

Semiconductor devices



Material classification

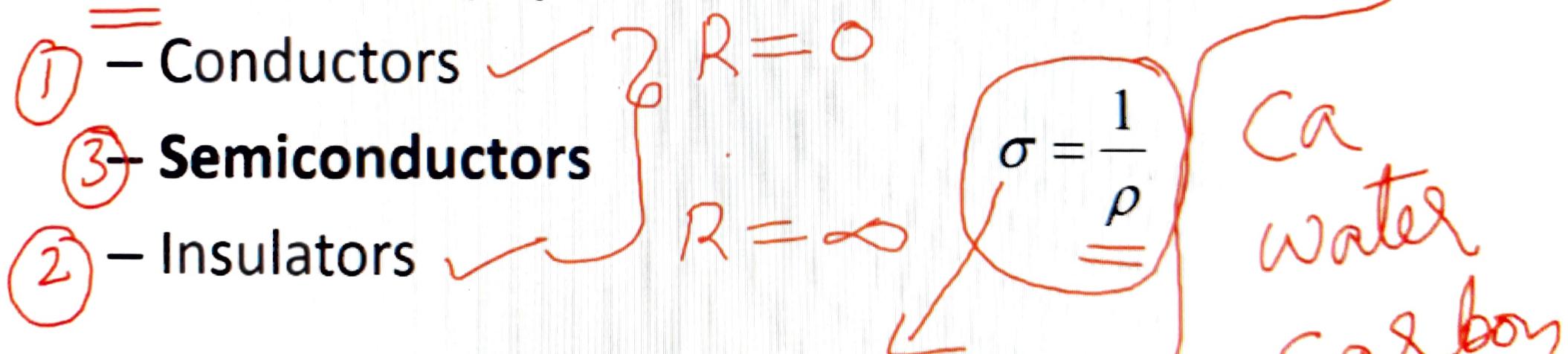
- Material classification based on conductivity (σ)/resistivity (ρ)
 - Conductors
 - **Semiconductors**
 - Insulators

$$\sigma = \frac{1}{\rho}$$

Material classification

{ Gold
O₂

- Material classification based on conductivity (σ)/resistivity (ρ)



$$R = \rho \frac{l}{A}$$

General constants and conversion factors

Angstrom

$$\text{\AA} \quad 1 \text{\AA} = 10^{-4} \mu\text{m} = 10^{-8} \text{cm} = 10^{-10} \text{m}$$

Boltzmann's constant

$$k \quad k = 1.38 \times 10^{-23} \text{J/K} = 8.6 \times 10^{-5} \text{eV/K}$$

Electron-volt

$$\text{eV} \quad 1 \text{eV} = 1.6 \times 10^{-19} \text{J}$$

Electronic charge

$$e \text{ or } q \quad q = 1.6 \times 10^{-19} \text{C}$$

→ Micron

$$\mu\text{m} \quad 1 \mu\text{m} = 10^{-4} \text{cm} = \underline{\underline{10^{-6} \text{m}}}$$

Mil

$$\text{---} \quad 1 \text{ mil} = 0.001 \text{in.} = 25.4 \mu\text{m}$$

→ Nanometer

$$\text{nm} \quad 1 \text{ nm} = 10^{-9} \text{m} = 10^{-3} \mu\text{m} = 10 \text{\AA}$$

Permittivity of free space

$$\varepsilon_0 \quad \varepsilon_0 = 8.85 \times 10^{-14} \text{F/cm}$$

Permeability of free

$$\mu_0 \quad \mu_0 = 4\pi \times 10^{-9} \text{H/cm}$$

space

Planck's constant

$$h \quad h = 6.625 \times 10^{-34} \text{J-s}$$

Thermal voltage

$$V_T \quad V_T = kT/q \cong 0.026 \text{V at 300 K}$$

Velocity of light in
free space

$$c \quad c = 2.998 \times 10^{10} \text{cm/s}$$

Semiconductor constants

$$\underline{\epsilon = \epsilon_0}$$



insulator
dielectric

	Si	Ge	GaAs	SiO ₂
Relative dielectric constant	11.7	16.0	13.1	3.9
Bandgap energy, E_g (eV)	1.1	0.66	1.4	
Intrinsic carrier concentration, n_i (cm ⁻³ at 300 K)	1.5×10^{10}	2.4×10^{13}	1.8×10^6	

Elemental and compound semiconductors

- Elements in the periodic table can be grouped according to the number of valence electrons
- elemental semiconductors (group IV)**
 - Silicon (Si)
 - Germanium (Ge)
- compound semiconductor (group III–V)**

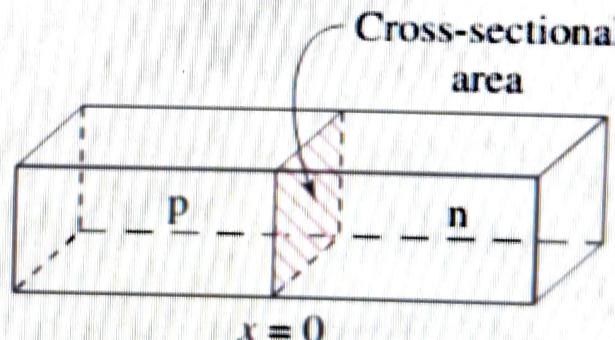
GaAs	Gallium arsenide
GaP	Gallium phosphide
AlP	Aluminum phosphide
AlAs	Aluminum arsenide
InP	Indium phosphide

