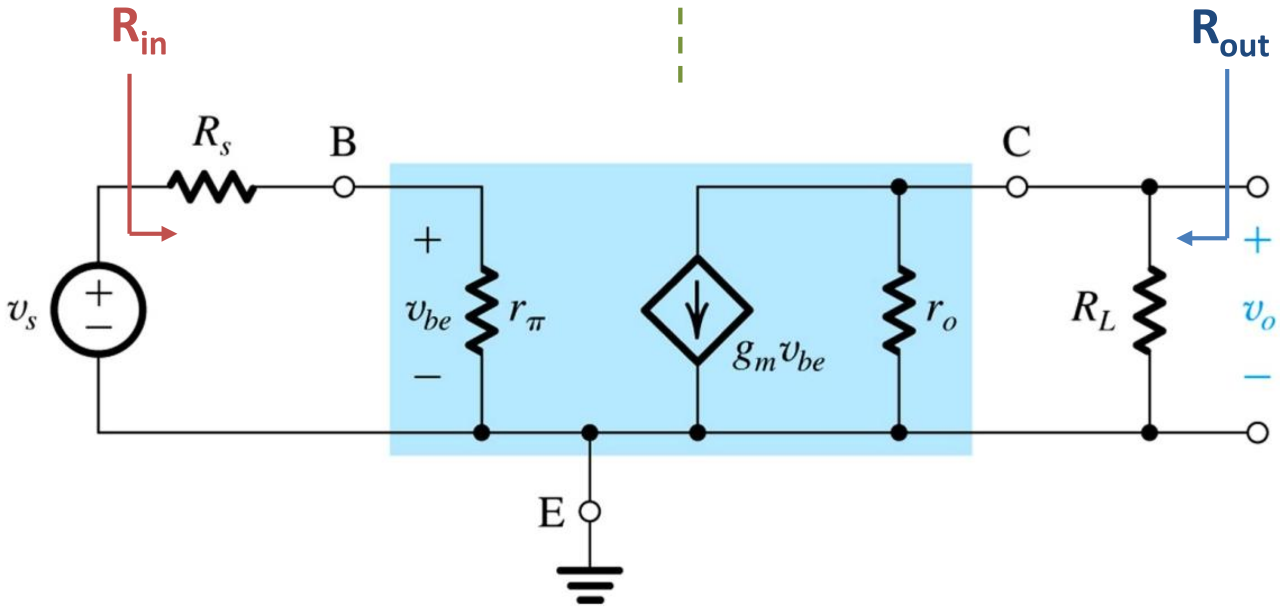
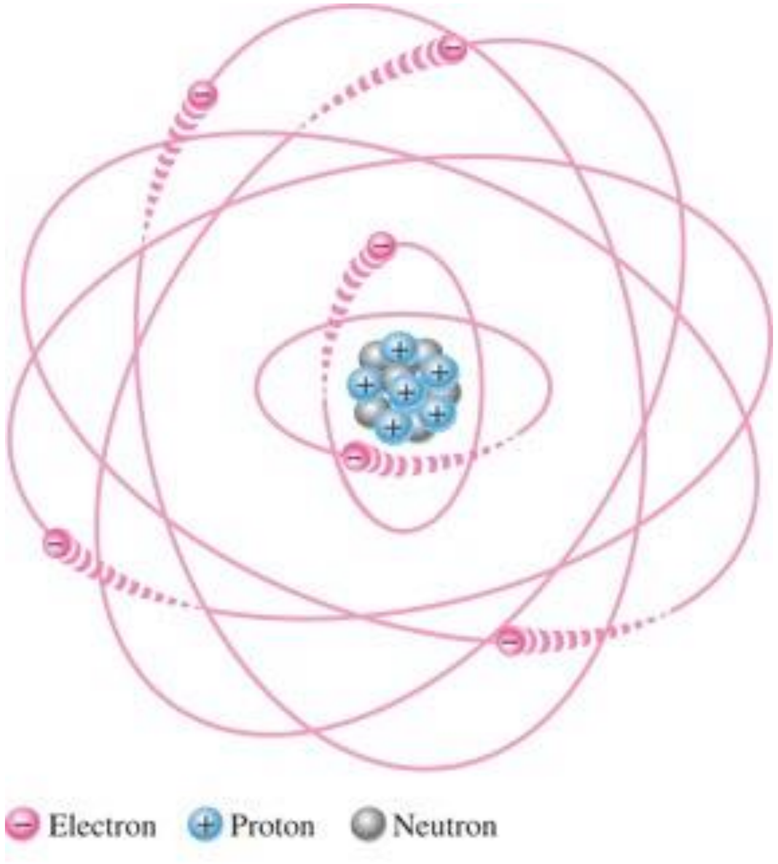
Last Lecture → Input / Output Impedance of a Circuit

- **How can one calculate input resistance from terminal behavior?**
  1. place a test source V_x at the input terminals
  2. observe v_x and i_x
  3. calculate via $R_{in} = v_x / i_x$

- **How can one calculate output resistance from terminal behavior?**
  1. place a test source V_y at the output terminals
  2. *turn of the input source (V*
  3. observe v_y and i_y
  4. calculate via $R_{out} = v_y / i_y$

