ROYAL INSTITUTE OF TECHNOLOGY

Semiconductor Devices Spring 2019

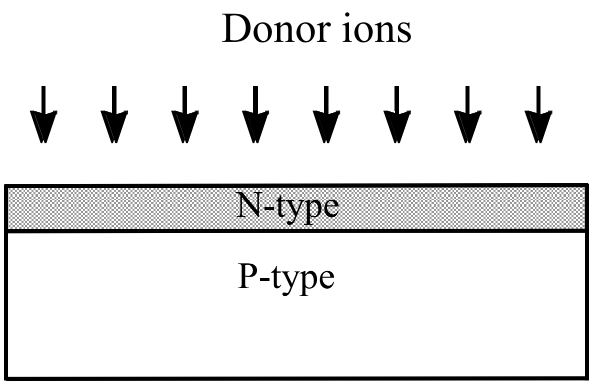
Lecture 4

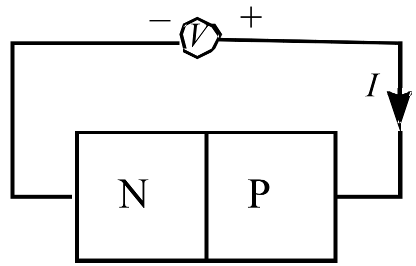
ROYAL INSTITUTE OF TECHNOLOGY

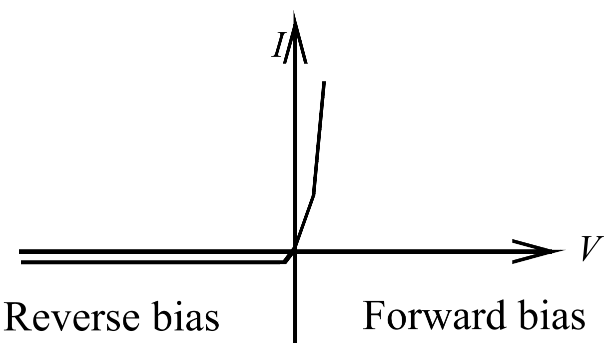
This Lecture

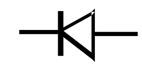
- Reading
  - 4.1-4.5 PN and Metal Semiconductor Junctions
- Concepts:
  - Joining different materials together (p & n or semiconductor and metal)
  - Two terminal devices, diode, solar-cell, LED (laser), schottky diode, protection circuits (LV), blocking (HV)
  - Some physics including neutral regions, depletion, poisson’s equation

