN-junctions are created by several processes including:

1. Diffusion
2. Ion-implantation
3. Epitaxial deposition

Each process results in different doping profiles

Ideal step-junction doping profile



(a)

Figure 5.2

Equilibrium energy band diagram for the pn junction

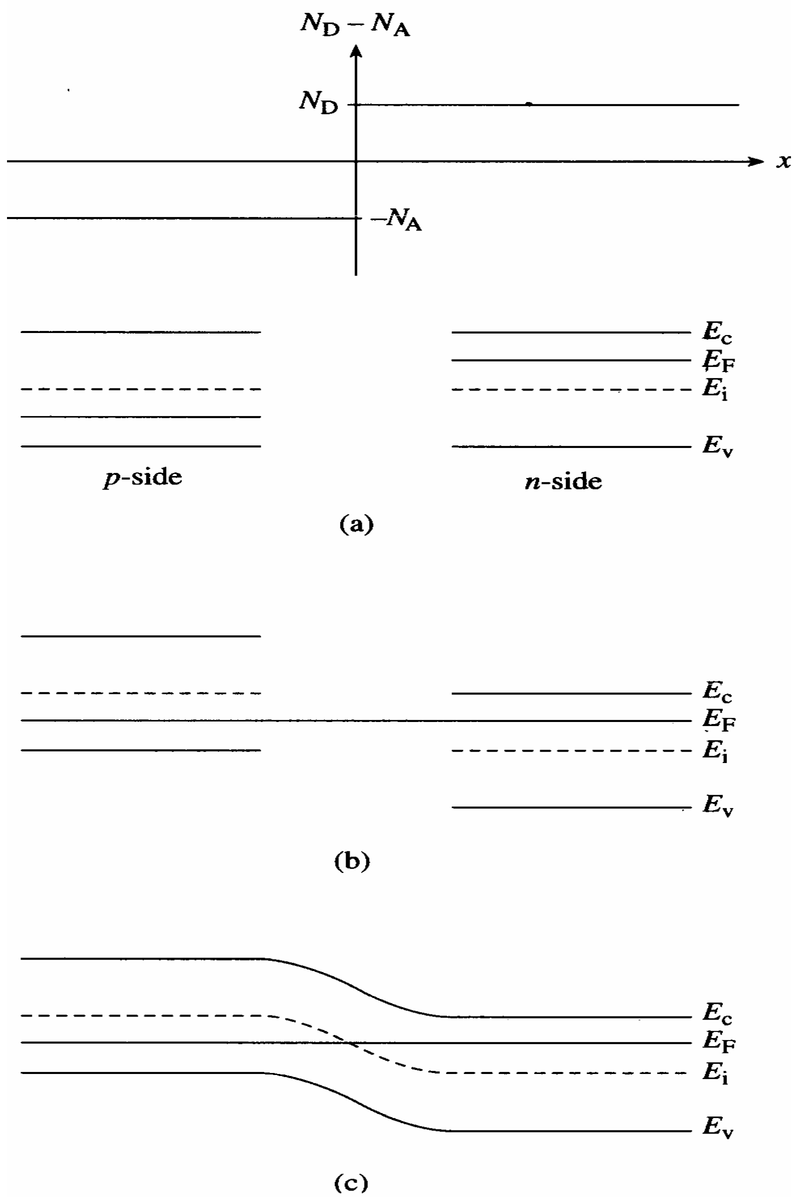


Figure 5.3

$$n = n_i \exp\left(\frac{E_F - E_i}{kT}\right)$$

$$p = n_i \exp\left(\frac{E_i - E_F}{kT}\right)$$

E_F = same everywhere under equilibrium

Join the two sides of the band by a smooth curve.

