Semiconductor devices

Material classification

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

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

Material classification

Gold
O_2

- Material classification based on conductivity (σ)/resistivity (ρ)
  1 – Conductors $R = 0$
  3 – **Semiconductors**
  2 – Insulators $R = \infty$

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

Ca
water
carbon
P

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

General constants and conversion factors

Angstrom	Å	$1\ \text{Å} = 10^{-4}\ \mu\text{m} = 10^{-8}\ \text{cm} = 10^{-10}\ \text{m}$
Boltzmann's constant	k	$k = 1.38 \times 10^{-23}\ \text{J/K} = 8.6 \times 10^{-5}\ \text{eV/K}$
Electron–volt	eV	$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}$
Electronic charge	e or q	$q = 1.6 \times 10^{-19}\ \text{C}$
Micron	μm	$1\ \mu\text{m} = 10^{-4}\ \text{cm} = 10^{-6}\ \text{m}$
Mil		$1\ \text{mil} = 0.001\ \text{in.} = 25.4\ \mu\text{m}$
Nanometer	nm	$1\ \text{nm} = 10^{-9}\ \text{m} = 10^{-3}\ \mu\text{m} = 10\ \text{Å}$
Permittivity of free space	ε_o	$\varepsilon_o = 8.85 \times 10^{-14}\ \text{F/cm}$
Permeability of free space	μ_o	$\mu_o = 4\pi \times 10^{-9}\ \text{H/cm}$
Planck's constant	h	$h = 6.625 \times 10^{-34}\ \text{J–s}$
Thermal voltage	V_T	$V_T = kT/q \cong 0.026\ \text{V at 300 K}$
Velocity of light in free space	c	$c = 2.998 \times 10^{10}\ \text{cm/s}$

Semiconductor constants

$\varepsilon = \varepsilon_0$

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)

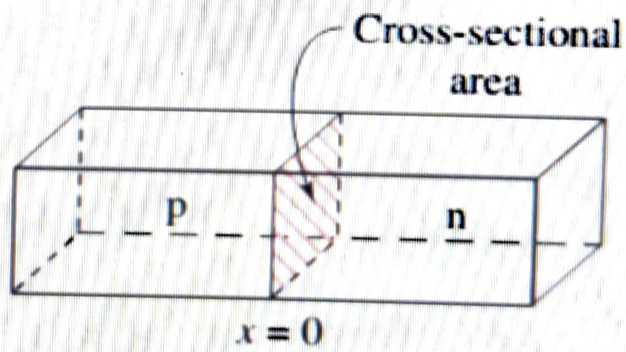
GaAs	**Gallium arsenide**
GaP	**Gallium phosphide**
AlP	**Aluminum phosphide**
AlAs	**Aluminum arsenide**
InP	**Indium phosphide**