III	IV	V
5 B Boron	6 C Carbon	
13 Al Aluminum	14 Si Silicon	15 P Phosphorus
31 Ga Gallium	32 Ge Germanium	33 As Arsenic
49 In Indium		51 Sb Antimony

Periodic table

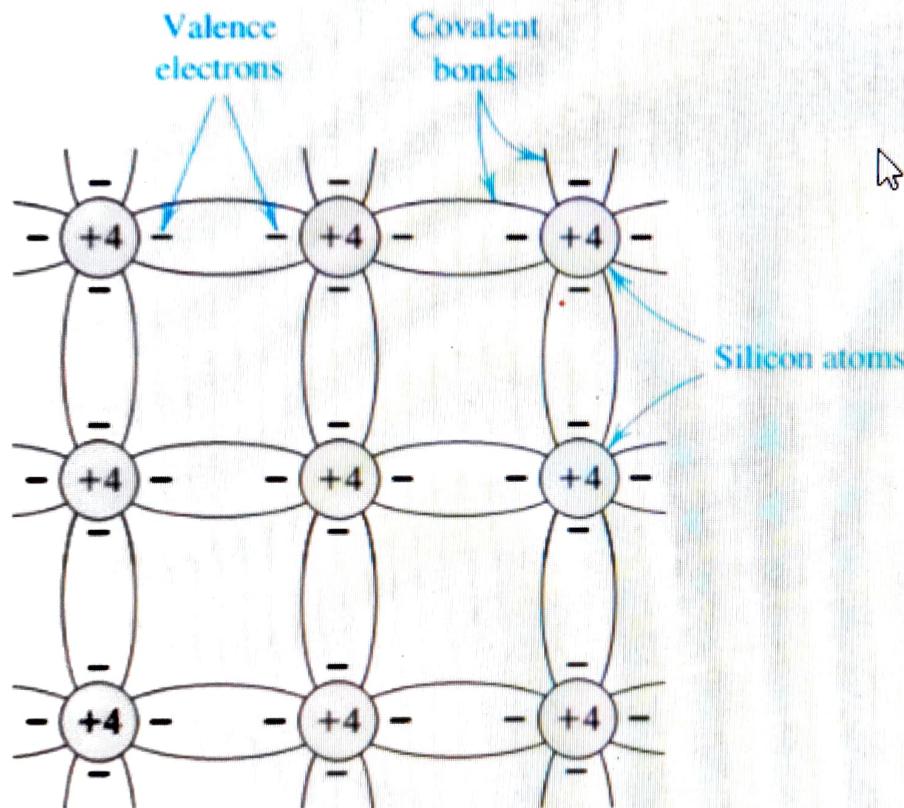
The pn Junction

- Operation with
 - Open-Circuit Terminals
 - Applied voltage across the terminals
 - Forward Bias
 - Reverse Bias



3D representation showing
the cross-sectional area

Single crystal silicon at $T = 0 \text{ K}$

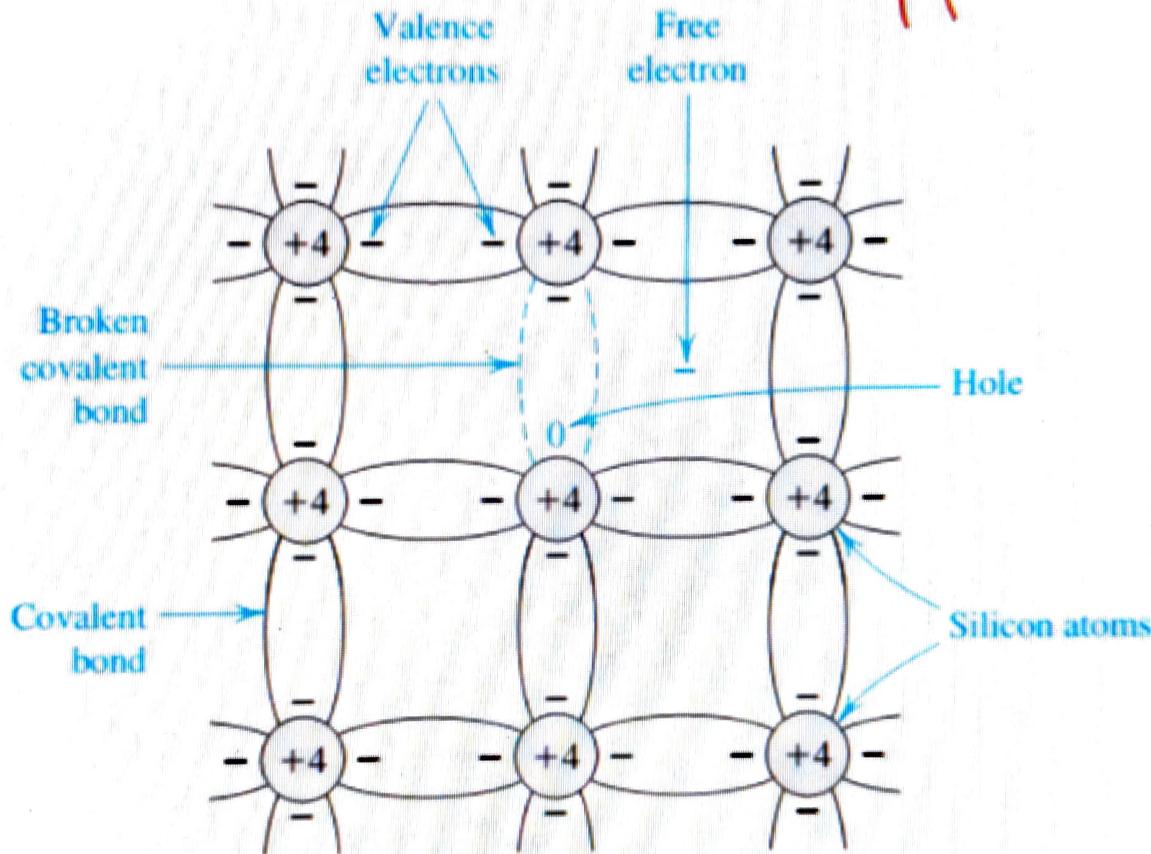


Silicon Lattice constant 5.43 \AA

Two-dimensional representation of single crystal silicon at $T = 0 \text{ K}$; all valence electrons are bound to the silicon atoms by covalent bonding