Electrostatic variables for the equilibrium pn junction

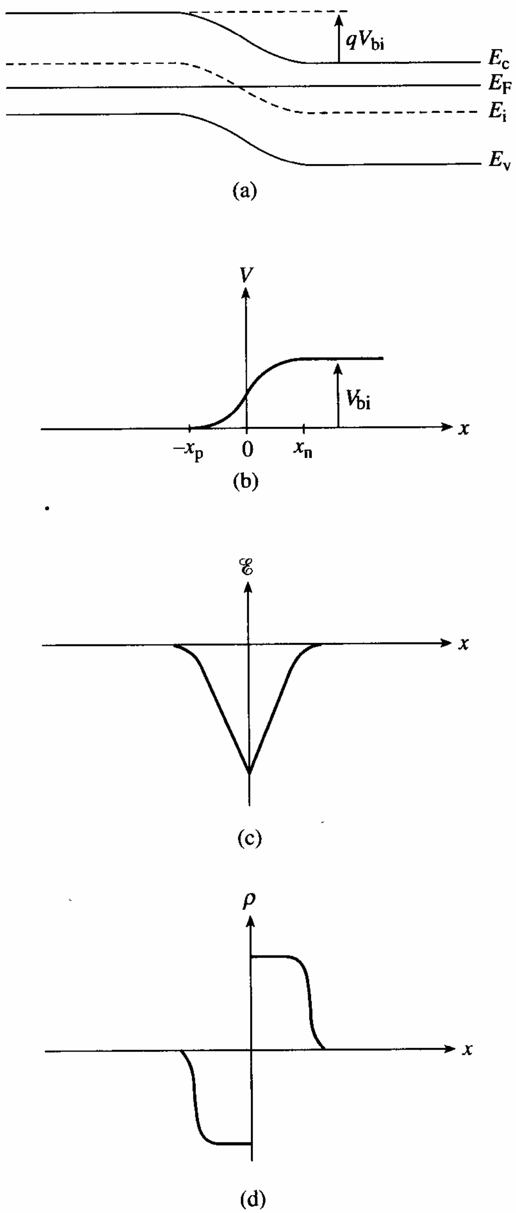


Figure 5.4

Potential, $V = -(1/q)(E_C - E_{ref})$. So, potential difference between the two sides (also called built-in voltage, V_{bi}) is equal to $-(1/q)(\Delta E_C)$.

$$V = -\frac{1}{q}\left(E_C - E_{ref}\right)$$

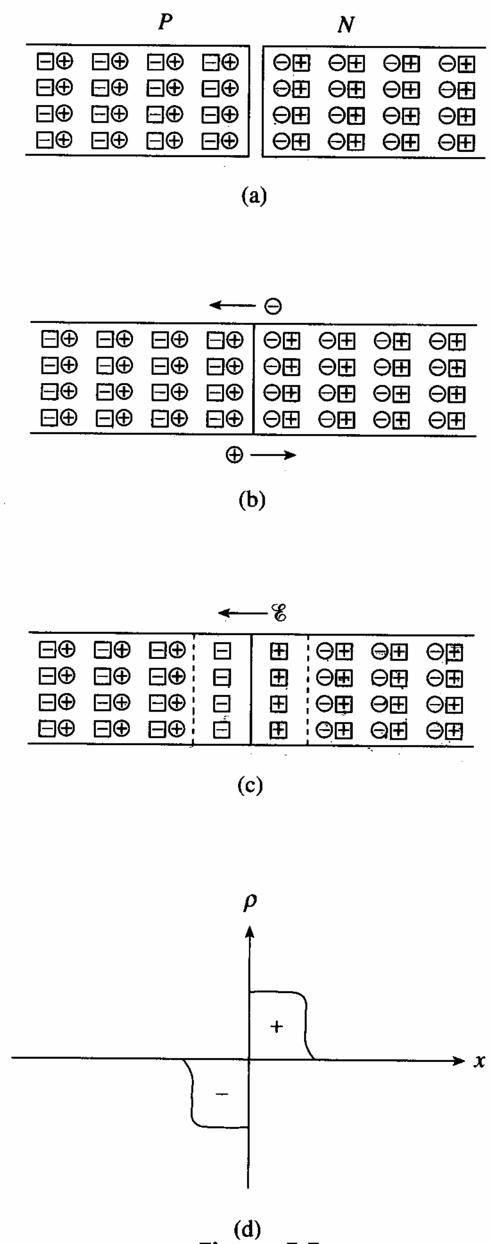
$$\mathcal{E} = \frac{1}{q}\frac{dE_C}{dx} = \frac{1}{q}\frac{dE_i}{dx}$$