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

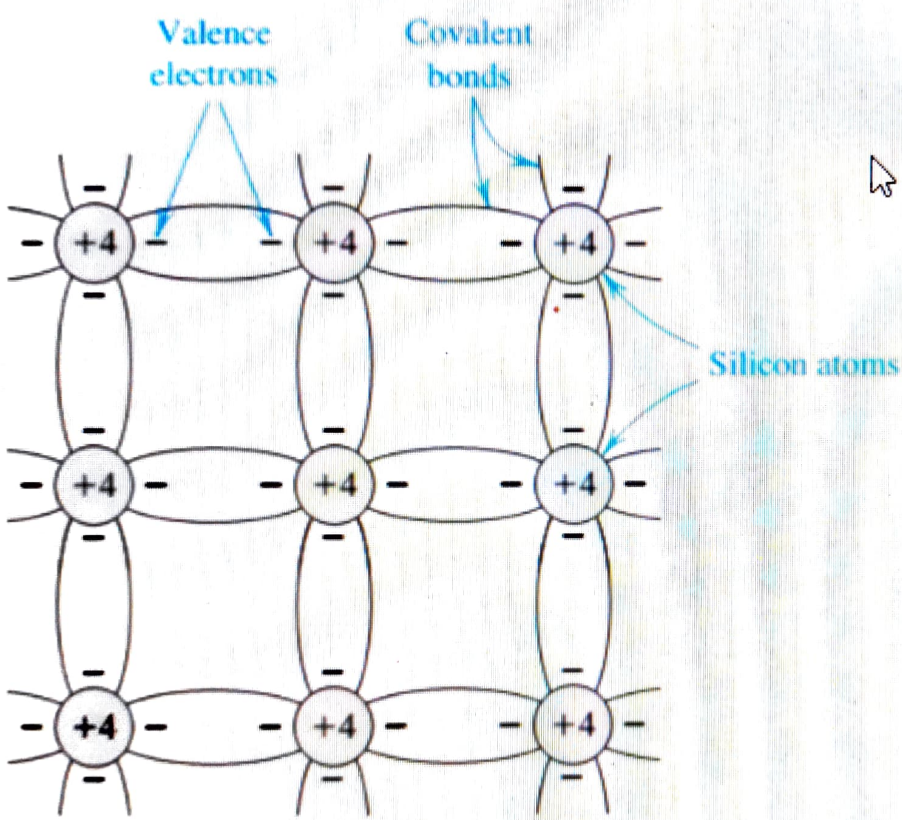
The pn Junction

- 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 $T = 0$ K

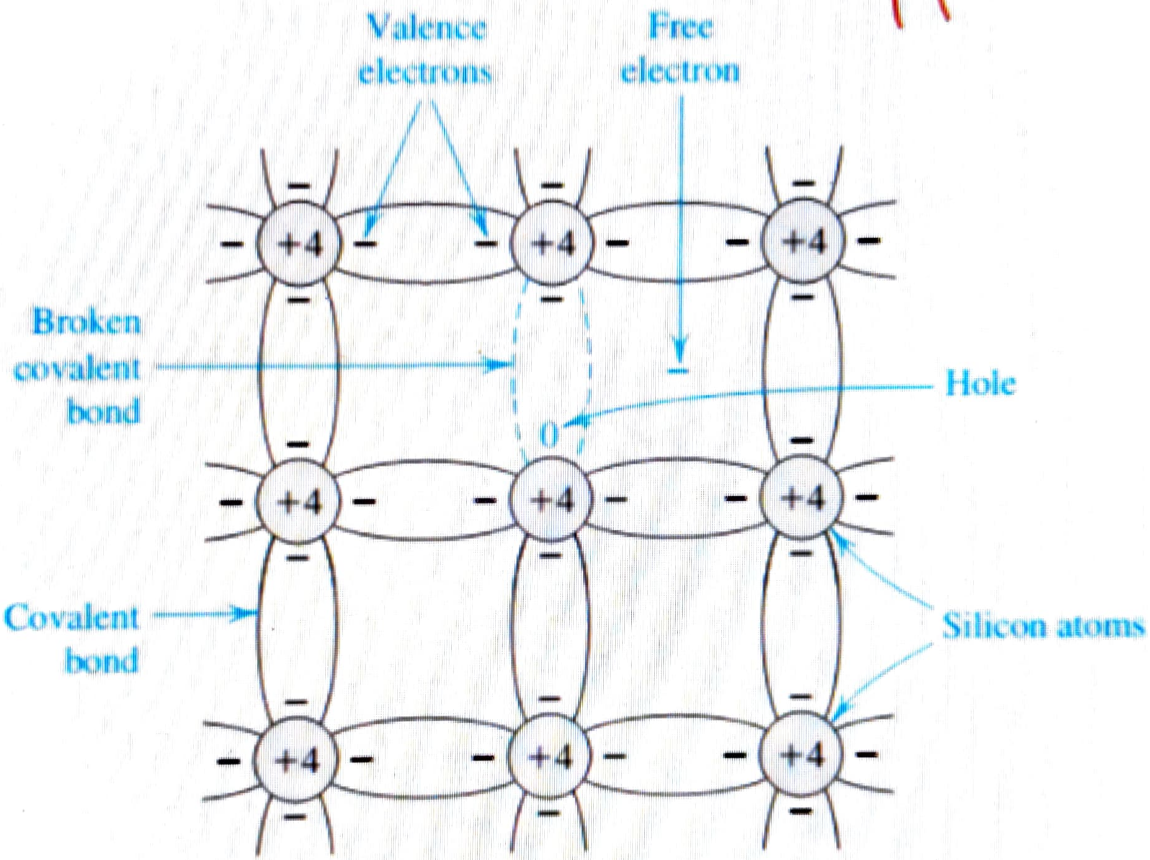


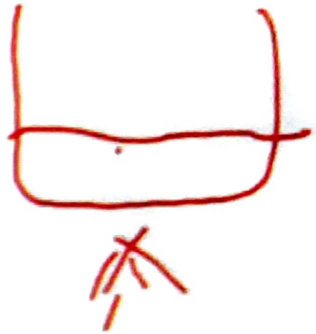
Silicon Lattice constant 5.43 Å

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

Silicon at $T > 0$ K

Heat energy



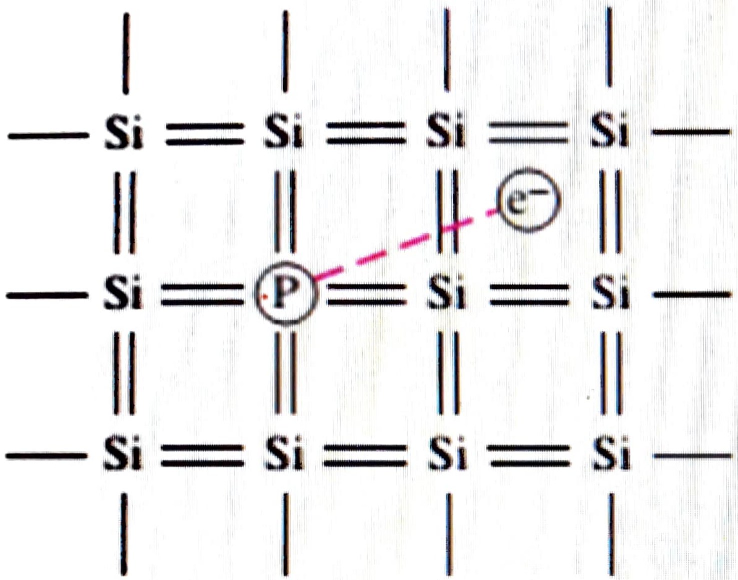


The breaking of a covalent bond for $T > 0$ K creating an electron in the conduction band and a positively charged "empty state"