Silicon at $T > 0$ K

~~Heat~~ charge

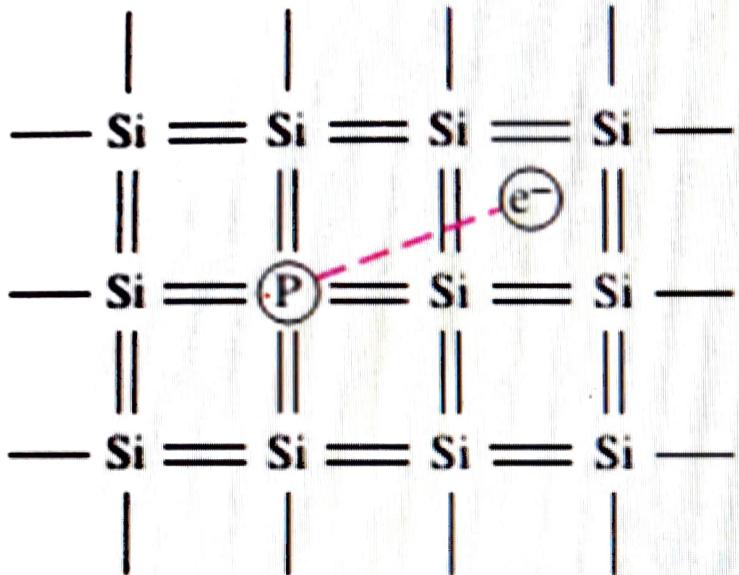


The breaking of a covalent bond for $T > 0$ K creating an electron in the conduction band and a positively charged "empty state"

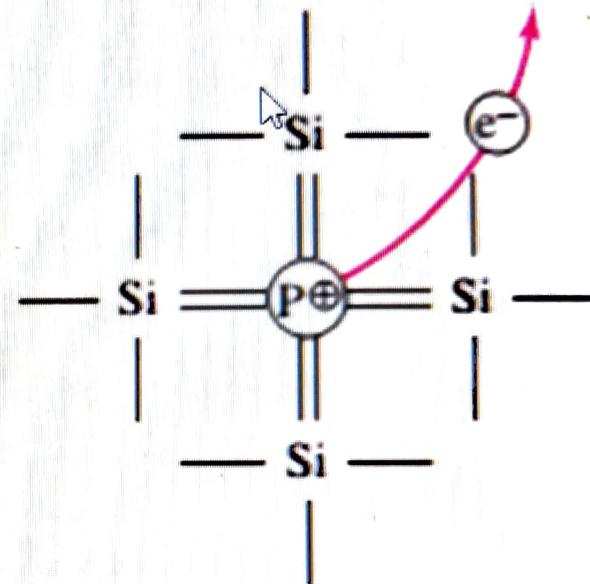
Extrinsic Semiconductors

- the electron and hole concentrations in an intrinsic semiconductor are relatively small
 - The resulting currents are small
- The carrier concentrations can be greatly increased by adding controlled amounts of certain impurities
 - To enhance currents
- Doping: The process of adding impurities
- Semiconductors added with impurity atoms are called **extrinsic semiconductors, or doped semiconductors**
- For silicon, the desirable substitutional impurities are from the group III and V elements of periodic table
- Group V: Phosphorous, Arsenic
- Group III: Boron

n-type semiconductor



Two-dimensional
representation of
a silicon lattice
doped with a
phosphorus
atom and valence
electron
 e^- mobile carrier

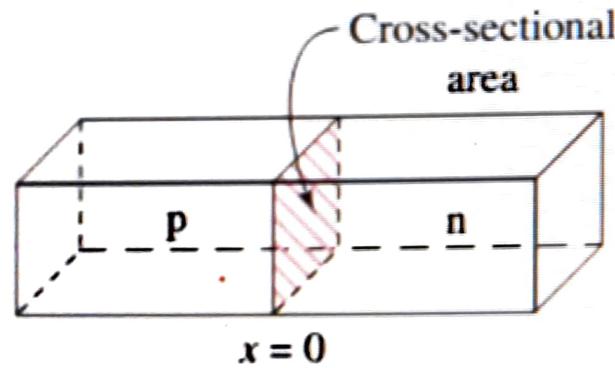


the resulting
positively charged
phosphorus ion
after the fifth
valence electron
has moved into the
conduction band
 P^+ immobile ion

