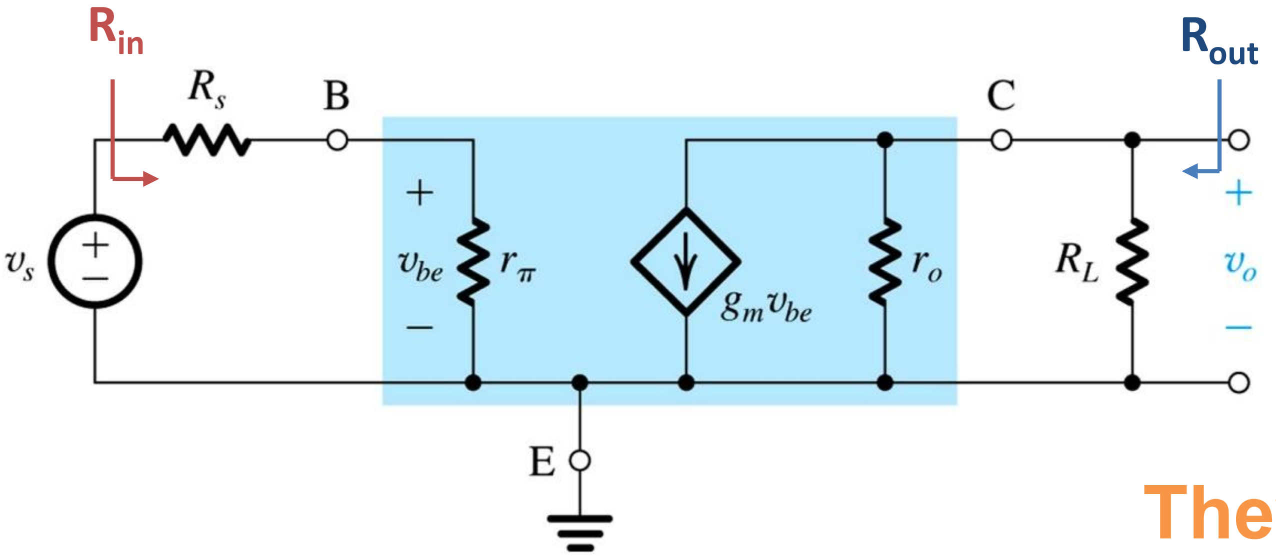
Last Lecture → Input / Output Resistance