$$\left.\frac{d\mathcal{E}}{dx} = \frac{\rho}{\varepsilon}\right\}$$

ρ = charge density

$\varepsilon = K_s \varepsilon_o$

Conceptual pn-junction formation



(d)
Figure 5.5

p and n type regions
before junction formation

Holes and electrons will diffuse towards opposite directions, uncovering ionized dopant atoms. This will build up an electric field which will prevent further movement of carriers.

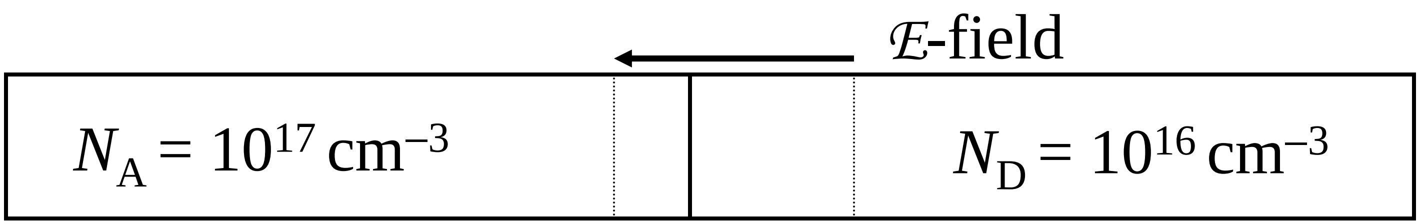
The built-in potential, V_{bi}

When the junction is formed, electrons from the n-side and holes from the p-side will diffuse leaving behind charged dopant atoms. Remember that the dopant atoms cannot move! Electrons will leave behind positively charged donor atoms and holes will leave behind negatively charged acceptor atoms.

The net result is the build up of an electric field from the positively charged atoms to the negatively charged atoms, i.e., from the n-side to p-side. When steady state condition is reached after the formation of junction (how long this takes?) the net electric field (or the built in potential) will prevent further diffusion of electrons and holes. In other words, there will be drift and diffusion currents such that net electron and hole currents will be zero.

Equilibrium conditions

Under equilibrium conditions, the net electron current and hole current will be zero.