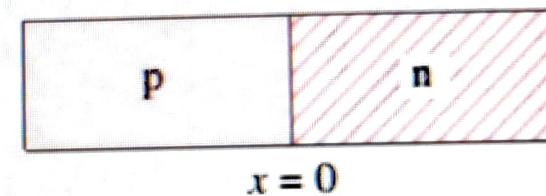
The pn Junction

Operation with Open-Circuit Terminals

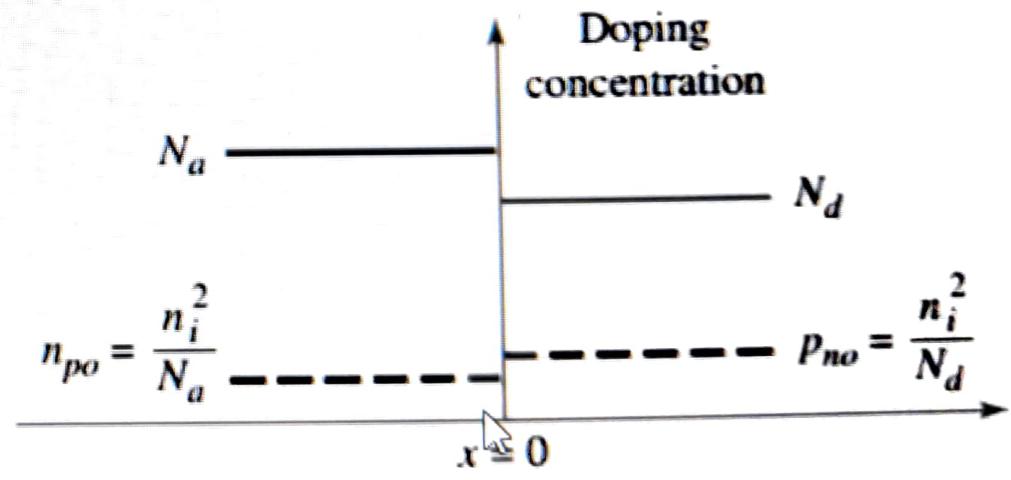
- The interface at $x = 0$ is called the **metallurgical junction**