4.1 Building Blocks of the PN Junction Theory



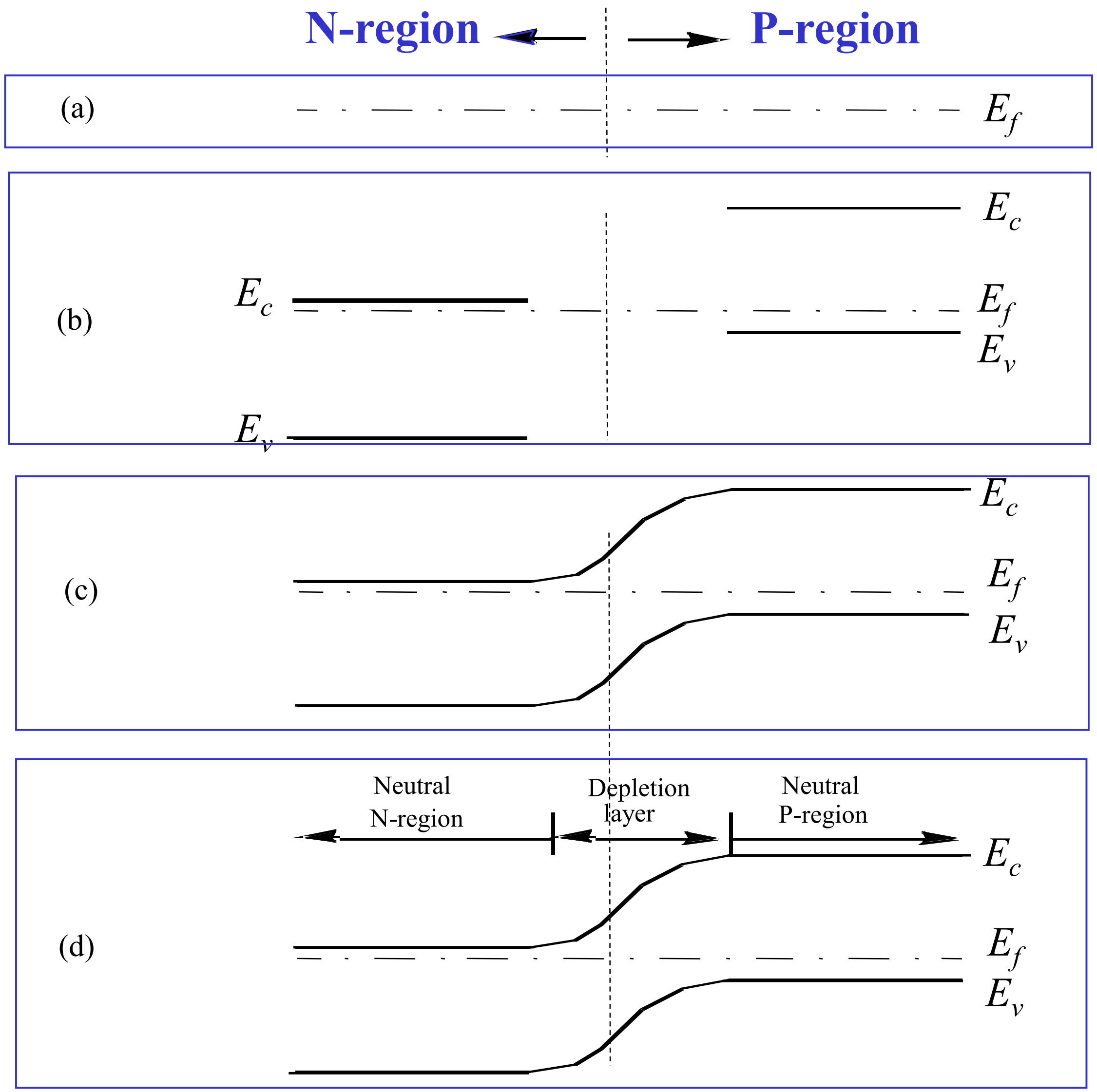






diode
symbol

4.1.1 Energy Band Diagram of a PN Junction



E_f is constant at equilibrium

E_c and E_v are known relative to E_f

E_c and E_v are smooth, the exact shape to be determined.

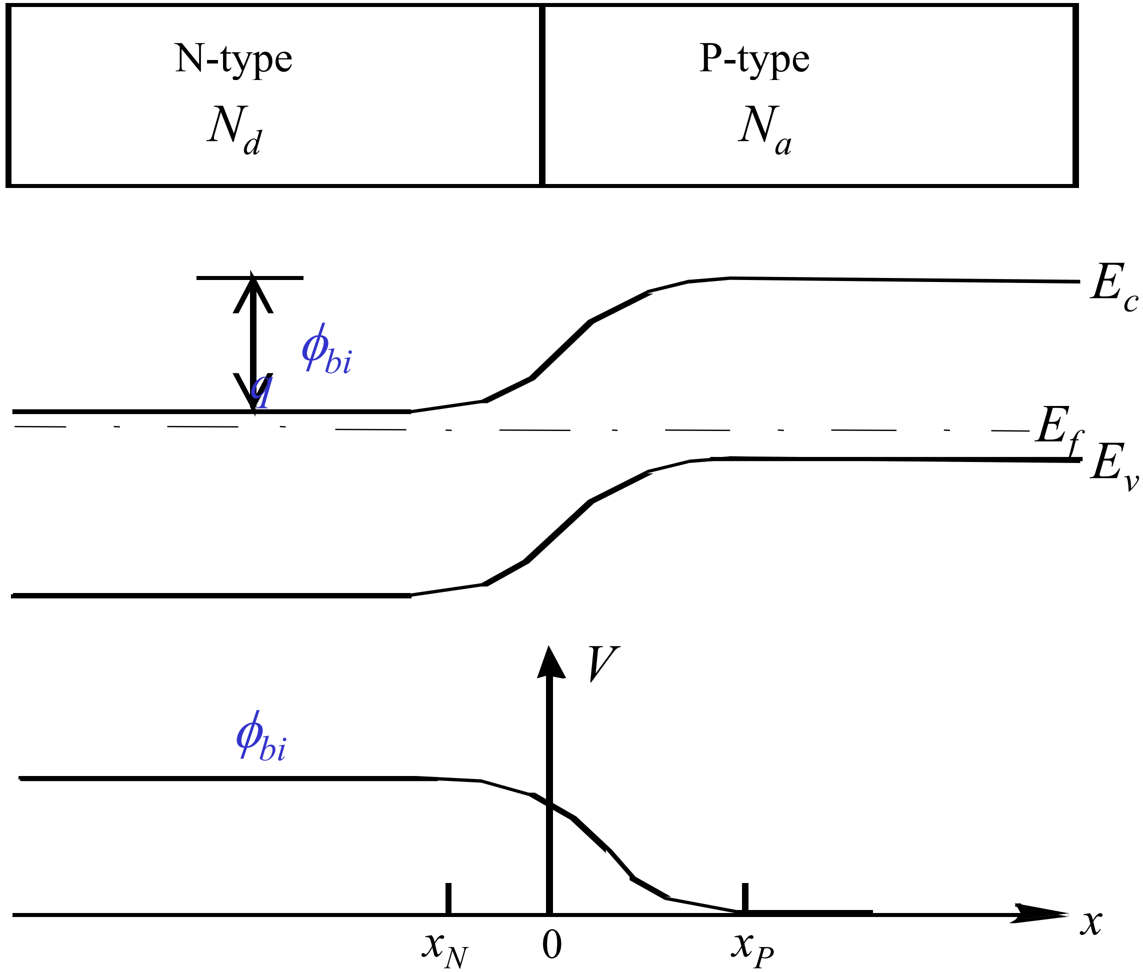
A depletion layer exists at the PN junction where $n \approx 0$ and $p \approx 0$.