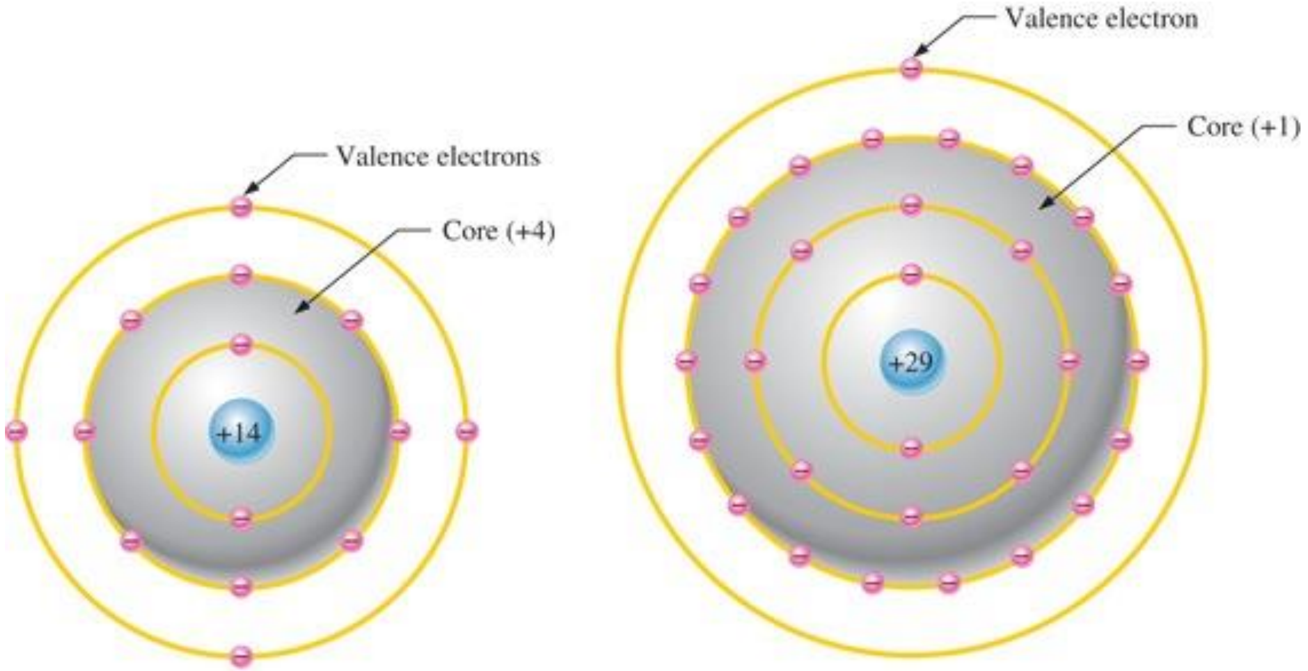


Atom – Bohr Model → Chp. #3



… **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**.