Extrinsic Semiconductors

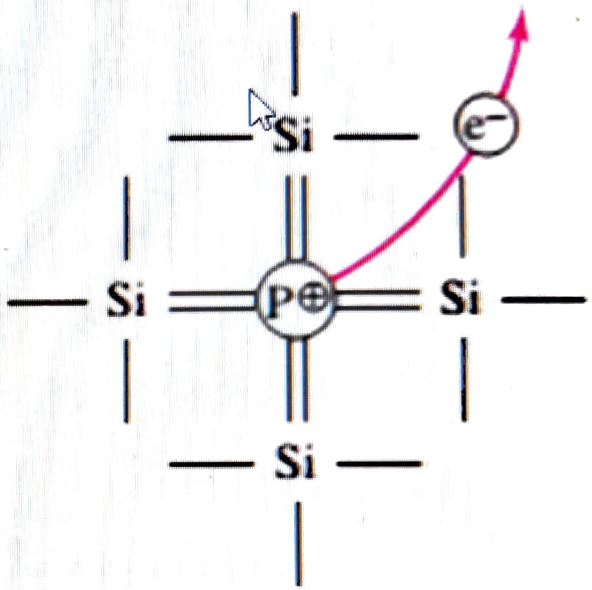
- the electron and hole concentrations in an intrinsic semiconductor are relatively small
  - The resulting currents are small
- The carrier concentrations can be greatly increased by adding controlled amounts of certain impurities
  - To enhance currents
- Doping: The process of adding impurities
- 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



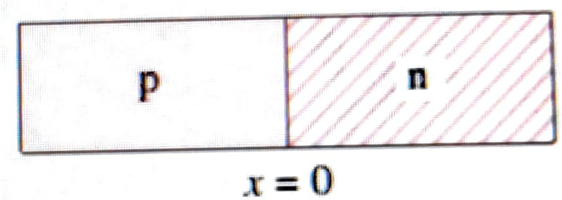
the resulting positively charged phosphorus ion after the fifth valence electron has moved into the conduction band