4.1.2 Built-in Potential

(a)

(b)

(c)



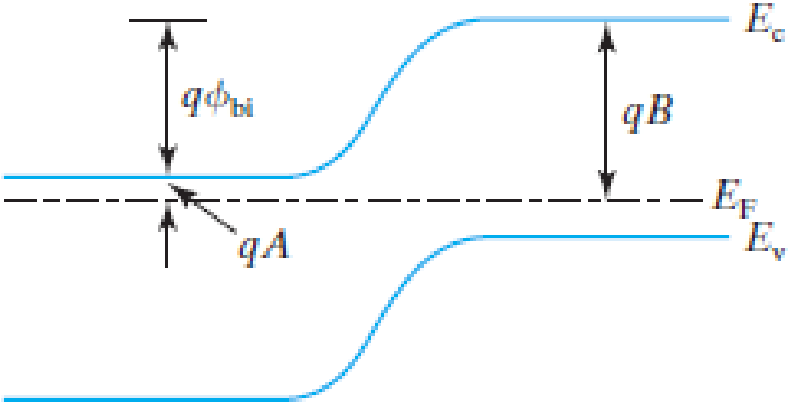
4.1.2 Built-in Potential

N-region $n = N_d = N_c e^{-qA/kT} \Rightarrow A = \dfrac{kT}{q}\ln\dfrac{N_c}{N_d}$

P-region $n = \dfrac{n_i^2}{N_a} = N_c e^{-qB/kT} \Rightarrow B = \dfrac{kT}{q}\ln\dfrac{N_c N_a}{n_i^2}$

$$\phi_{bi} = B - A = \frac{kT}{q}\left(\ln\frac{N_c N_a}{n_i^2} - \ln\frac{N_c}{N_d}\right)$$

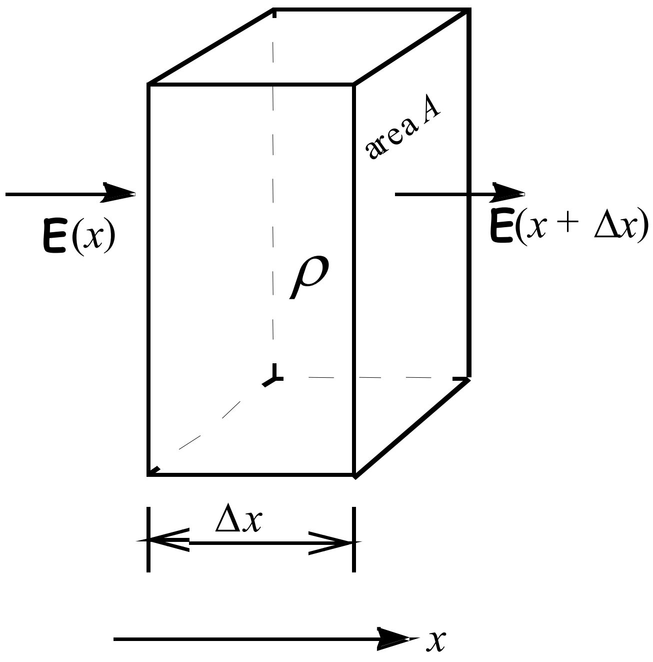
$$\boxed{\phi_{bi} = \frac{kT}{q}\ln\frac{N_d N_a}{n_i^2}}$$



4.1.3 Poisson's Equation

Gauss's Law:

$$\varepsilon_s \mathscr{E}(x+\Delta x)A - \varepsilon_s \mathscr{E}(x)A = \rho \Delta x A$$



ε_s: permittivity (~12ε_o for Si)

ρ: charge density (C/cm^3)

$$\frac{\mathscr{E}(x+\Delta x) - \mathscr{E}(x)}{\Delta x} = \frac{\rho}{\varepsilon_s}$$

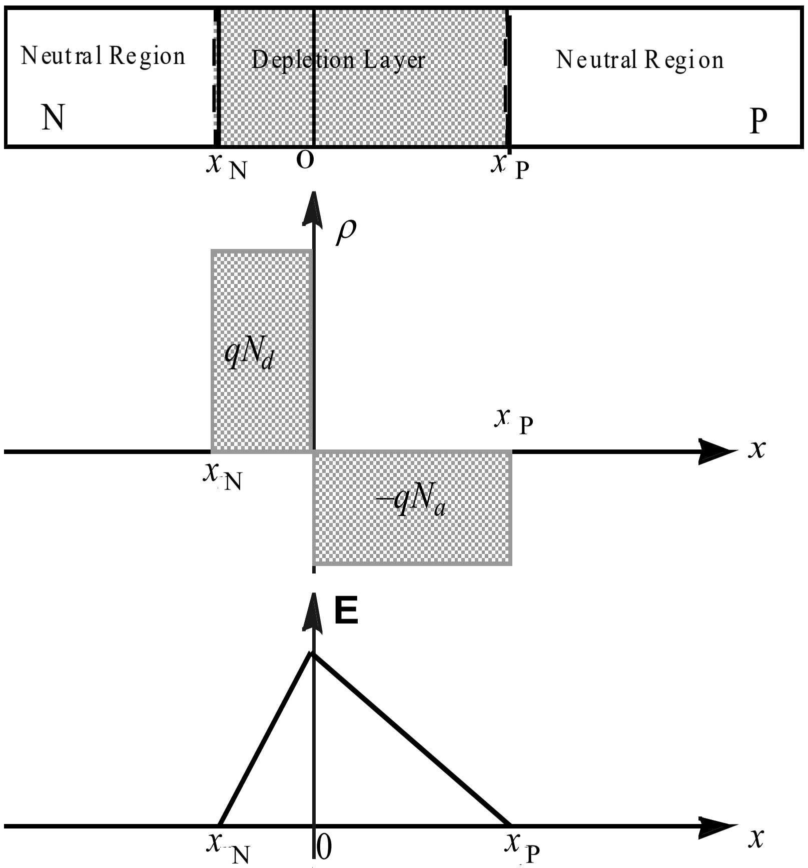
$$\frac{d\mathscr{E}}{dx} = \frac{\rho}{\varepsilon_s}$$

$$\boxed{\frac{d^2V}{dx^2} = -\frac{d\mathscr{E}}{dx} = -\frac{\rho}{\varepsilon_s}}$$