3D representation showing
the cross-sectional area



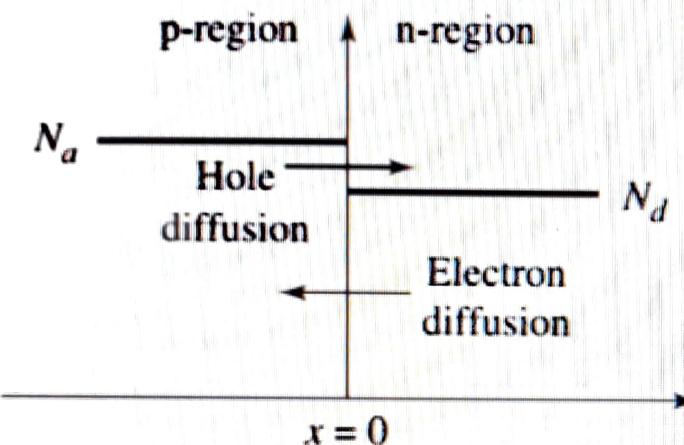
simplified 1D geometry



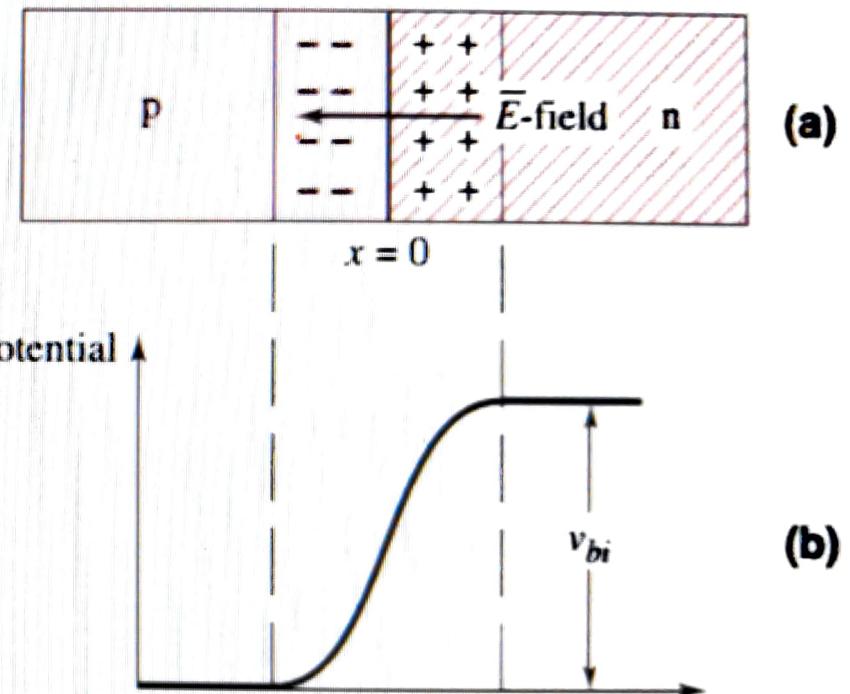
doping profile

The pn Junction

Operation with Open-Circuit Terminals



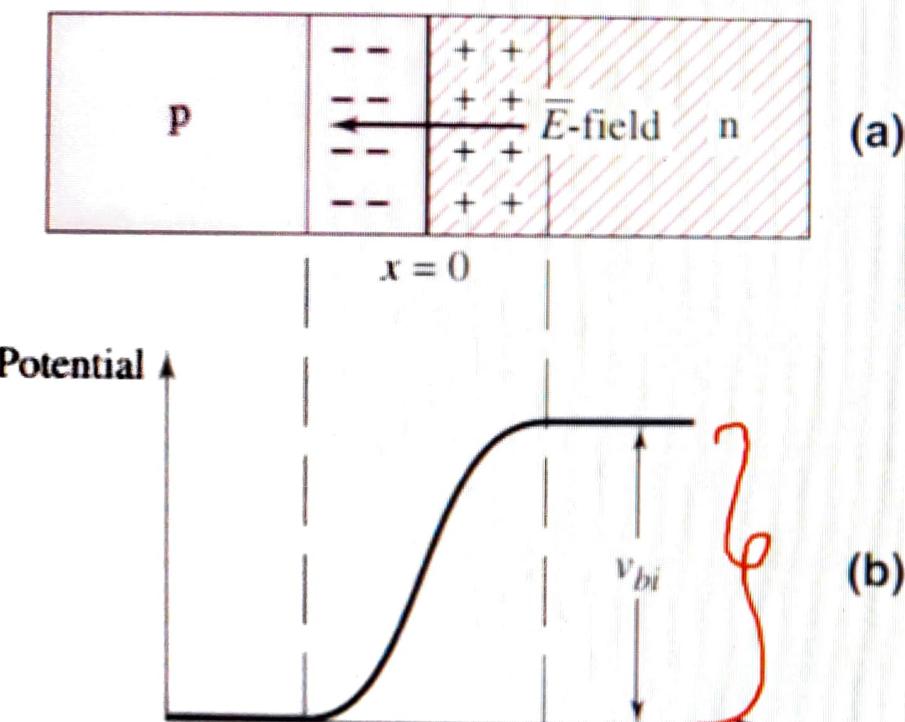
Initial diffusion of holes and electrons



The pn junction in thermal equilibrium.

- (a) The space charge region with negatively charged acceptor ions in the p-region and positively charged donor ions in the n-region; the resulting electric field from the n- to the p-region.
- (b) The potential through the junction and the built-in potential barrier V_{bi} across the junction.

Built-in potential



Barrier

The pn Junction

Operation with Open-Circuit Terminals

- Diffusion of holes from the p-region into the n-region, and a diffusion of electrons from the n-region into the p-region
- The flow of holes from the p-region results in negatively charged acceptor ions
- The flow of electrons from the n-region results in positively charged donor ions
- Diffusion results in charge separation, which sets up electric field
- The positively charged region and the negatively charged region comprise the **space-charge** region, or **depletion region**
 - no mobile electrons or holes
- Because of the electric field in the space charge region, there is a potential difference across that region
- This potential difference is called the **built-in potential barrier**, or **built-in voltage**

$$V_{bi} = \frac{kT}{e} \ln\left(\frac{N_a N_d}{n_i^2}\right) = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

Objective: To calculate the built-in potential barrier of a pn junction

Problem: Consider a silicon pn junction at $T = \underline{300} \text{ K}$, doped at $N_a = 10^{16} \text{ cm}^{-3}$ in the p-region and $N_d = 10^{17} \text{ cm}^{-3}$ in the n-region.

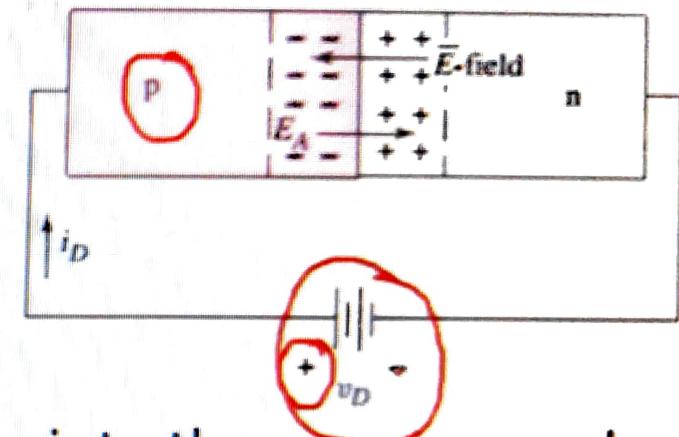
Solution:

$n_i = 1.5 \times 10^{10} \text{ cm}^{-3}$ for silicon at room temperature

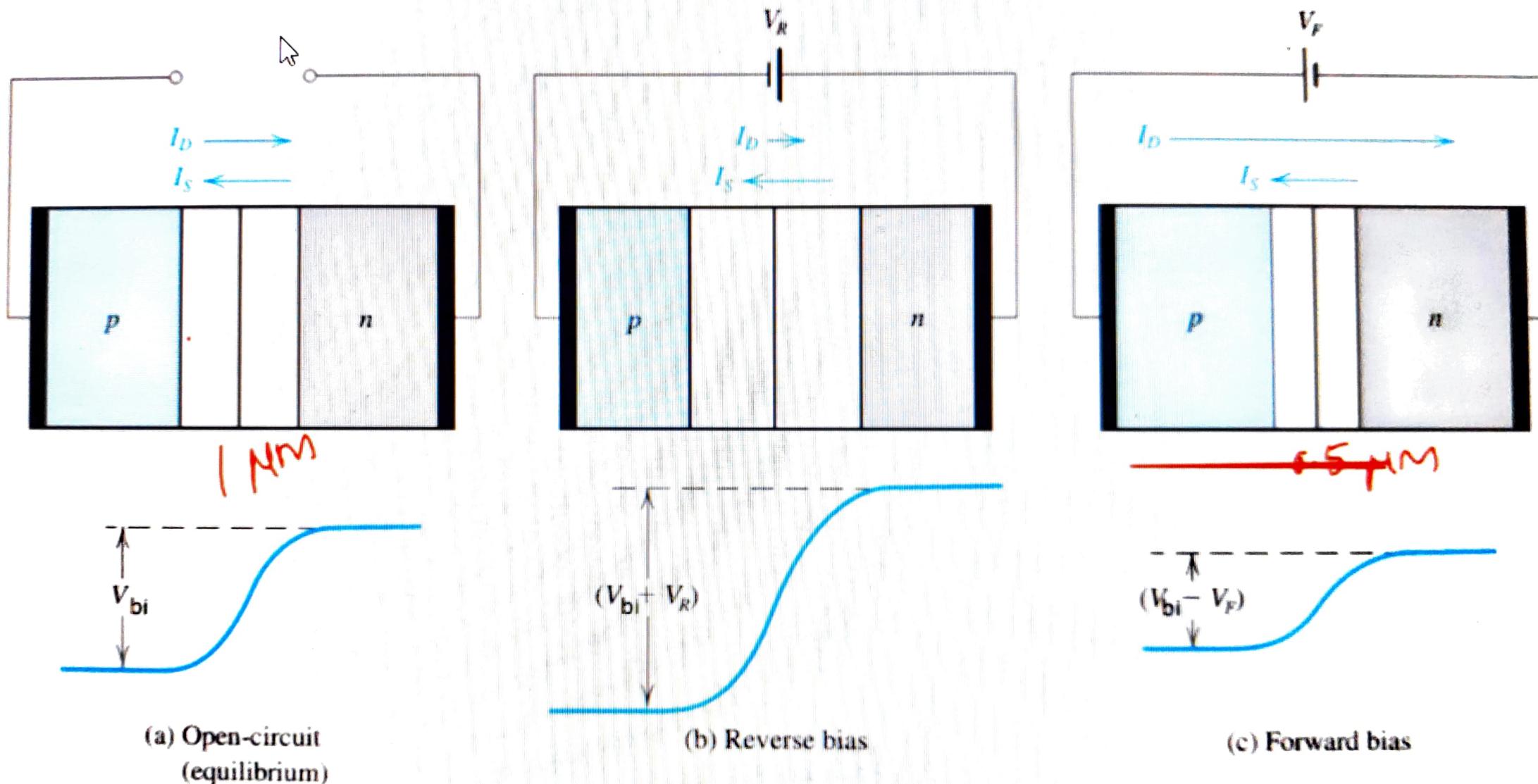
$$V_{bi} = V_T \ln \left[\frac{N_a N_d}{n_i^2} \right] = 0.026 \ln \left[\frac{10^{16} \times 10^{17}}{(1.5 \times 10^{10})^2} \right] = 0.757 \text{ V}$$

Forward-Biased pn Junction

- If a positive voltage v_D is applied to the p-region and negative voltage to n-region then the diode is forward biased
- Majority carrier electrons from the n-region diffuse into the p-region, and majority carrier holes from the p-region diffuse into the n-region
- Width of the space charge region decreases compared to equilibrium width of the space charge region



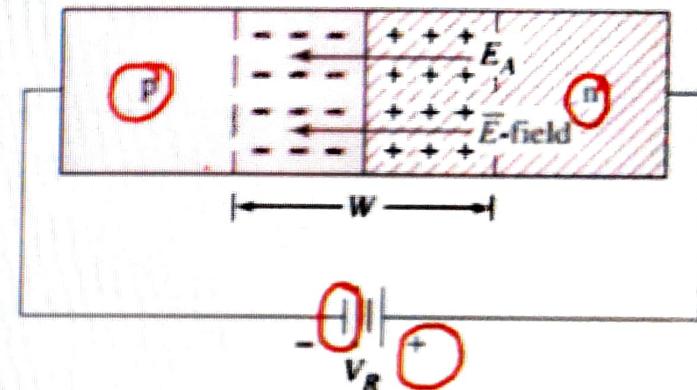
pn junction summary



The *pn* junction in: **(a)** equilibrium; **(b)** reverse bias; **(c)** forward bias

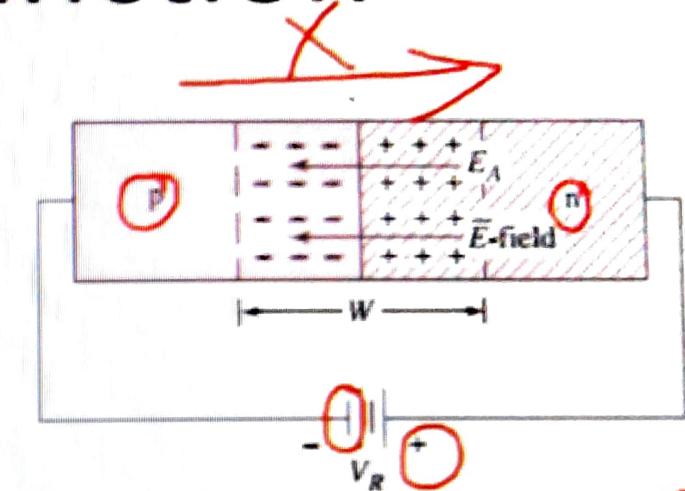
Reverse-Biased pn Junction

- When a positive voltage is applied to the n-region and negative voltage is applied to the p-region of a pn junction, then the diode is said to be reverse biased
- This increased electric field holds back the holes in the p-region and the electrons in the n-region, so there is essentially no current across the pn junction.
- Width of the space charge region increases compared to equilibrium width of the space charge region