hole diffusion current →

hole drift current ←

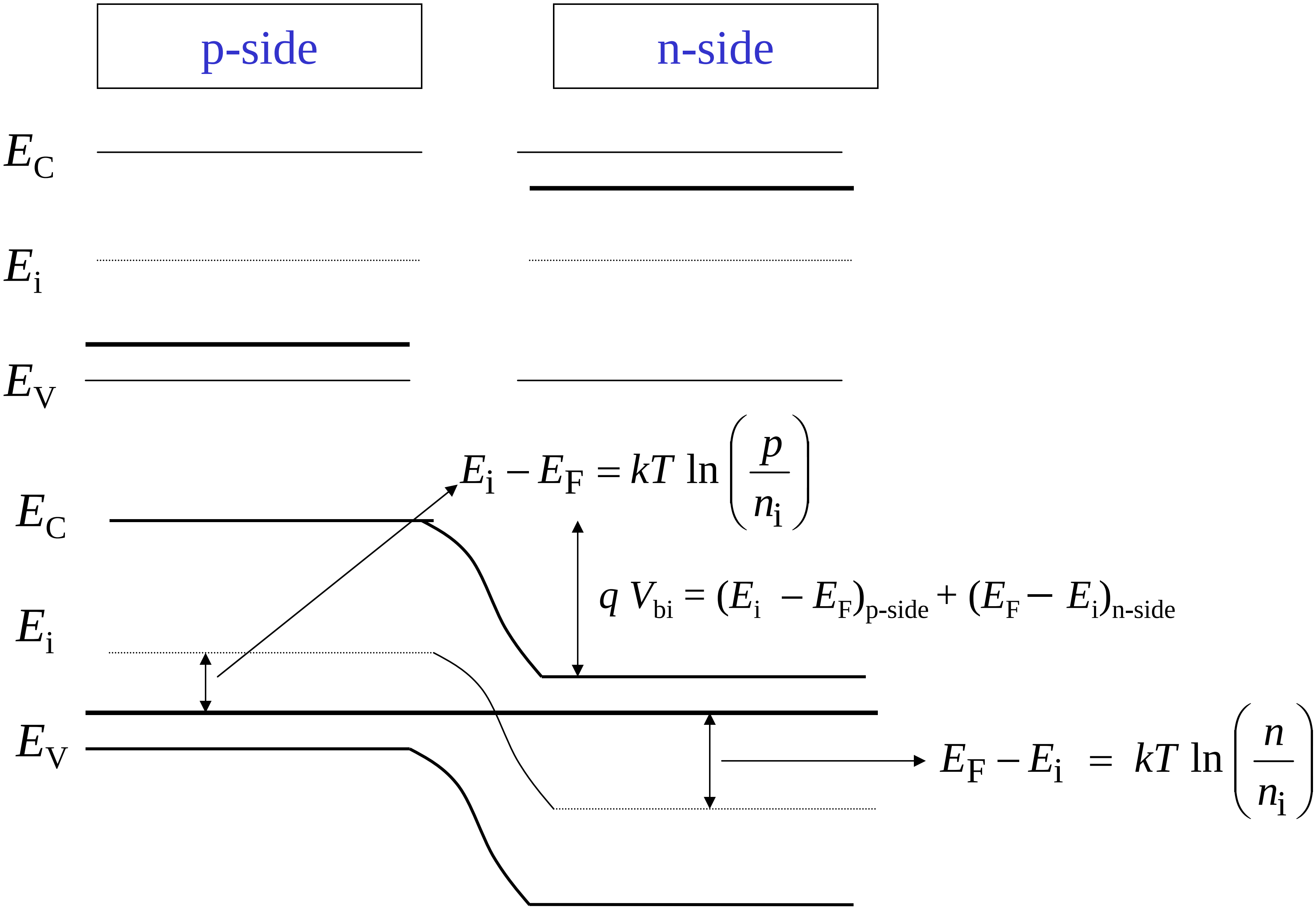
net = 0

electron diffusion current →
opposite to electron flux

electron drift current ←
opposite to electron flux

net = 0

The built-in potential, V_{bi}



The built-in potential, V_{bi}

The built-in potential, V_{bi}, measured in Volts, is numerically equal to the "shift" in the bands expressed in eV.

$$V_{bi} = (1/q)\,\{(E_i - E_F)_{\text{p-side}} + (E_F - E_i)_{\text{n-side}}\}$$

$$= \frac{kT}{q}\ln\left(\frac{p}{n_i}\right) + \frac{kT}{q}\ln\left(\frac{n}{n_i}\right)$$