Poisson's equation

4.2 Depletion-Layer Model

4.2.1 Field and Potential in the Depletion Layer



On the ***P-side*** of the depletion layer, $\rho = -qN_a$

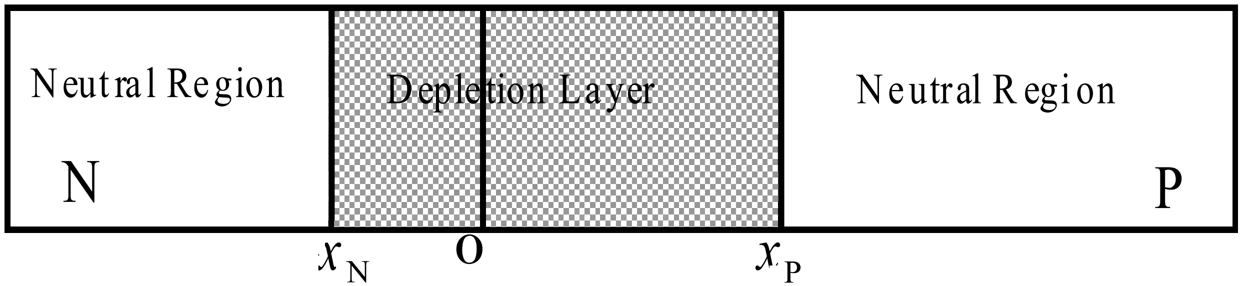
$$\frac{d\mathcal{E}}{dx} = -\frac{qN_a}{\varepsilon_s}$$

$$\mathcal{E}(x) = -\frac{qN_a}{\varepsilon_s}x + C_1 = \boxed{\frac{qN_a}{\varepsilon_s}(x_P - x)}$$

On the ***N-side***, $\rho = qN_d$

$$\boxed{\mathcal{E}(x) = \frac{qN_d}{\varepsilon_s}(x - x_N)}$$

4.2.1 Field and Potential in the Depletion Layer



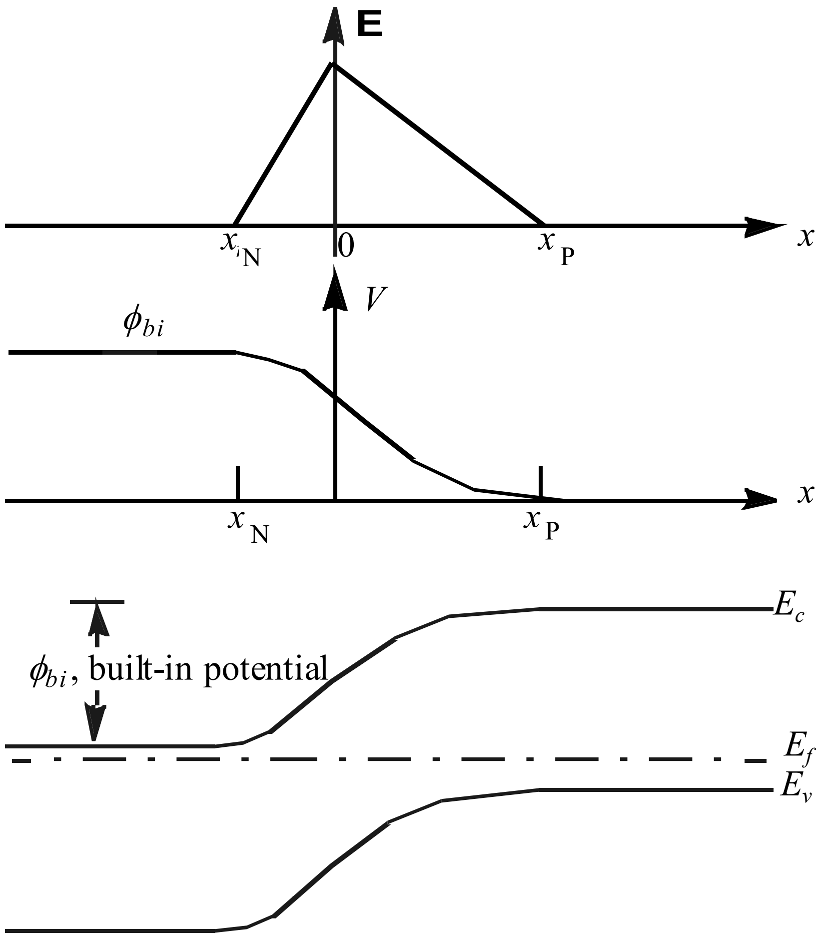
The electric field is continuous at $x = 0$.

$$\boxed{N_a\,|x_P| = N_d|x_P|}$$

Which side of the junction is depleted more?