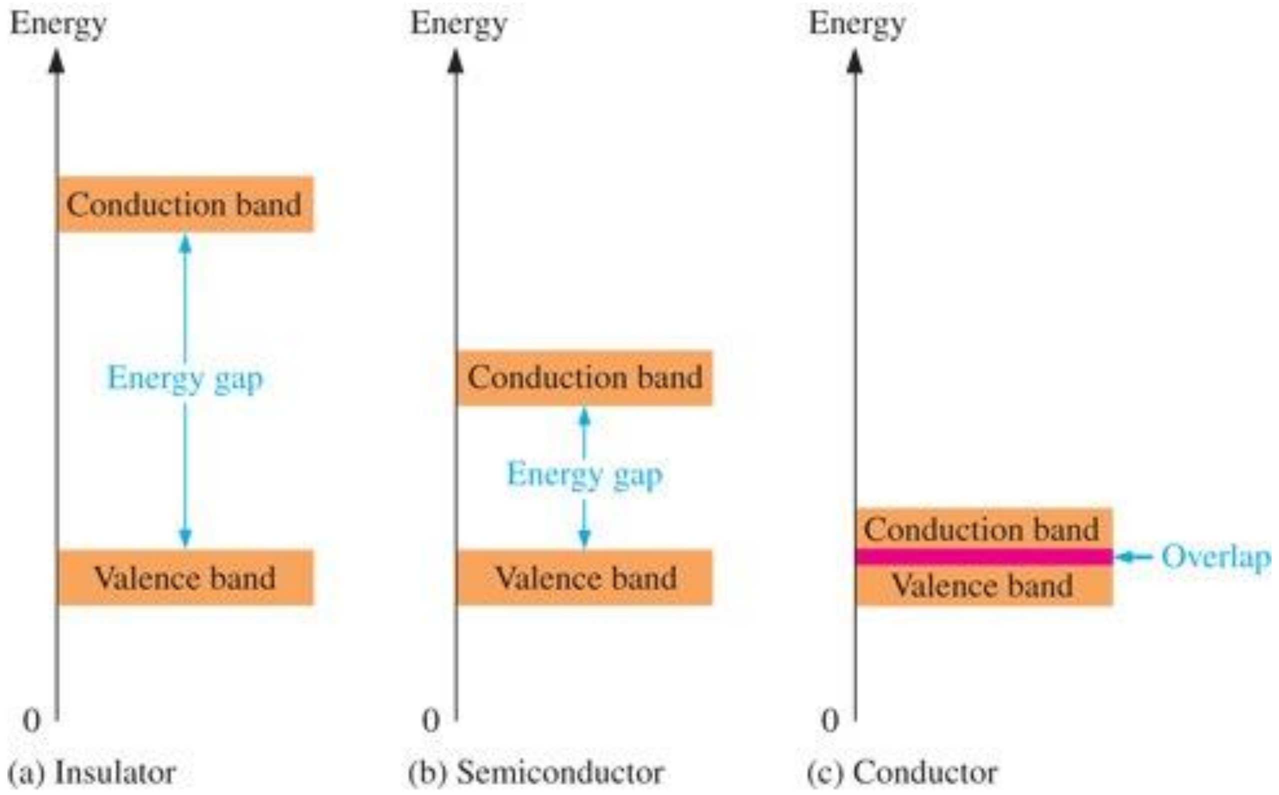
(a) Silicon atom

(b) Copper atom

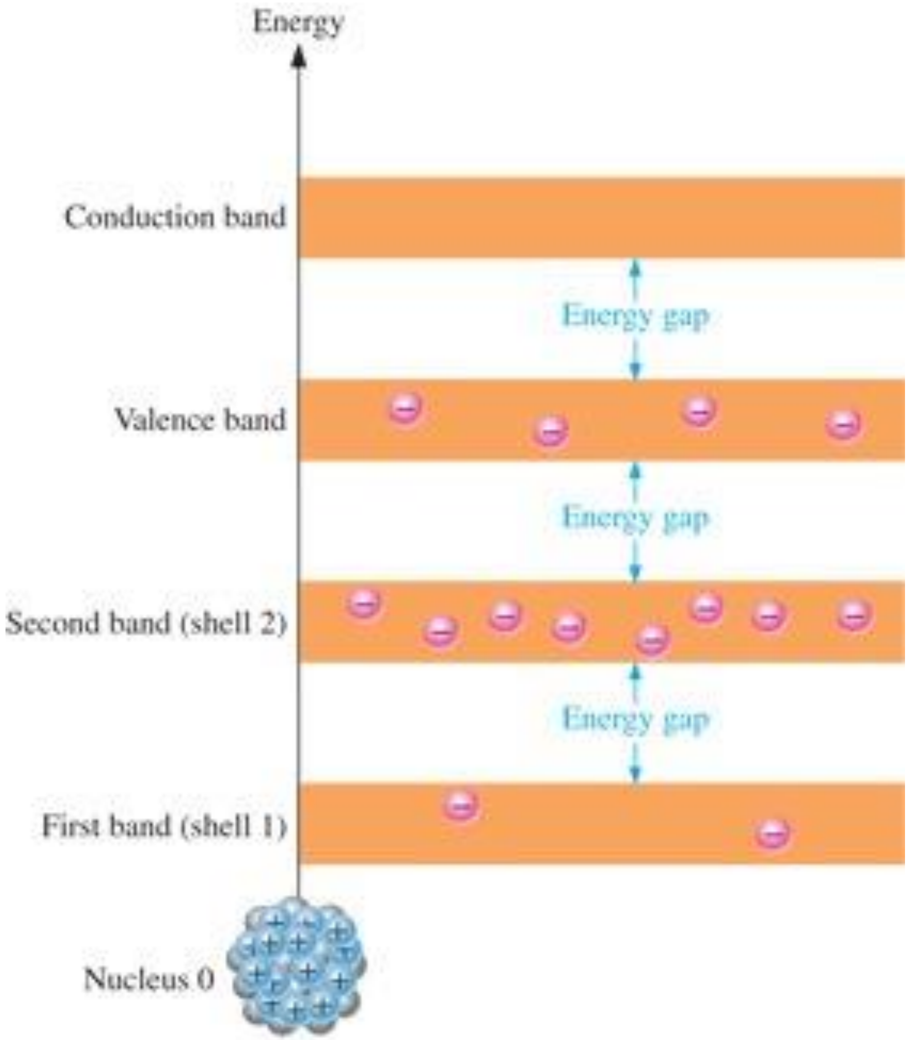
Energy Diagram

Si

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

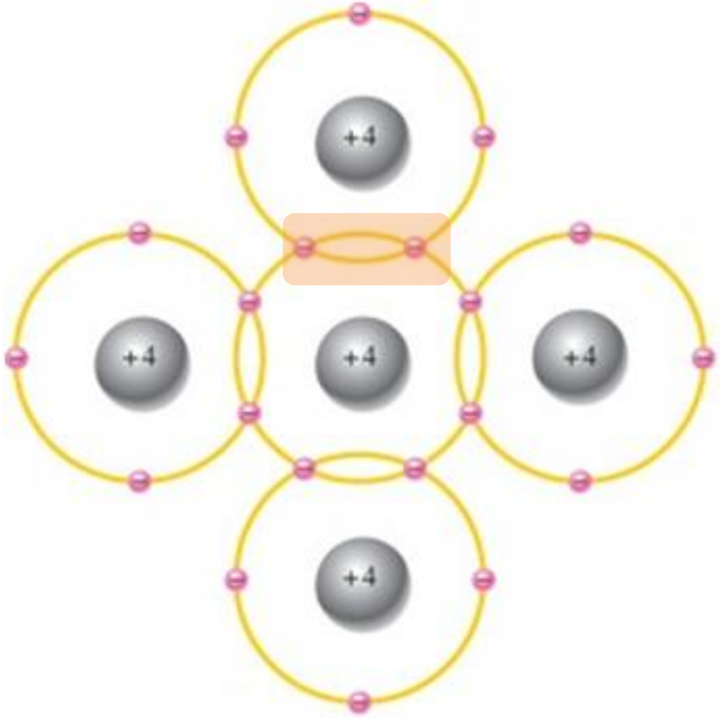


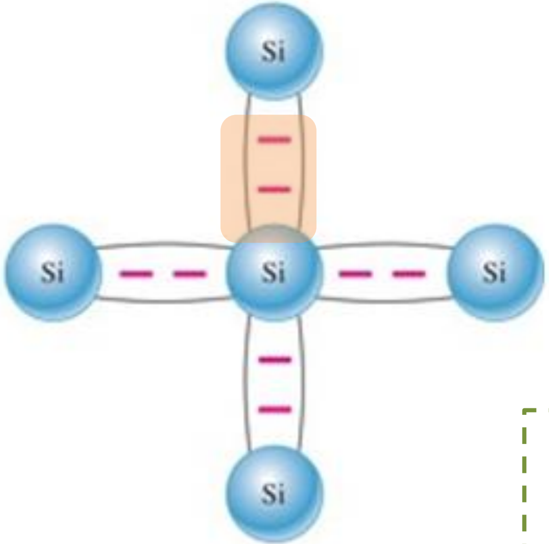