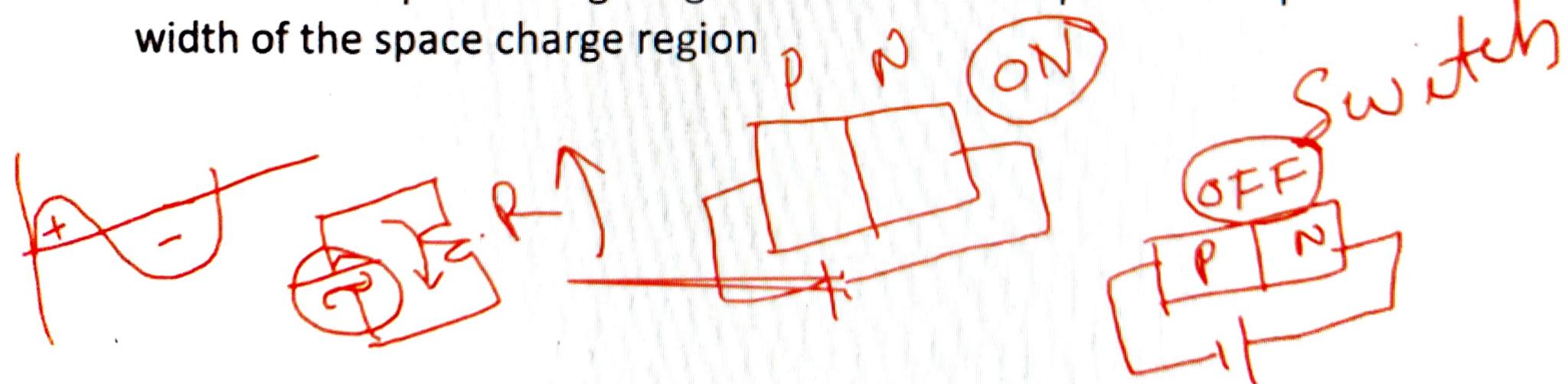


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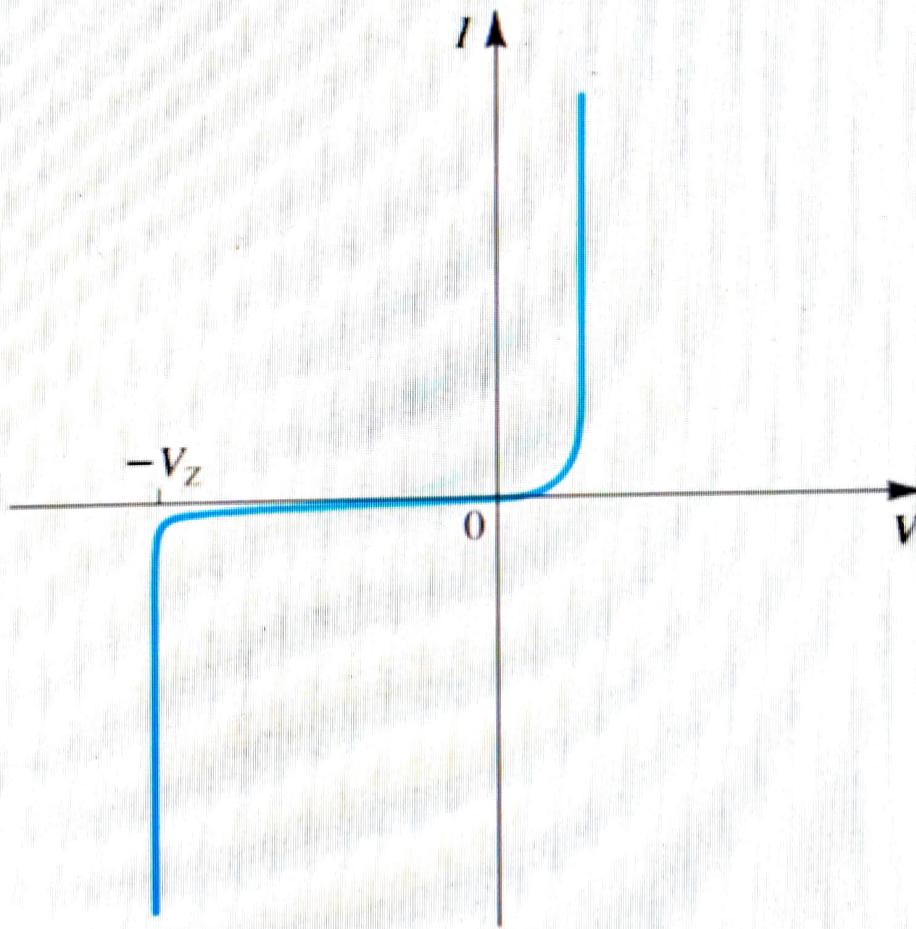
Ideal Current–Voltage Relationship of diode