P⁺ immobile ion

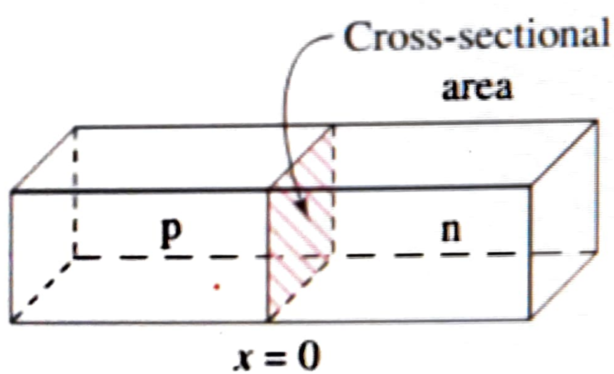
The pn Junction

Operation with Open-Circuit Terminals

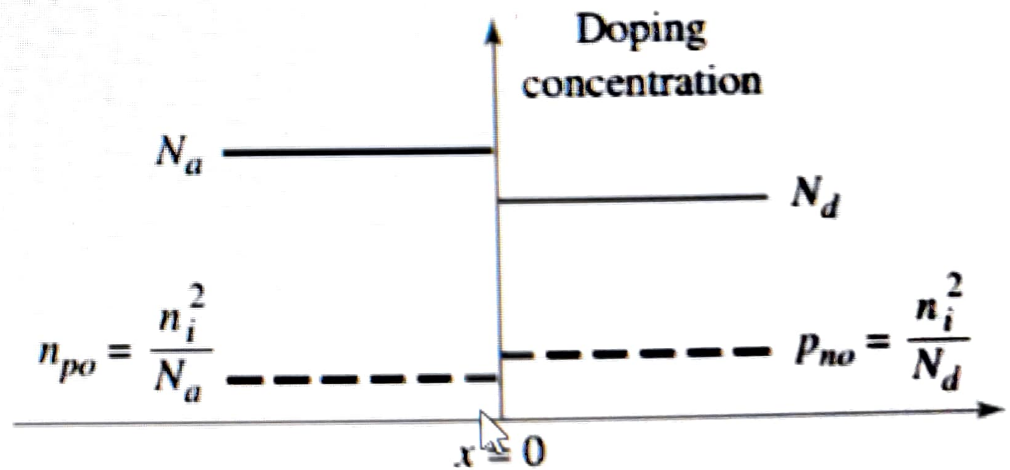
- The interface at $x = 0$ is called the **metallurgical junction**



simplified 1D geometry



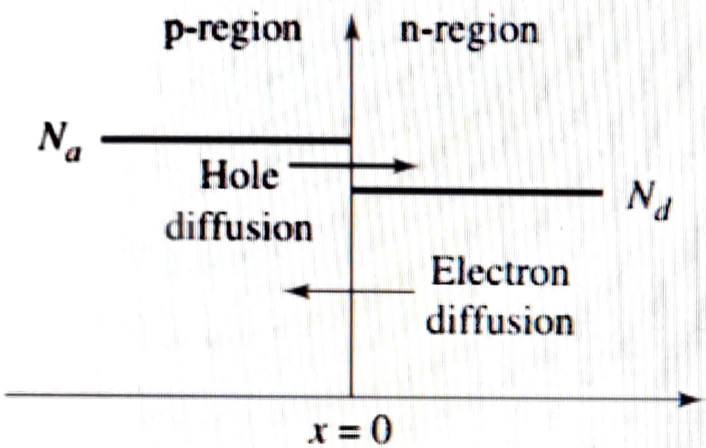
3D representation showing the cross-sectional area



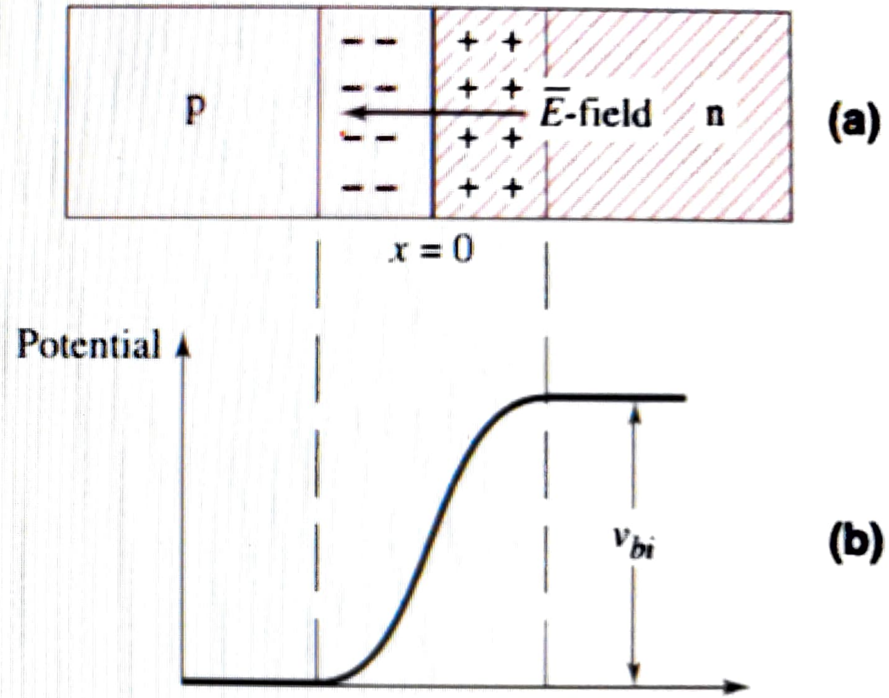
doping profile

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.

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 $T = 300$ K, doped at $N_a = 10^{16}$ cm^{-3} in the p-region and $N_d = 10^{17}$ cm^{-3} in the n-region.

Solution:

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

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