(a) Insulator (b) Semiconductor (c) Conductor

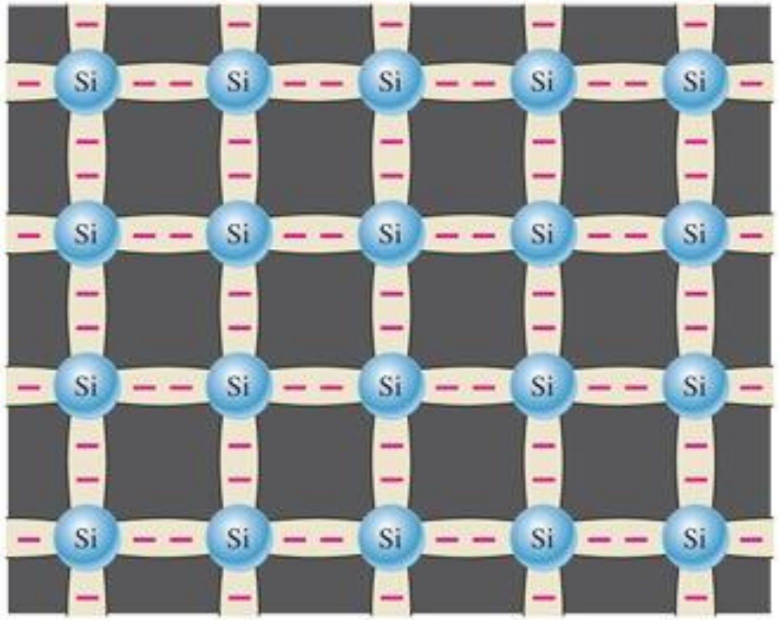


Covalent Bonds

- 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.



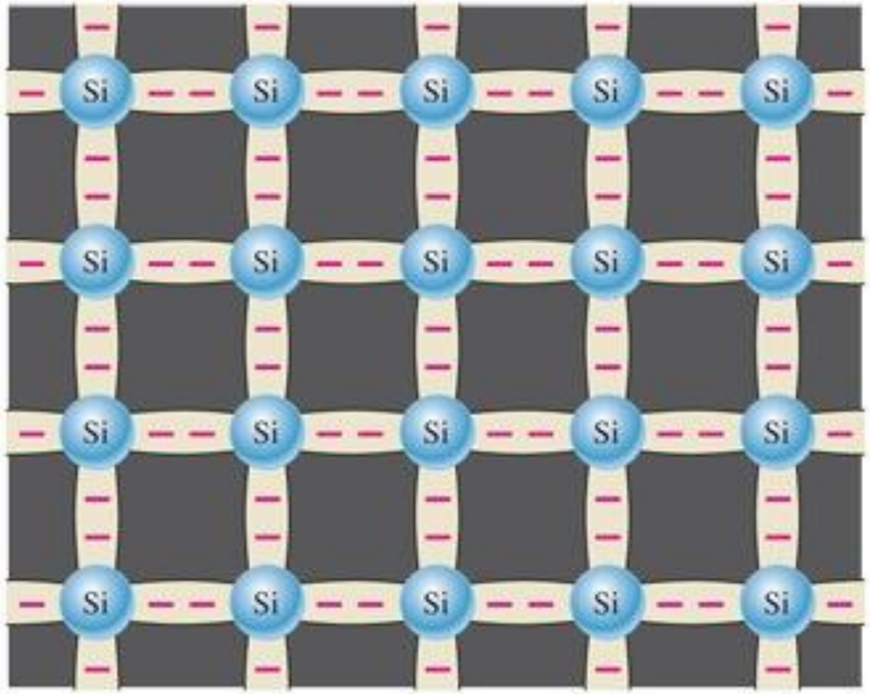




Intrinsic Semiconductor: is a single-crystal semiconductor with no other types of atoms within the crystal.