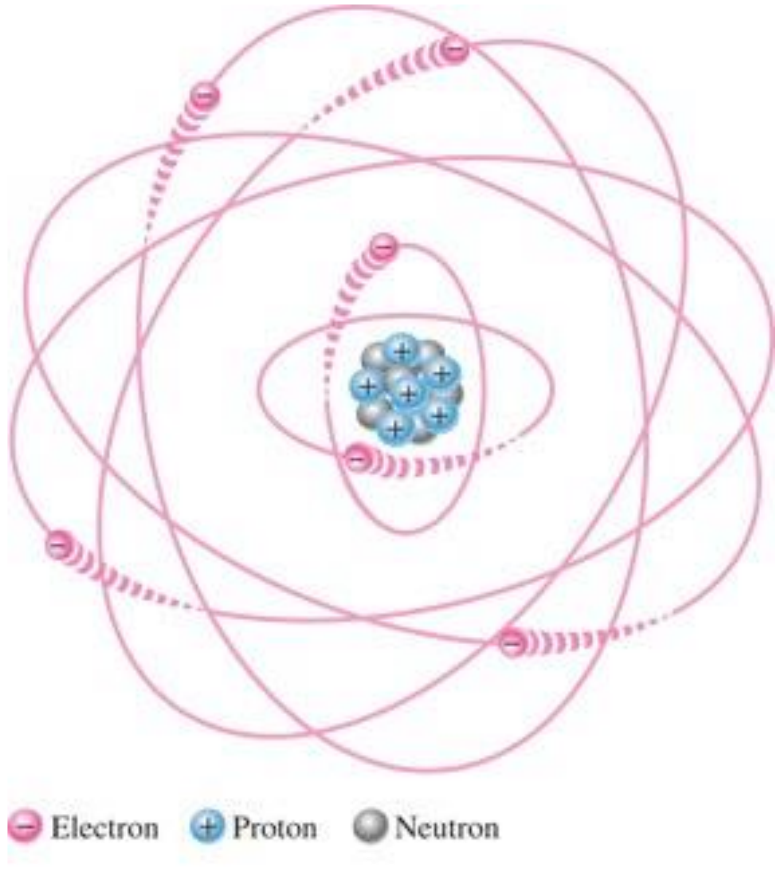
R_{in} → input impedance

R_{out} → output impedance

Thevenin's Resistance

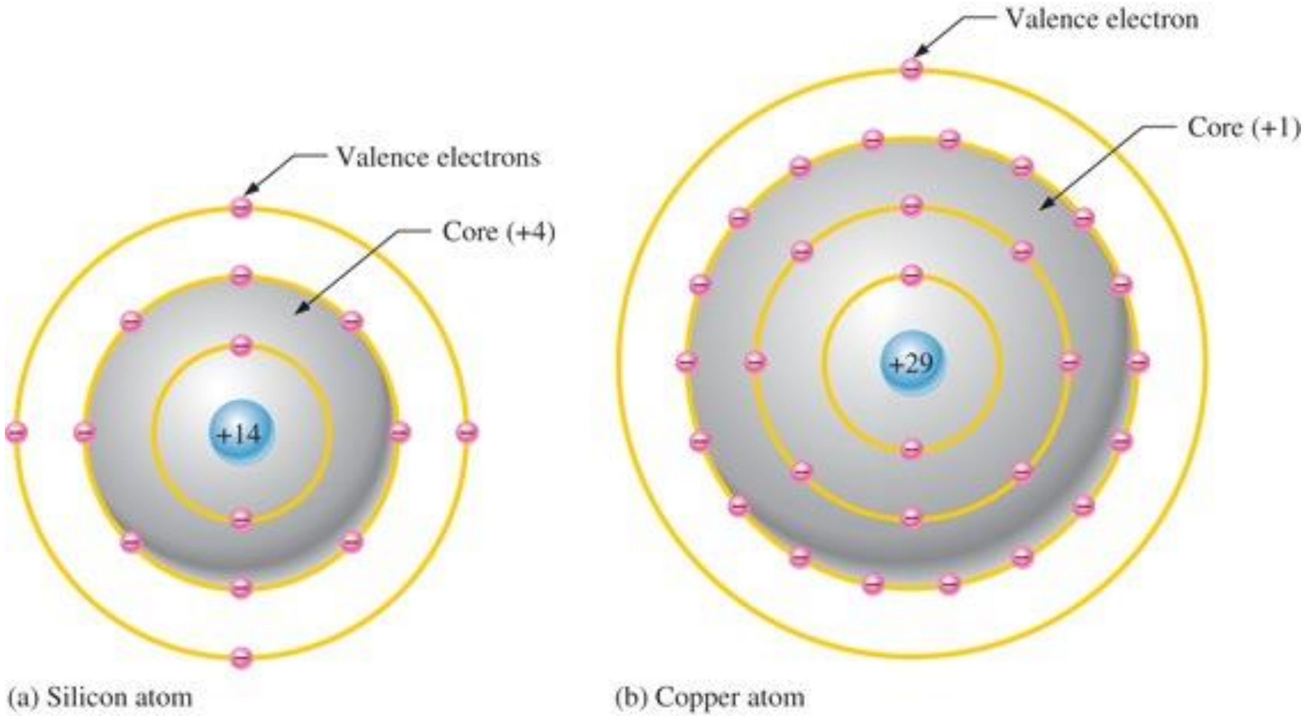
- No dependent Source
  - R_{th} → series / parallel combination
- Dependent Source
  - *Place test source V_x=1V at terminals*
  - $R_{th} = \frac{V_x}{I_x} = \frac{1}{I_x}$
- For R_{out} turn "off" input source!

Atom – Bohr Model → Chp. #3



… **electrons** move in orbits around the nucleus, which consists of **protons** and neutrons.

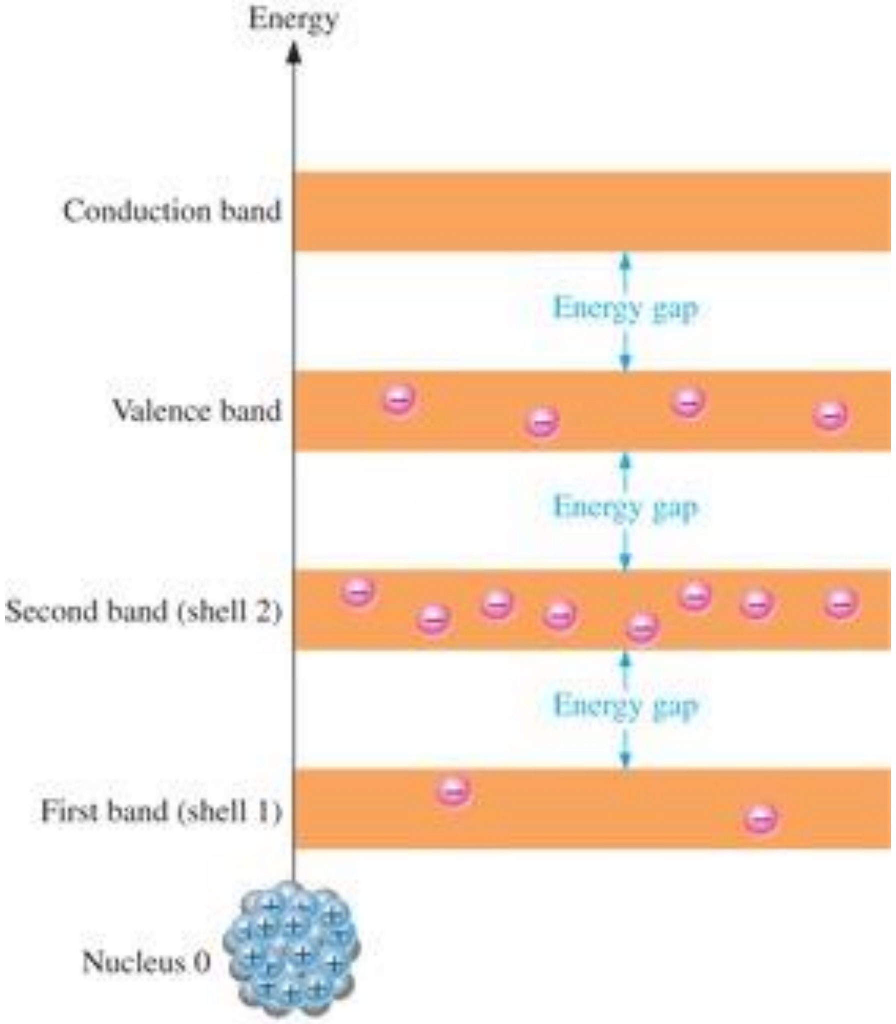
- Elements in the periodic table are grouped according to the number of **valence electrons.**
- **Valence electron** – an electron that participates in the formation of **chemical bonds**.