A one-sided junction is called a ***N*⁺*P* junction** or ***P*⁺*N* junction**

4.2.1 Field and Potential in the Depletion Layer



On the P-side,

$$V(x) = \frac{qN_a}{2\varepsilon_s}(x_P - x)^2$$

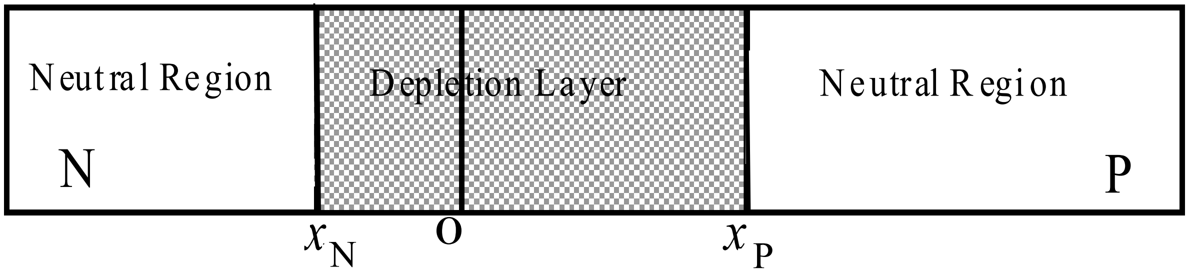
Arbitrarily choose the voltage at $x = x_P$ as $V = 0$.

On the N-side,

$$V(x) = D - \frac{qN_d}{2\varepsilon_s}(x - x_N)^2$$

$$= \phi_{bi} - \frac{qN_d}{2\varepsilon_s}(x - x_N)^2$$

4.2.2 Depletion-Layer Width



V is continuous at $x = 0$ →

$$x_P - x_N = W_{dep} = \sqrt{\frac{2\varepsilon_s \phi_{bi}}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)}$$

If $N_a >> N_d$, as in a P⁺N junction,

$$W_{dep} = \sqrt{\frac{2\varepsilon_s \phi_{bi}}{qN_d}} \approx |x_N|$$

$$|x_P| = |x_N| N_d / N_a \cong 0$$

What about a N^+P junction?

$$W_{dep} = \sqrt{2\varepsilon_s \phi_{bi} / qN} \quad \text{where} \quad \frac{1}{N} = \frac{1}{N_d} + \frac{1}{N_a} \approx \frac{1}{\textit{lighter dopant density}}$$

EXAMPLE: *A P^+N junction has $N_a = 10^{20}$ cm^{-3} and $N_d = 10^{17}$ cm^{-3}. What is a) its built in potential, b) W_{dep} , c) x_N , and d) x_P ?*

Solution:

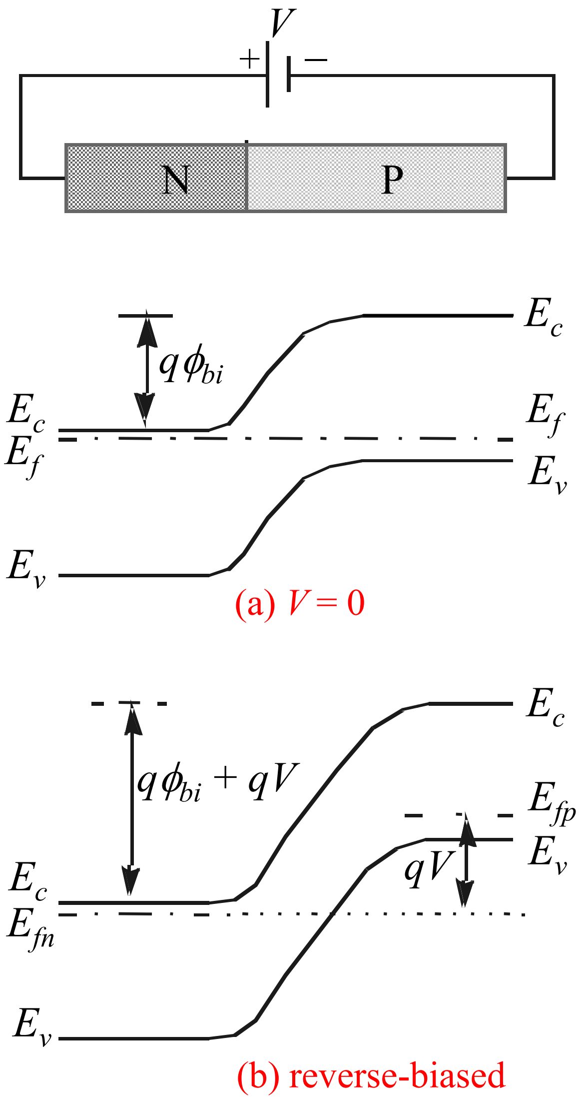
a)
$$\phi_{bi} = \frac{kT}{q} \ln \frac{N_d N_a}{n_i^2} = 0.026\,\text{V} \ln \frac{10^{20} \times 10^{17}\,\text{cm}^{-6}}{10^{20}\,\text{cm}^{-6}} \approx 1\,\text{V}$$

b)
$$W_{dep} \approx \sqrt{\frac{2\varepsilon_s \phi_{bi}}{qN_d}} = \left(\frac{2 \times 12 \times 8.85 \times 10^{-14} \times 1}{1.6 \times 10^{-19} \times 10^{17}} \right)^{1/2} = 0.12\,\mu\text{m}$$

c) $\left| x_N \right| \approx W_{dep} = 0.12\,\mu\text{m}$

d) $\left| x_P \right| = \left| x_N \right| N_d / N_a = 1.2 \times 10^{-4}\,\mu\text{m} = 1.2\,\text{Å} \approx 0$