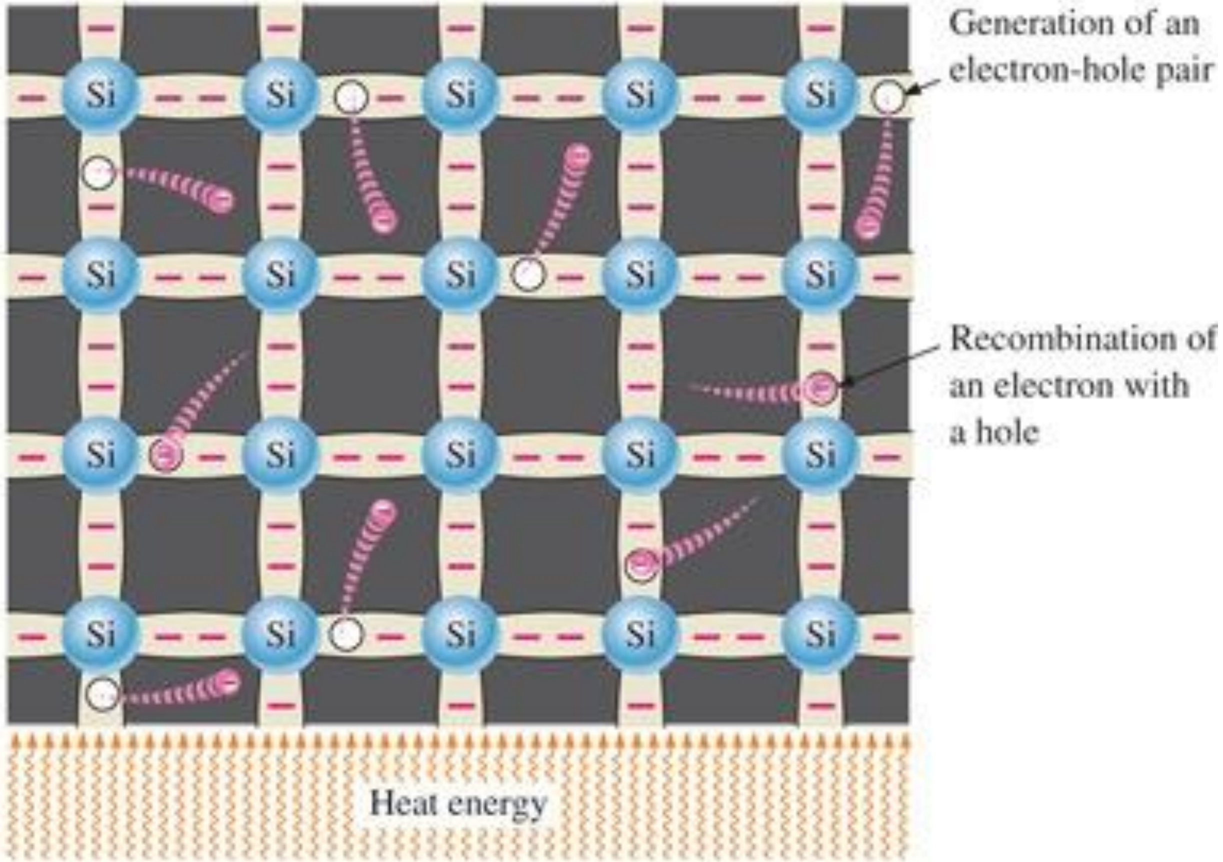
Silicon Crystal

@ low temp.