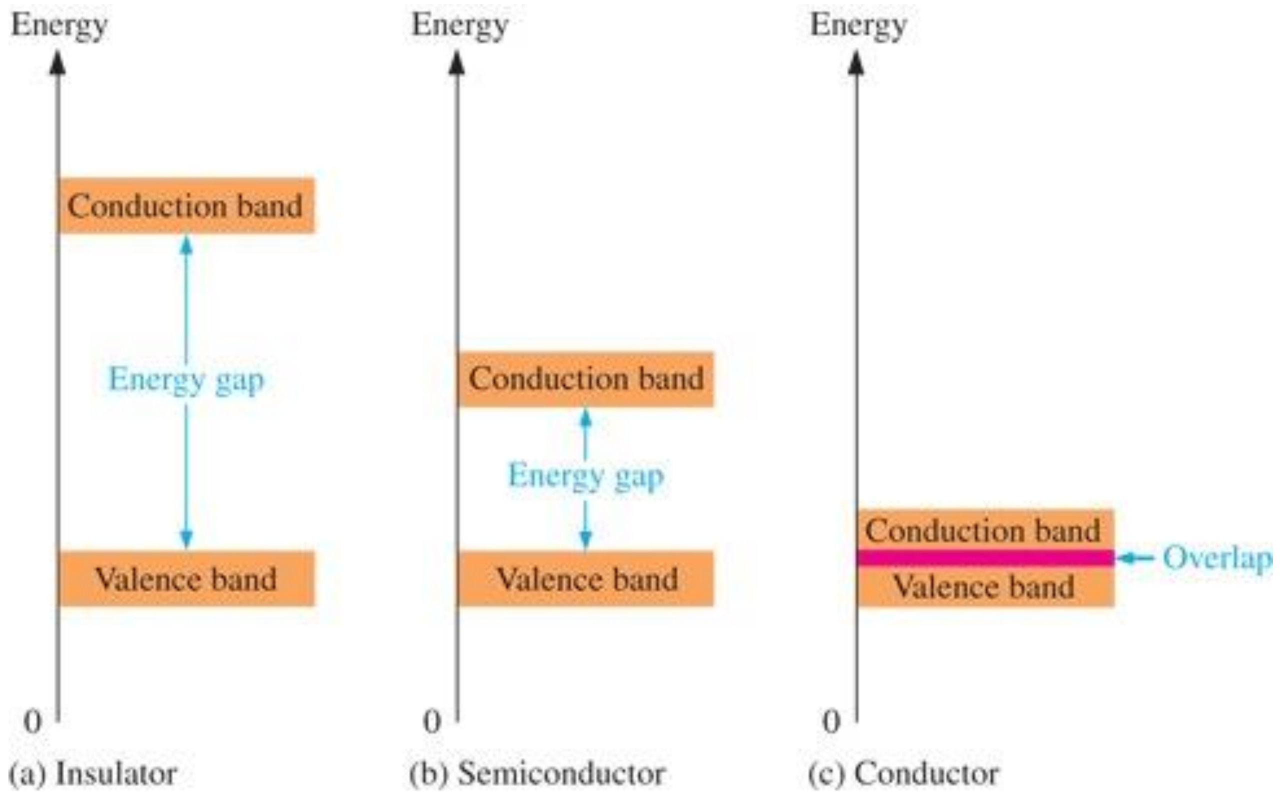
(a) Silicon atom

(b) Copper atom

Energy Diagram



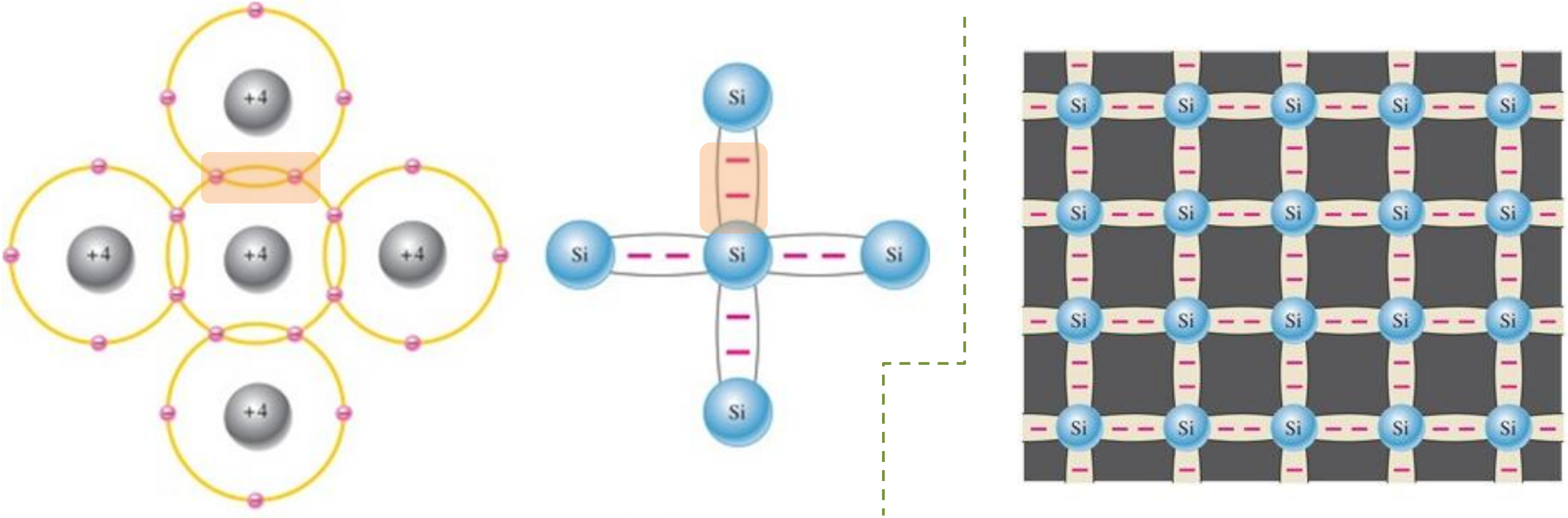
- **Energy Gap (Eg)** – minimum energy needed by a valence electron in order to jump into the conduction band.
- **Types of Material**