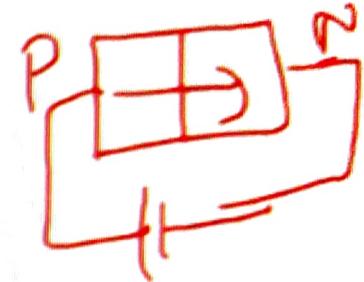
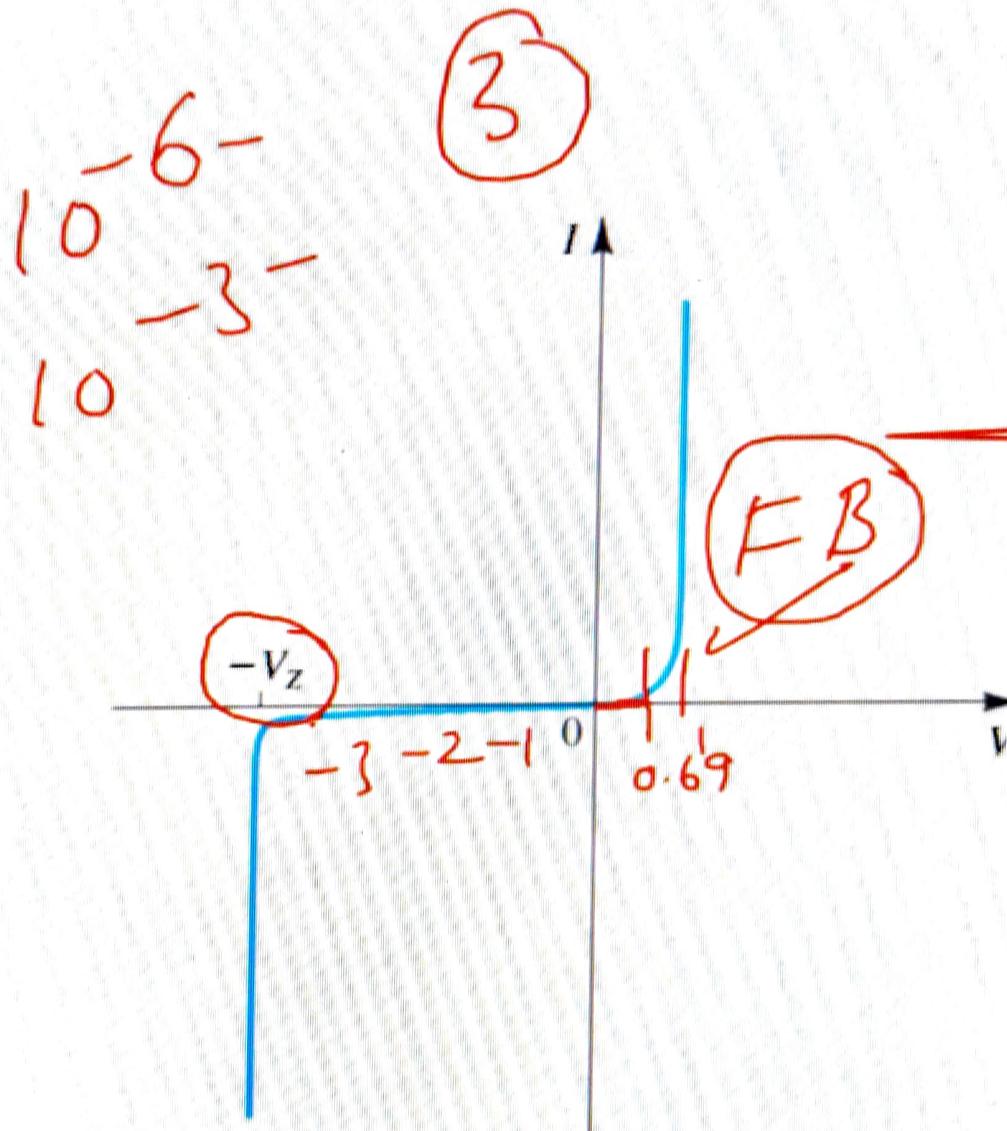
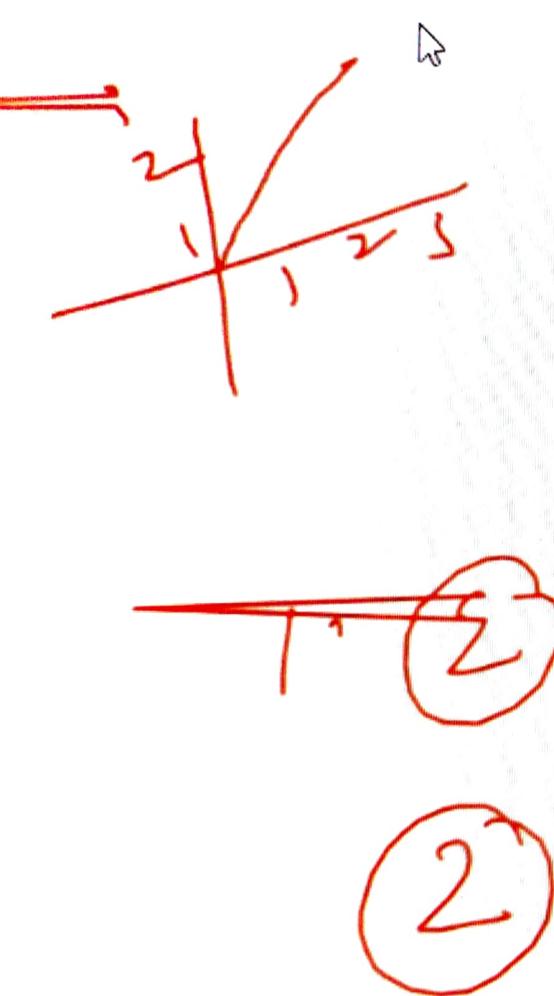
$$i_D = I_S \left(e^{\frac{v_D}{V_T}} - 1 \right) \approx I_S e^{\frac{v_D}{V_T}}$$

- I_S is the **reverse-bias saturation current**. For silicon pn junctions, typical values of I_S are in the range of 10^{-18} to 10^{-12} A
- The parameter V_T is the **thermal voltage**
- Nonlinear rectifying current characteristics

I-V characteristics of diode



I-V characteristics of diode



$$0.69 \approx 0A$$

$$0.7 \approx mA$$

$$\frac{0.7}{0.71} \approx mA$$

$$\frac{0.75}{0.75} = 100mA$$

half-wave rectifier