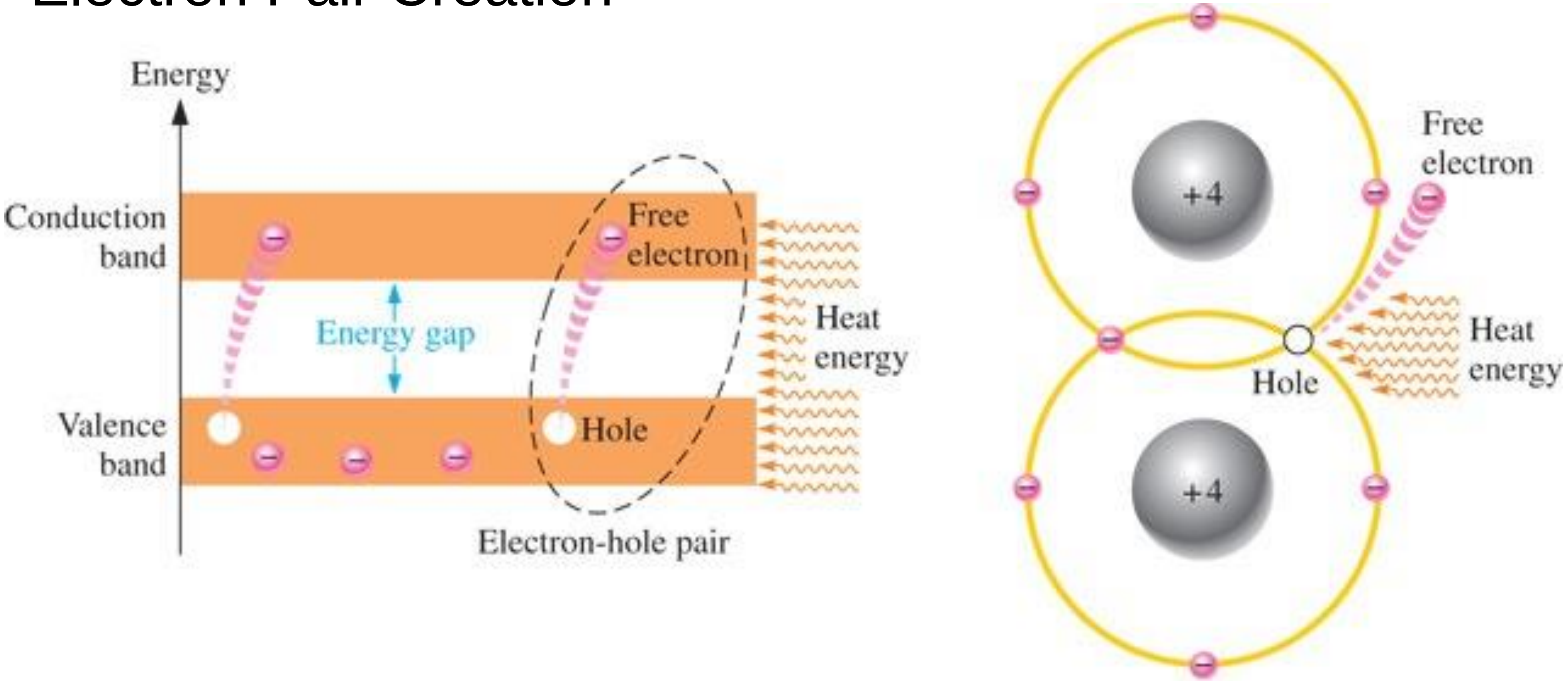
- All **covalent bonds** are intact
- No **electrons** are available for conduction
- **Conductivity** is zero

@ room temp.