(a) Insulator
(b) Semiconductor
(c) Conductor

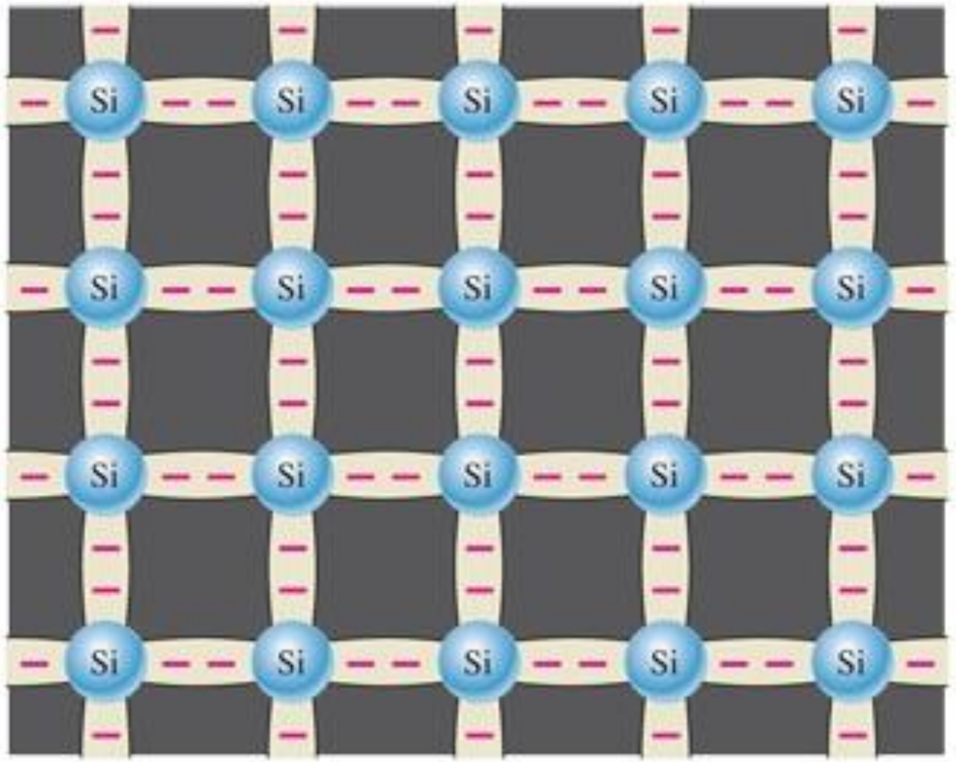
Covalent Bonds

- As silicon atoms come into proximity to each other , the valence electrons interact to from a crystal
- The **valence electrons are shared between atoms**, forming what are called **covalent bonds**, a stable balance of attractive and repulsive forces between atoms.



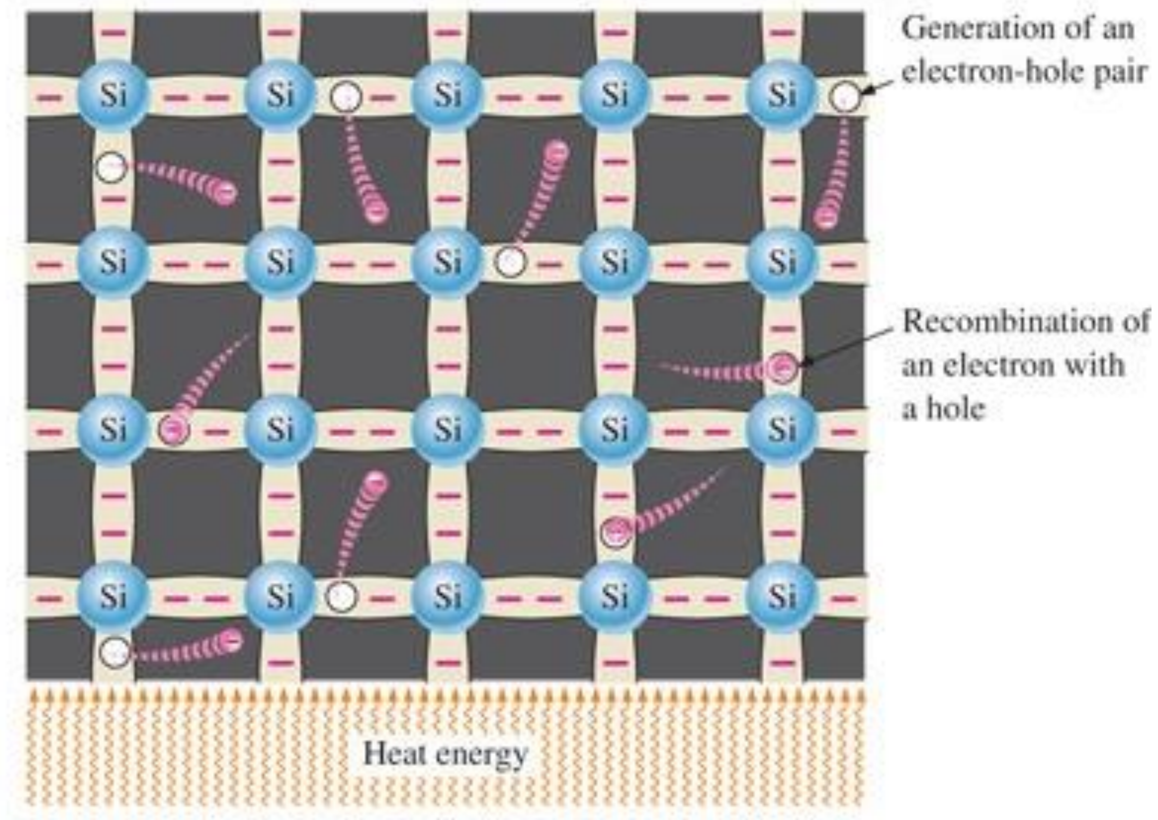
Silicon Crystal

@ low temp.