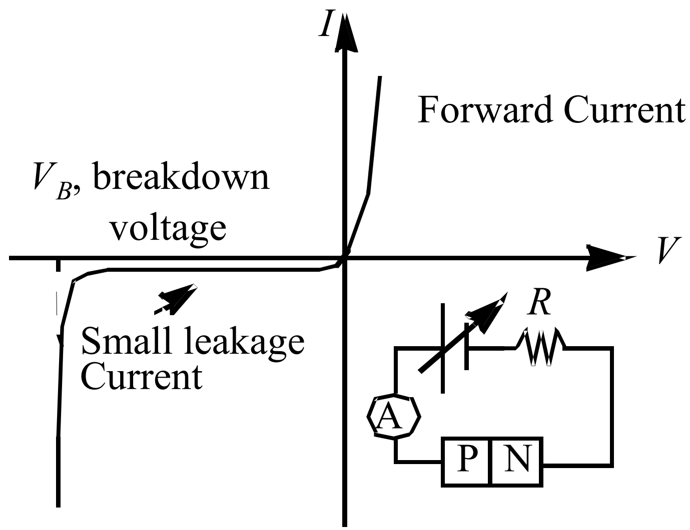
4.3 Reverse-Biased PN Junction

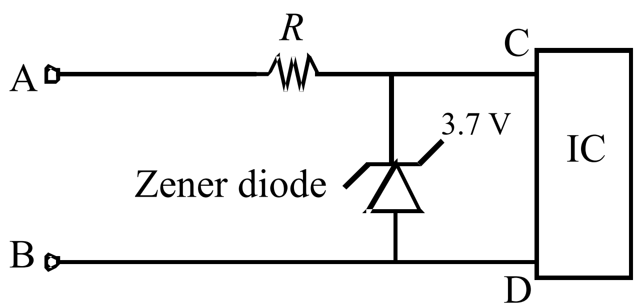


$$\boxed{W_{dep} = \sqrt{\frac{2\varepsilon_s(\phi_{bi} + |V_r|)}{qN}} = \sqrt{\frac{2\varepsilon_s \cdot potential\ barrier}{qN}}}$$

$$\frac{1}{N} = \frac{1}{N_d} + \frac{1}{N_a} \approx \frac{1}{lighter\ \ dopant\ \ density}$$

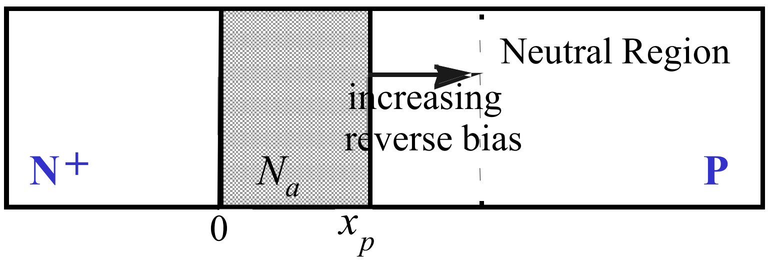
4.5 Junction Breakdown

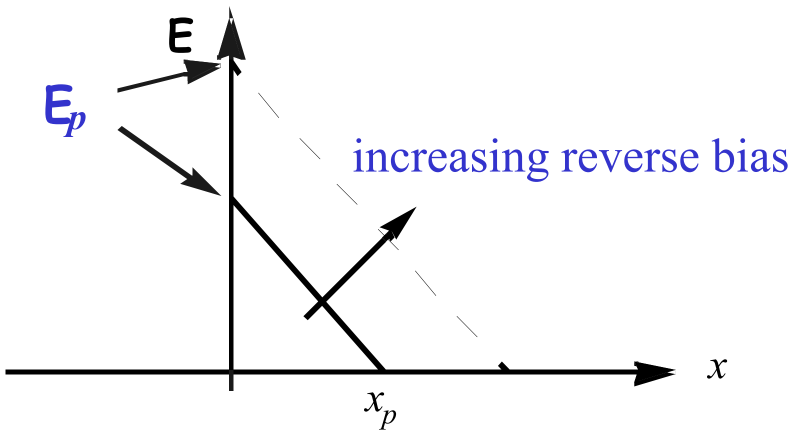




A ***Zener diode*** is designed to operate in the breakdown mode.

4.5.1 Peak Electric Field

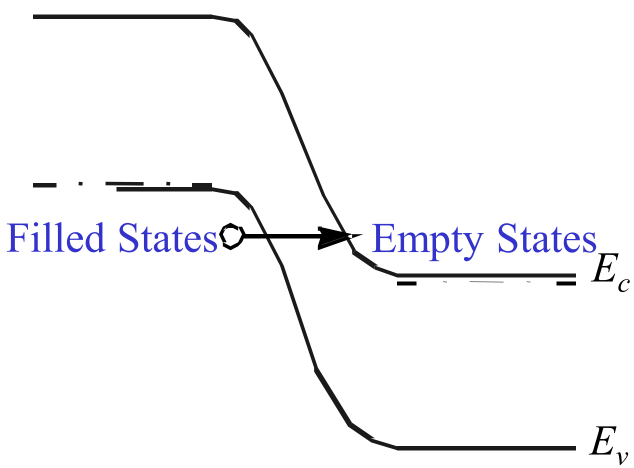


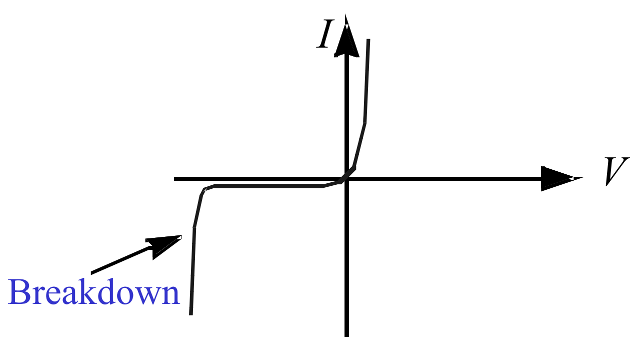


$$E_p = E(0) = \left[\frac{2qN}{\varepsilon_s} (\phi_{bi} + |V_r|) \right]^{1/2}$$