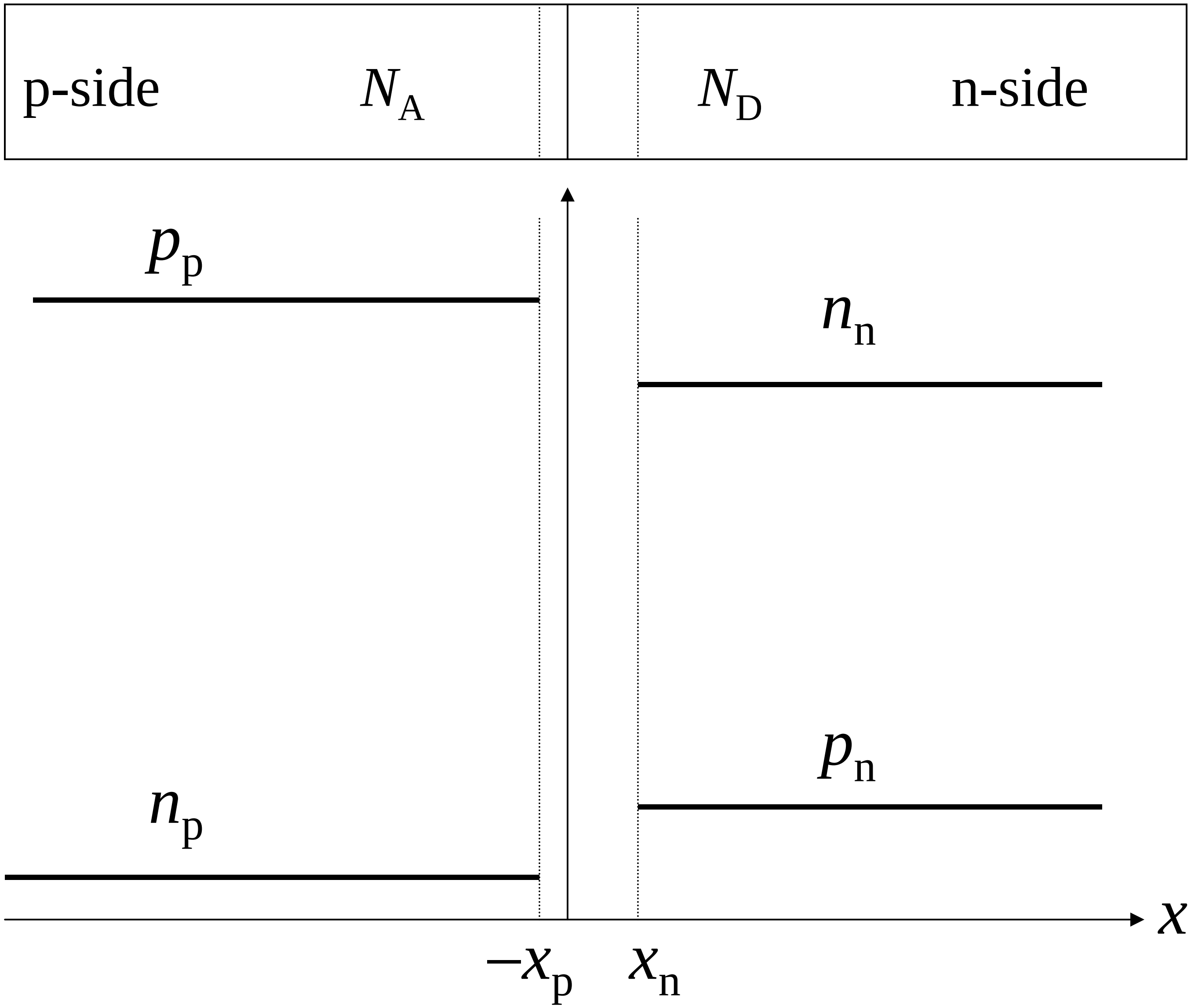
$$= \frac{kT}{q}\ln\left(\frac{p_p n_n}{n_i^2}\right)$$

where $p_p = \text{hole-concentration on p-side}$

and $n_n = \text{electron-concentration on n-side}$

An interesting fact: $$\frac{p_p}{p_n} = \frac{n_n}{n_p} = \exp\left(\frac{qV_{bi}}{kT}\right)$$

Majority and minority carrier concentrations



Built-in potential as a function of doping concentration for an abrupt p^+n or n^+p junction