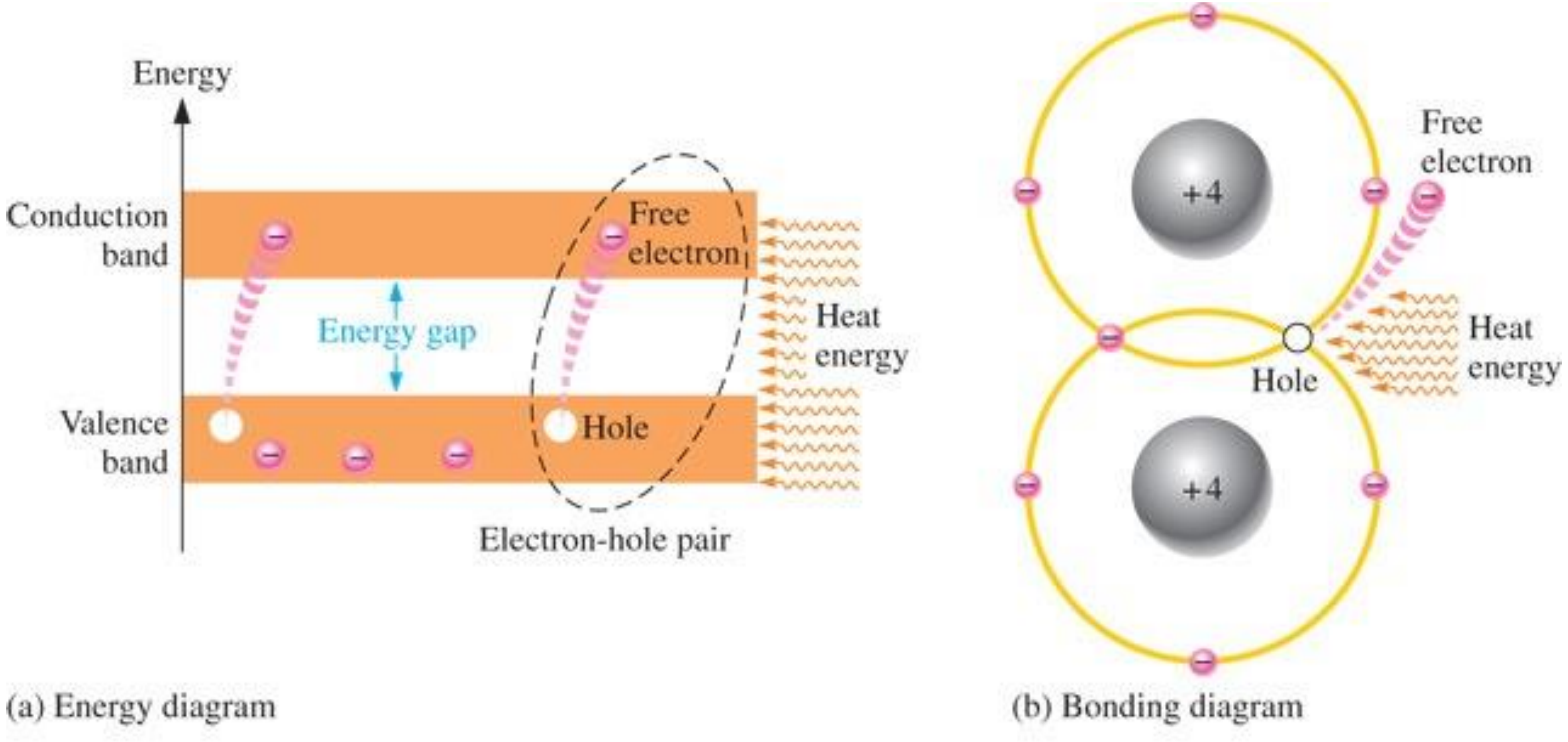
- All **covalent bonds** are intact
- No **electrons** are available for conduction
- **Conductivity** is zero

@ room temp.



- Some **covalent bonds** break
- Some **electrons** will become available for conduction
- **Conductivity** is greater than zero

Hole – Electron Pair Creation



(a) Energy diagram

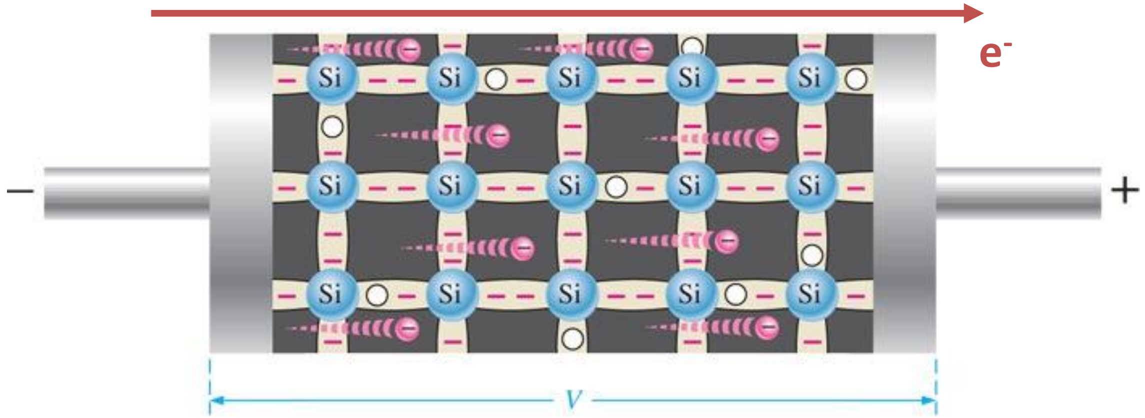
(b) Bonding diagram

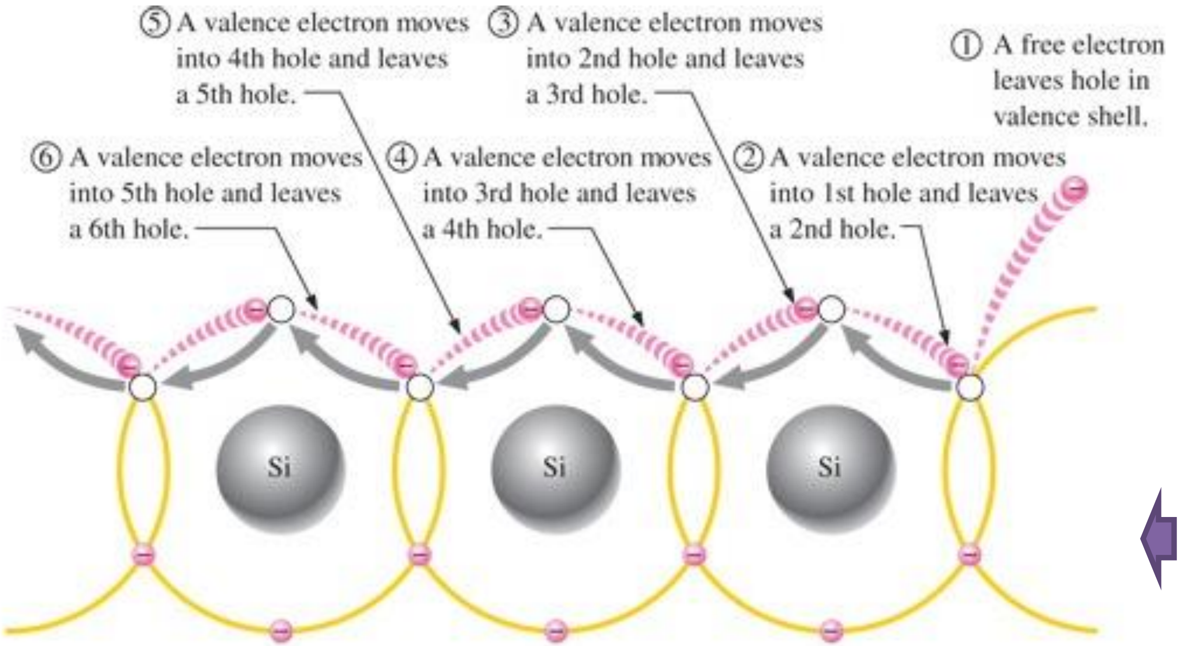
The process of freeing electrons, creating holes, and filling them **facilitates current flow**…