$$V_B = \frac{\varepsilon_s E_{crit}^{\,2}}{2qN} - \phi_{bi}$$

4.5.2 Tunneling Breakdown



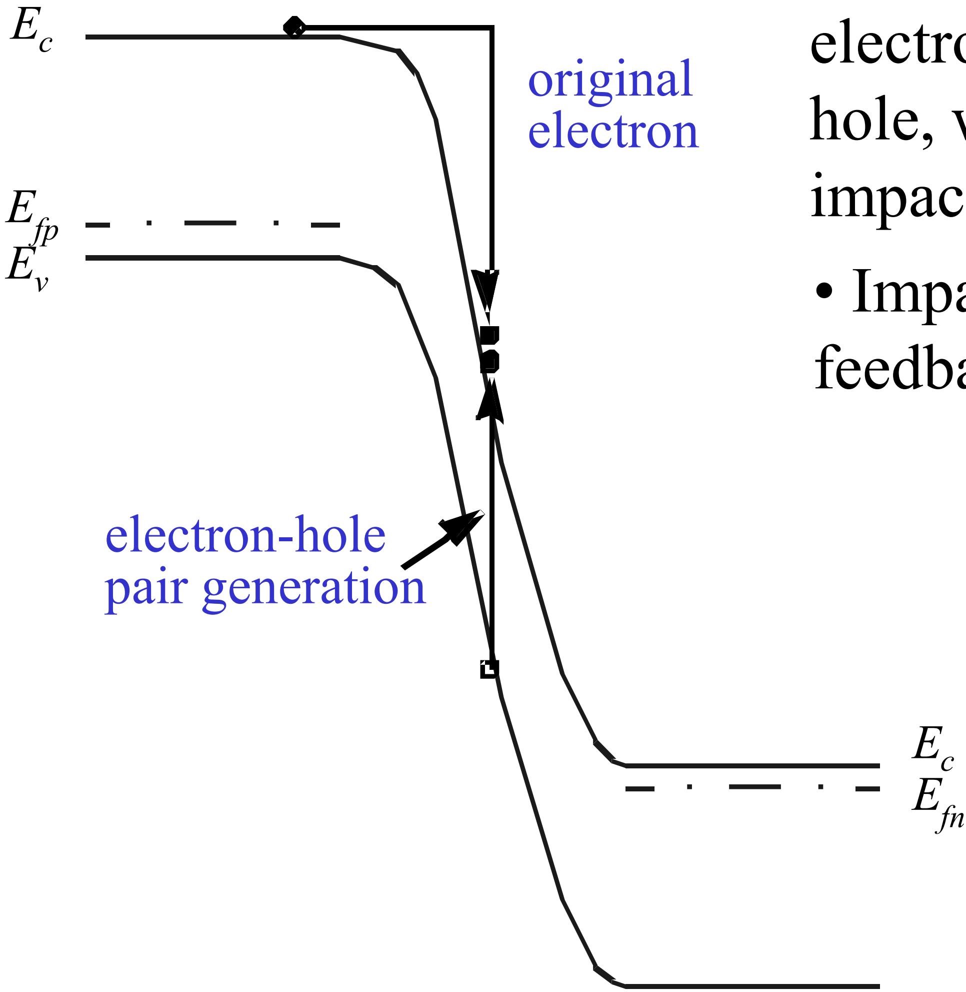


Dominant if both sides of a junction are very heavily doped.

$$J = G\, e^{-H/\mathcal{E}_p}$$

$$\mathcal{E}_p = \mathcal{E}_{crit} \approx 10^6 \text{ V/cm}$$

4.5.3 Avalanche Breakdown



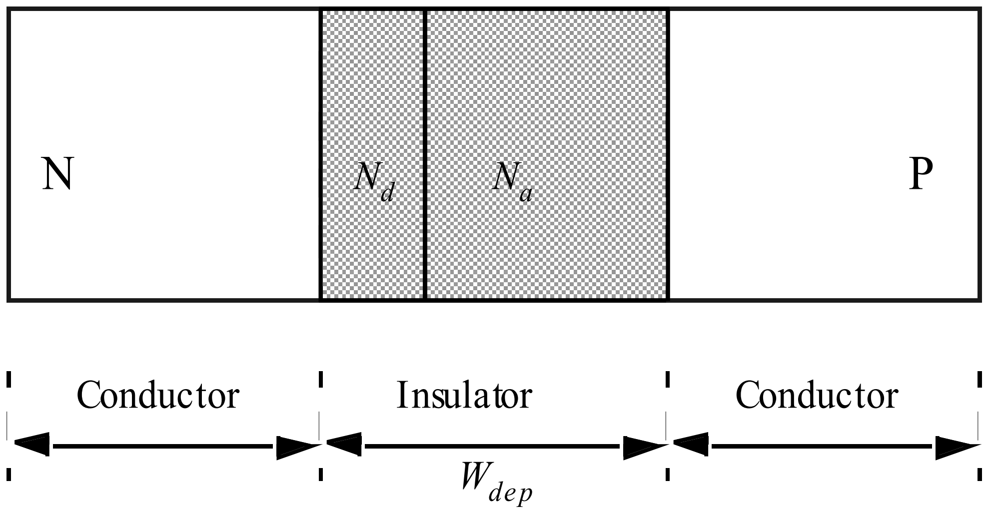
• *impact ionization*: an energetic electron generating electron and hole, which can also cause impact ionization.