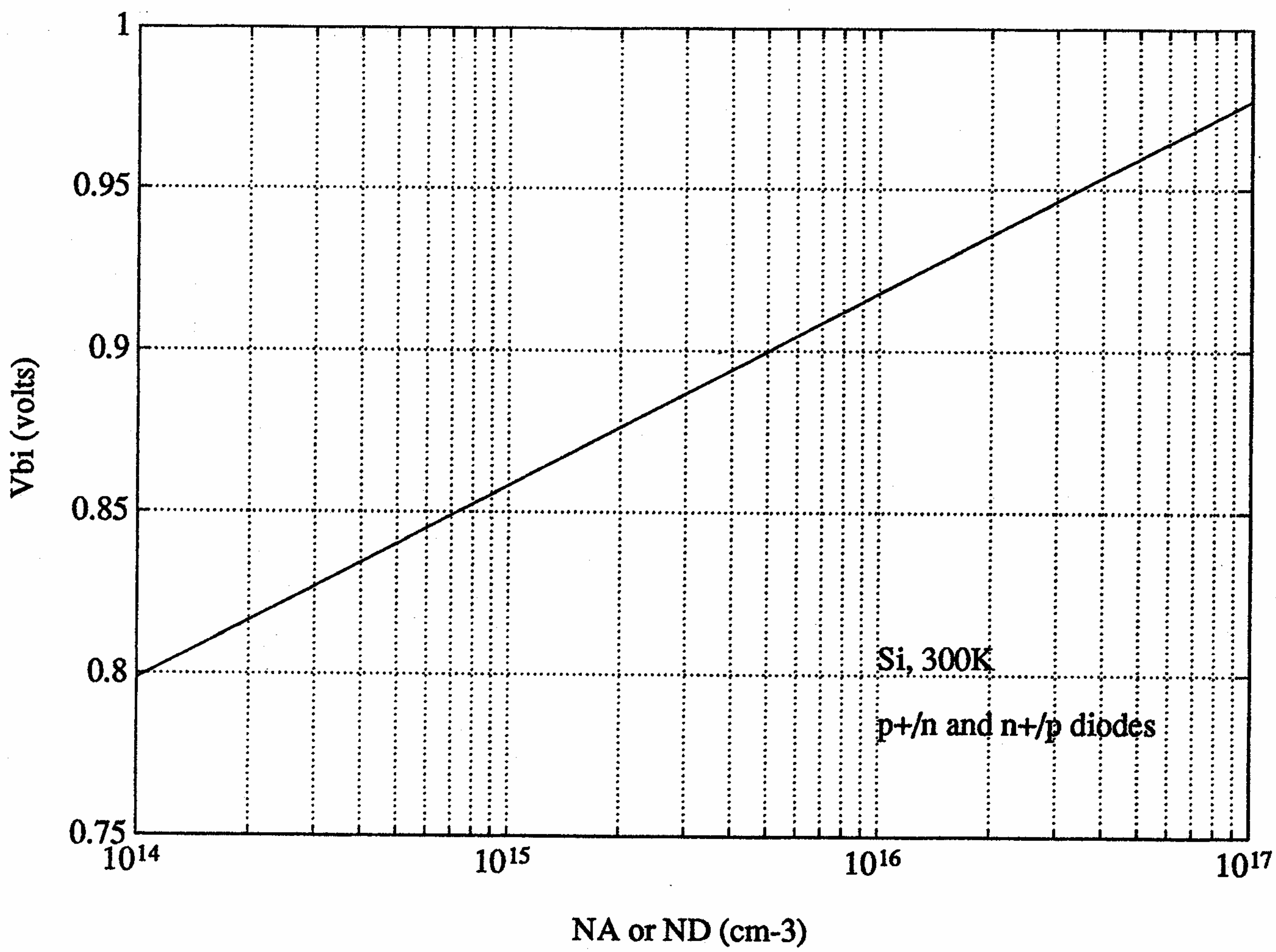


Figure E5.1

Depletion approximation

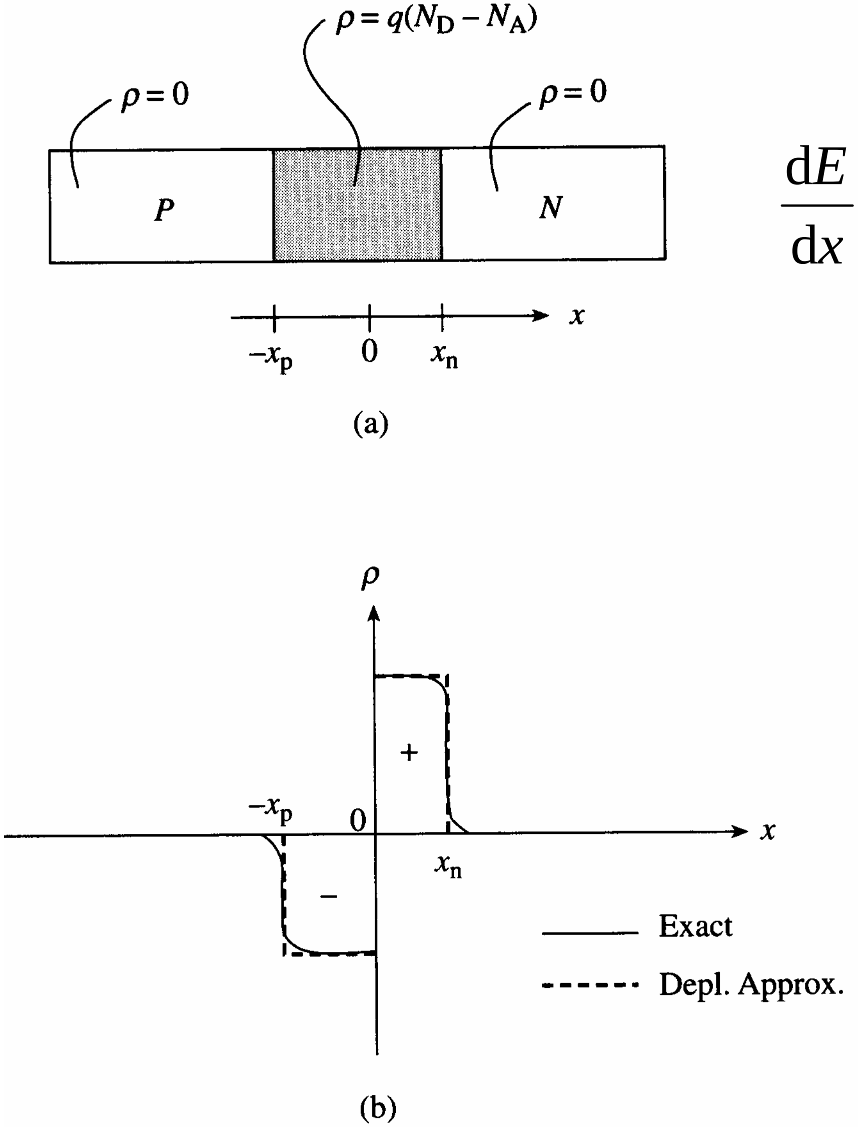


Figure 5.6

$$\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{\rho}{K_s\varepsilon_0}$$

Poisson equation

$$= \begin{cases} \dfrac{q}{K_s\varepsilon_0}(N_D - N_A) & \text{for} \quad -x_p \le x \le x_n \end{cases}$$

$$= \quad 0 \quad \text{everywhere} \quad \text{else}$$

We *assume* that the free carrier concentration inside the depletion region is zero.

Example 1

A p-n junction is formed in Si with the following parameters. Calculate the built-in voltage, V_{bi}.

$N_D = 10^{16}\ \text{cm}^{-3}$	$N_A = 10^{17}\ \text{cm}^{-3}$

Calculate majority carrier concentration in n-side and p-side. Assume $n_n = N_D = 10^{16}\ \text{cm}^{-3}$ and $p_p = N_A = 10^{17}\ \text{cm}^{-3}$.

$$V_{bi} = \frac{kT}{q}\ln\left(\frac{p_p n_n}{n_i^2}\right) = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right)$$

Plug in the numerical values to calculate V_{bi}.

Example 2

A pn junction is formed in Si with the following parameters. Calculate the built-in voltage, V_{bi}.

$N_D = 2 \times 10^{16}$ cm^{-3} $N_A = 10^{16}$ cm^{-3}	$N_A = 3 \times 10^{17}$ cm^{-3} $N_D = 2 \times 10^{17}$ cm^{-3}

Calculate majority carrier concentration in n-side and p-side.
n_n="effective N_D" = 10^{16} cm^{-3}. p_p = "effective N_A"=10^{17} cm^{-3}.

$$V_{bi} = \frac{kT}{q} \ln\left(\frac{p_p n_n}{n_i^2}\right) = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

Here N_A and N_D are "effective" or net values.

Plug in the numerical values to calculate V_{bi}.