Electron / Hole Current

Electron Current

- Movement of **free electrons** in the **conduction band**





When a valence electron moves left to right to fill a hole while leaving another hole behind, the hole has effectively moved from right to left. Gray arrows indicate effective movement of a hole.

Hole Current

- Movement of electrons in the **valence band**

Silicon Crystal → Intrinsic Charge Concentration

- **concentration of free electrons → n**
- **concentration of free holes → p**

$$n = p = n_i$$

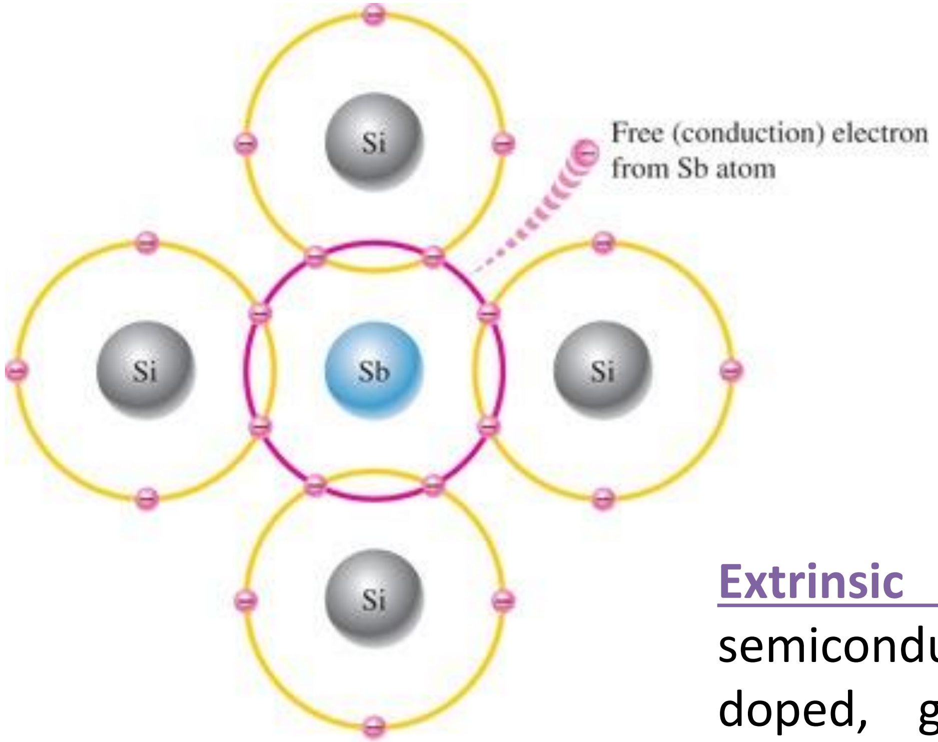
$$np = {n_i}^2$$

number of free electrons and holes in a unit volume (cm^3) of intrinsic silicon at a given temperature

$$n_i = BT^{3/2}e^{-E_g/2kT}$$

- **material-dependent parameter → B**
- **bandgap energy → E_g**
- **Boltzmann's constant → k**
- **Temperature → T**

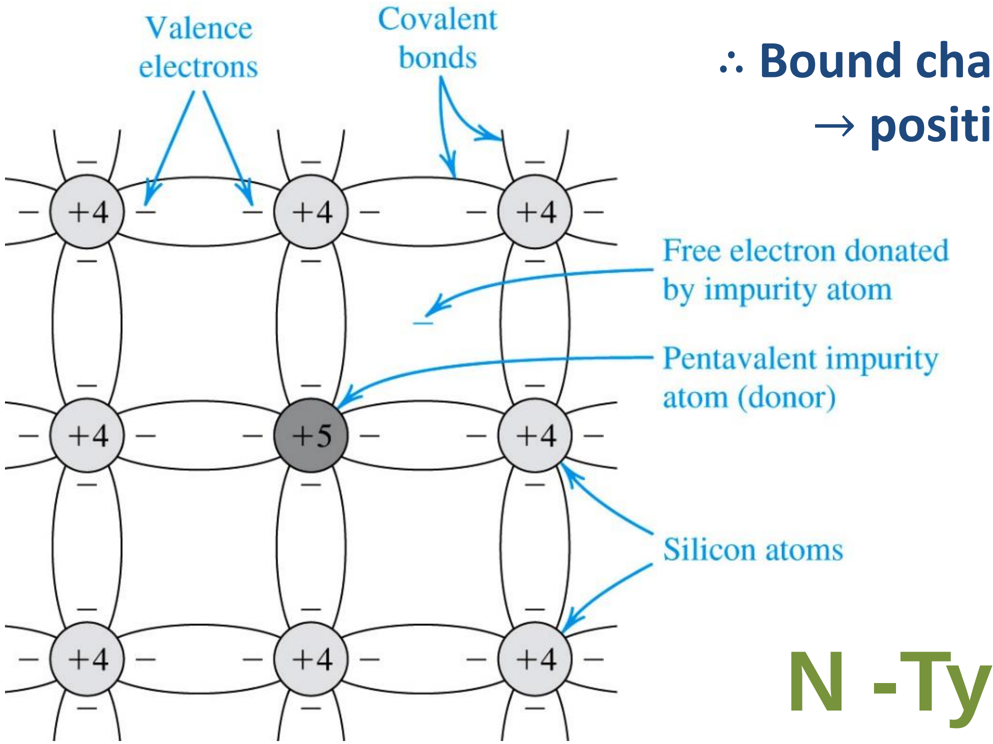
Doping: addition of impurities to the intrinsic semi-conductive material. Increases the number of current carriers.