• Impact ionization + positive feedback→*avalanche breakdown*

$$V_B = \frac{\varepsilon_s \mathcal{E}_{crit}^{\,2}}{2qN}$$

$$\boxed{V_B \propto \frac{1}{N}} = \frac{1}{N_a} + \frac{1}{N_d}$$

4.4 Capacitance-Voltage Characteristics

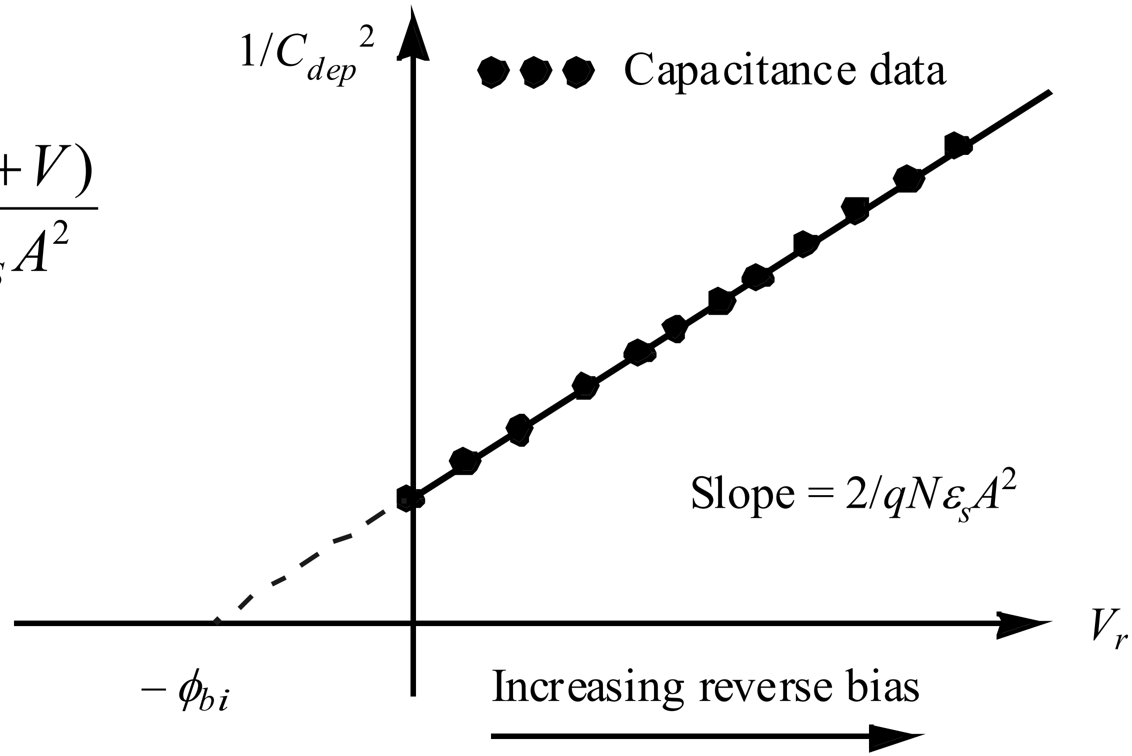


Reverse biased PN junction is a capacitor.

$$\boxed{C_{dep} = A\frac{\varepsilon_s}{W_{dep}}}$$

4.4 Capacitance-Voltage Characteristics

$$\frac{1}{C_{dep}{}^2} = \frac{W_{dep}{}^2}{A^2 \varepsilon_s{}^2} = \frac{2(\phi_{bi} + V)}{qN\varepsilon_S A^2}$$



- From this C-V data can N_a and N_d be determined?

EXAMPLE: *If the slope of the line in the previous slide is 2x10*^{23} *F*$^{-2}$ *V*$^{-1}$*, the intercept is 0.84V, and A is 1* μm^2*, find the lighter and heavier doping concentrations* N_l *and* N_h.

Solution:

$$\begin{aligned} N_l &= 2/(slope \times q\varepsilon_s A^2) \\ &= 2/(2\times10^{23}\times1.6\times10^{-19}\times12\times8.85\times10^{-14}\times10^{-8}\,\mathrm{cm}^2) \\ &= 6\times10^{15}\ \mathrm{cm}^{-3} \end{aligned}$$

$$\phi_{bi} = \frac{kT}{q}\ln\frac{N_h N_l}{n_i^{\,2}} \quad\Rightarrow\quad N_h = \frac{n_i^{\,2}}{N_l}e^{\frac{q\phi_{bi}}{kT}} = \frac{10^{20}}{6\times10^{15}}e^{\frac{0.84}{0.026}} = 1.8\times10^{18}\ \mathrm{cm}^{-3}$$

- *Is this an accurate way to determine* N_l*?* N_h*?*

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Summary

- Concepts:
  - Joining different materials together (p & n or semiconductor and metal)
  - Two terminal devices, diode, solar-cell, LED (laser), schottky diode, protection circuits (LV), blocking (HV)
  - Some physics including neutral regions, depletion, poisson's equation
- Reading for tomorrow
  - 4.6-9