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

Hole – Electron Pair Creation



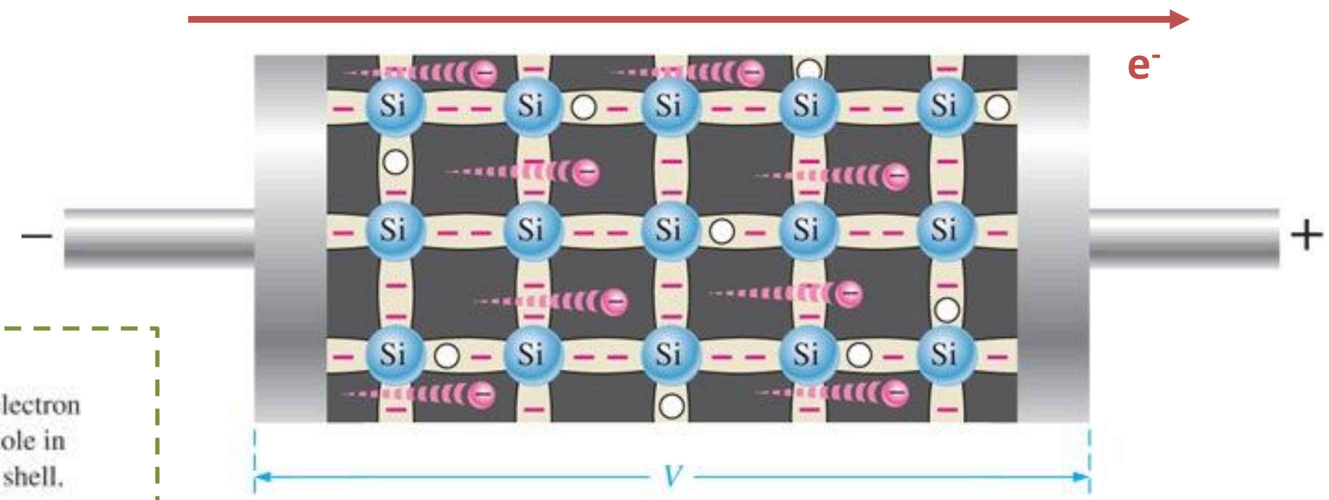
(a) Energy diagram

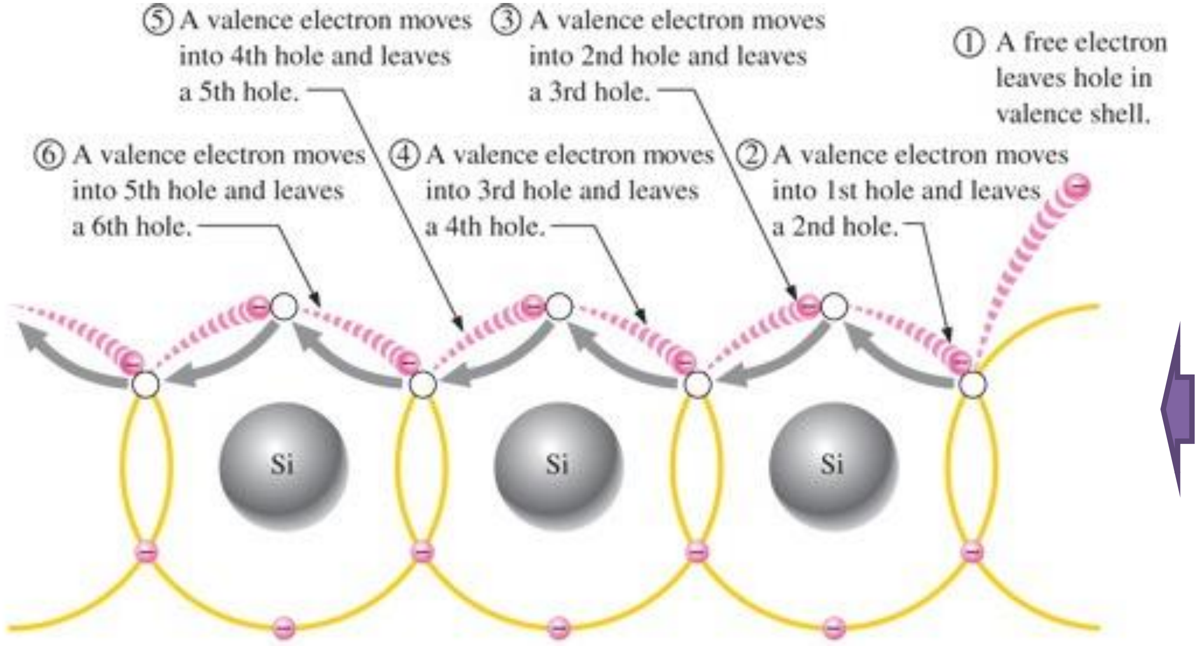
(b) Bonding diagram

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

Electron Current

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





① A free electron leaves hole in valence shell.

② A valence electron moves into 1st hole and leaves a 2nd hole.

③ A valence electron moves into 2nd hole and leaves a 3rd hole.

④ A valence electron moves into 3rd hole and leaves a 4th hole.

⑤ A valence electron moves into 4th hole and leaves a 5th hole.

⑥ A valence electron moves into 5th hole and leaves a 6th hole.

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 - Charge Concentration

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

$$n = p = n_i$$

$$np = {n_i}^2$$

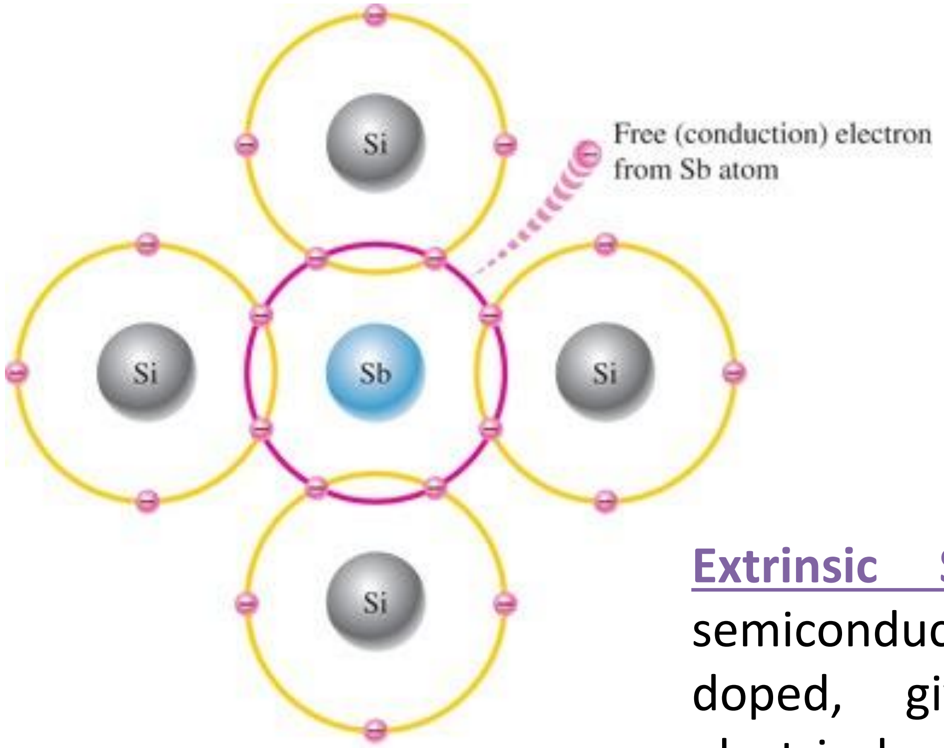
number of free electrons and holes in a unit volume (cm^3) of intrinsic silicon at a given temperature

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

- **material-dependent parameter → B**
- **bandgap energy → E_g**
- **Boltzmann's constant → k**