Extrinsic Semiconductor: a semiconductor that has been doped, giving it different electrical properties

Semiconductor Types

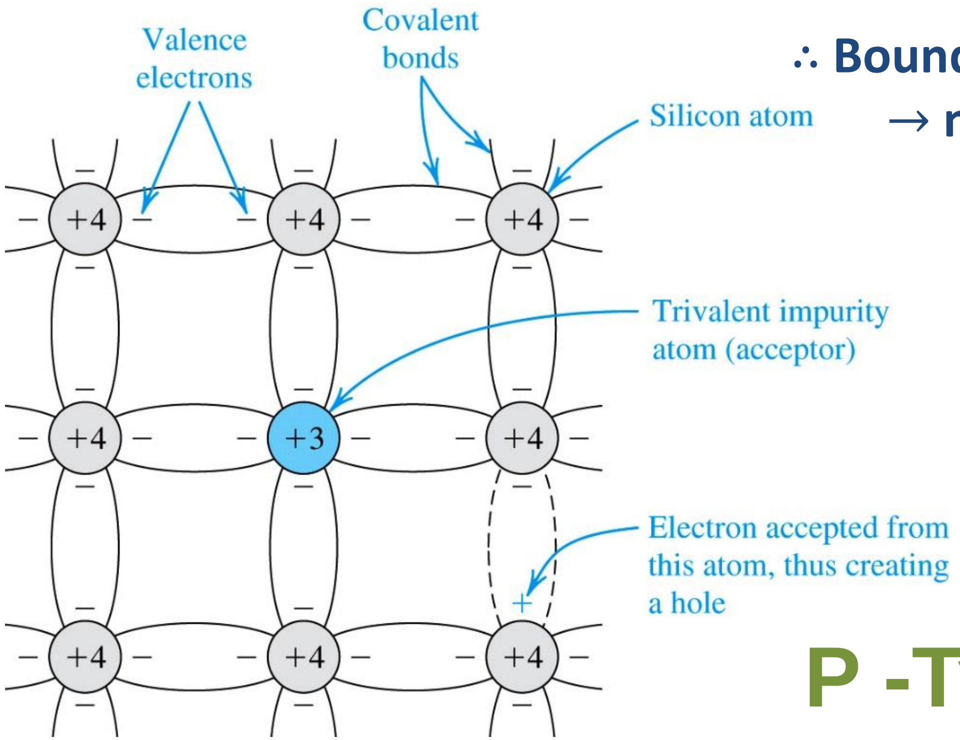
- **Antimony (Sb) – 5 Valence Electrons**
- **n-type: electrons >> holes**
  - **Majority carriers – electrons**
  - **Minority carriers - holes**



∴ Bound charge → positive

N -Type

- **Boron (B) – 3 Valence Electrons**
- **p-type: holes >> electrons**
  - **Majority carriers – holes**
  - **Minority carriers - electrons**



∴ Bound charge → negative

P -Type

Semiconductor Types

N -Type Semiconductor

- concentration of <u>donor</u> atoms ⟶ N_D
- concentration of free electrons in the n-type silicon ⟶ $n_n \simeq N_D$

$$\therefore\ p_n \simeq \frac{{n_i}^2}{N_D}$$

P -Type Semiconductor

- concentration of <u>acceptor</u> atoms ⟶ N_A
- concentration of holes in the p-type silicon ⟶ $p_p \simeq N_A$

$$\therefore\ n_p \simeq \frac{{n_i}^2}{N_A}$$

A piece of n-type or p-type silicon is electrically neutral; the charge of the majority free carriers are neutralized by the bound charges associated with the impurity atoms.

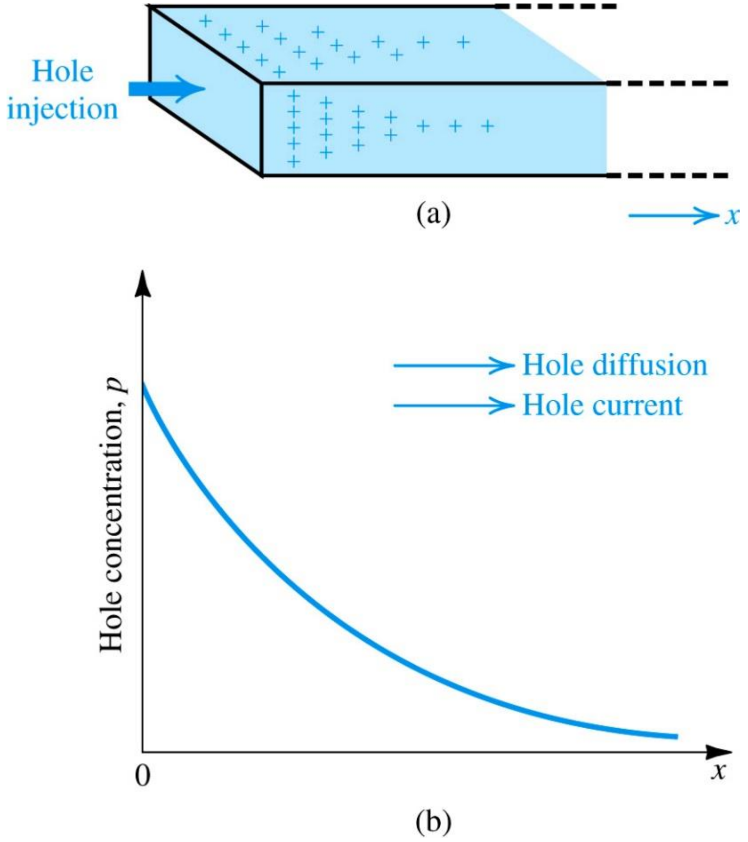
Exercise 3.3:

For silicon crystal doped with boron, what must N_A be if at T=300K the electron concentration drops below the intrinsic level by a factor of 10^6?

$B=7.3\text{x}10^{15}\ cm^{-3}K^{-3/2}$, $E_g=1.12\ eV$, $k=8.62\text{x}10^{-5} eV/K$

Current Flow in Semiconductors

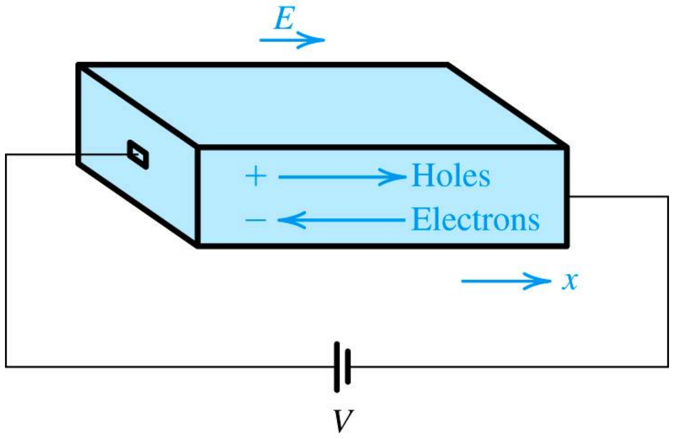
… there are two distinctly different mechanisms for the movement of charge carriers and hence for current flow in semiconductors: *drift* and *diffusion*



Drift Current

When and electrical field E is established in a semiconductor crystal…

- *Holes are accelerated in the direction of E!*
- *Free electrons are accelerated in the direction opposite of E!*



Diffusion Current

When the density of charge carrier in a piece of semiconductor is not uniform…

- *Charge carriers will diffuse from the region of high concentration to the region of low concentration!*

Current Flow in Semiconductors

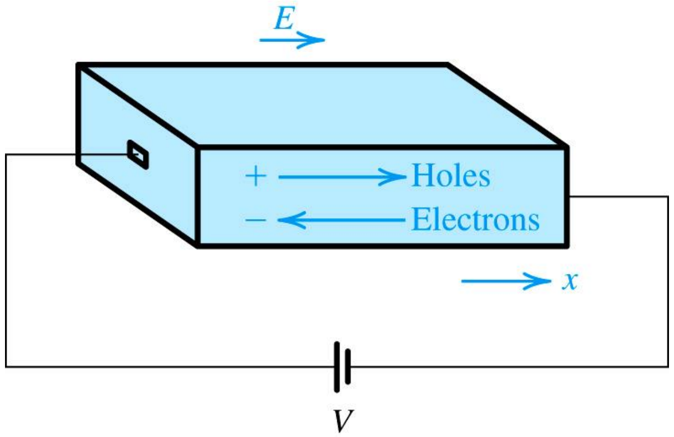
8/19/2019

… there are two distinctly different mechanisms for the movement of charge carriers and hence for current flow in semiconductors: *drift* and *diffusion*

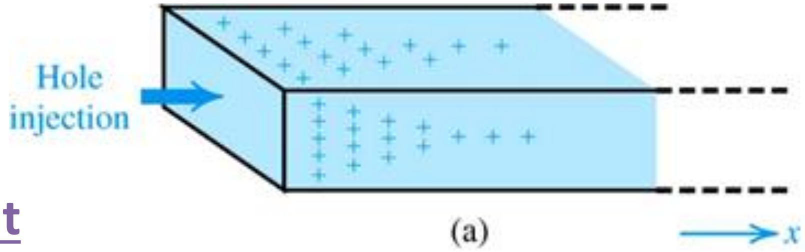
Drift Current

$$J_{drift} = J_{p-drift} + J_{n-drift}$$

$$= qp\mu_p E + qn\mu_n E = q(p\mu_p + n\mu_n)E$$



- J_x → current density [A/cm^3]
- μ_p → hole mobility [cm^2/V·s]
- μ_n → electron mobility [cm^2/V·s]
- D_p → hole diffusion constant [cm^2/s]
- D_n → electron diffusion constant [cm^2/s]



Diffusion Current

$$J_{diff} = J_{p-diff} + J_{n-diff}$$

$$= -qD_p\frac{dp(x)}{dx} - qD_n\frac{dn(x)}{dx}$$

- Ohm's Law [A/cm^2] $\quad J = \sigma \mathrm{E}$
- Conductivity [1/ Ω·cm] $\quad \sigma = q(p\mu_p + n\mu_n)$
- Resistivity [Ω·cm] $\quad \rho = \dfrac{1}{q(p\mu_p + n\mu_n)}$

Problem 3.6

A young designer, aiming to develop intuition concerning conducting paths within an integrated circuit, examines the end-to-end resistance of a connecting bar 10µm long, 3µm wide, and 1µm thick, made of various materials. The designer considers:

a) intrinsic silicon
b) n-doped silicon with $N_D=10^{16}/cm^3$
c) n-doped silicon with $N_D=10^{18}/cm^3$
d) p-doped silicon with $N_A=10^{16}/cm^3$
e) Aluminum with resistivity of 2.8 µΩ·cm.

Find the resistance in each case. For intrinsic silicon use the data in Table 3.1. For doped silicon, assume $\mu_n=2.5\cdot\mu_p=1200 cm^2/V\cdot s$. (Recall that $R=\rho L/A$)

- Silicon $n_i = 1.5 \times 10^{10}\ /cm^3$
- $q = 1.6 \times 10^{-19}$ C

	n (1/cm³)	p (1/cm³)	ρ Ω·cm	R Ω
a)	$1.5\text{x}10^{10}$	$1.5\text{x}10^{10}$	$227\text{x}10^{3}$	7.57M
b)	10^{16}	$2.25\text{x}10^{4}$	0.463	15
c)	10^{18}	$2.25\text{x}10^{2}$	4.63m	0.15
d)	$2.25\text{x}10^{4}$	10^{16}	0.768	25.6
e)	-	-	2.8µ	93.3µ