Extrinsic Semiconductors

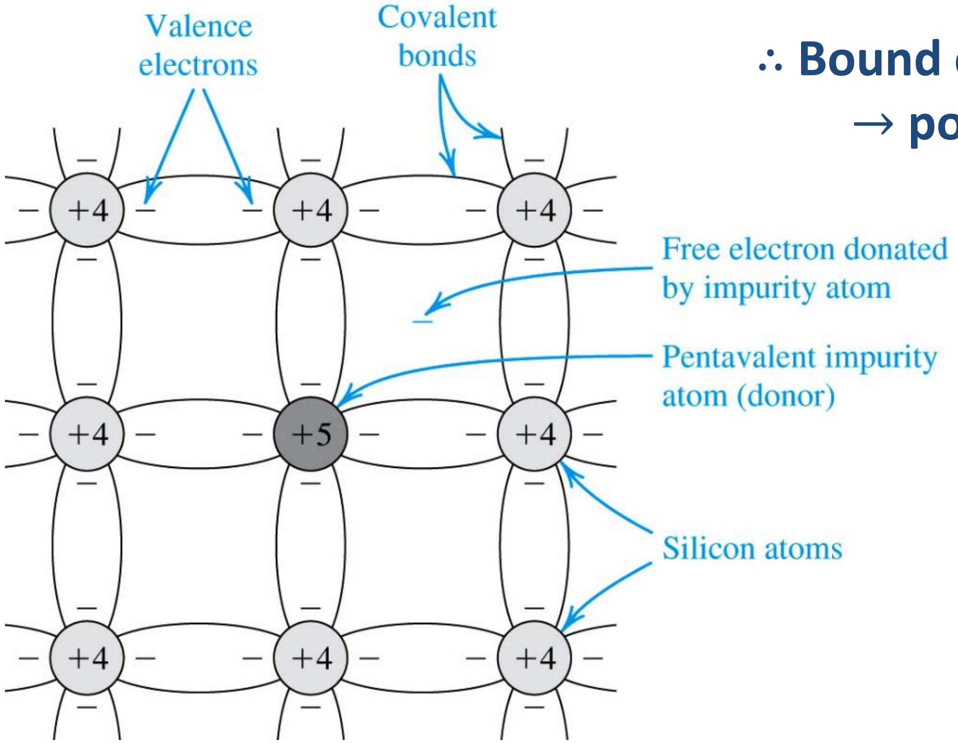
Doping: addition of impurities to the intrinsic semi-conductive material. Increases the number of current carriers.



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

N -Type Semiconductor

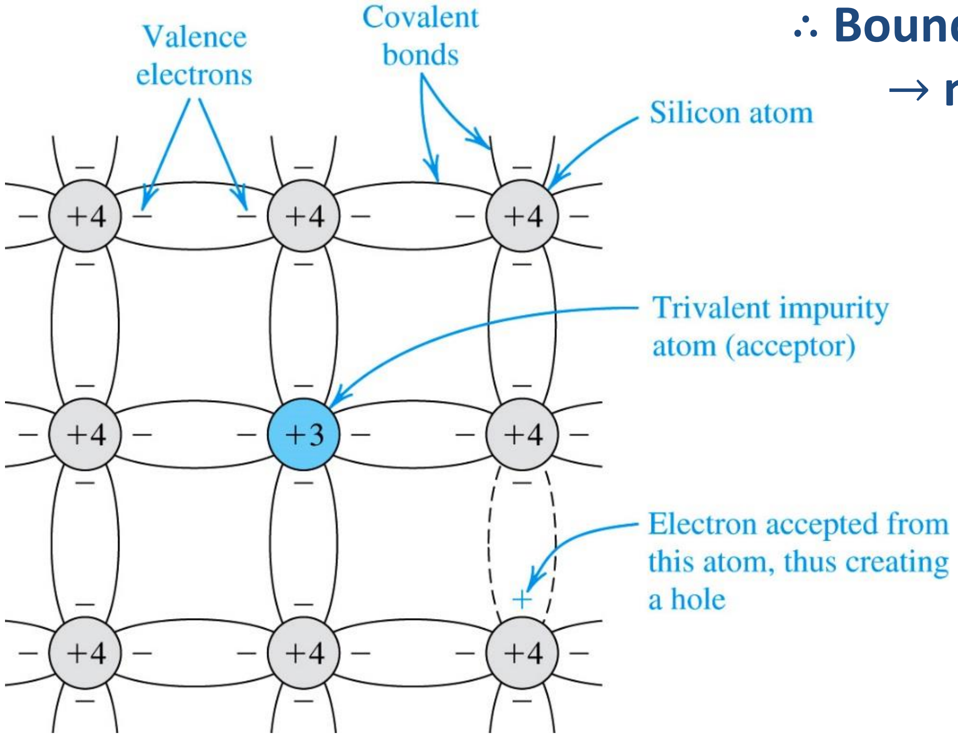
- Antimony (Sb) – 5 Valence Electrons
- n-type: electrons >> holes
  - Majority carriers – electrons
  - Minority carriers - holes



∴ Bound charge → positive

P -Type Semiconductor

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

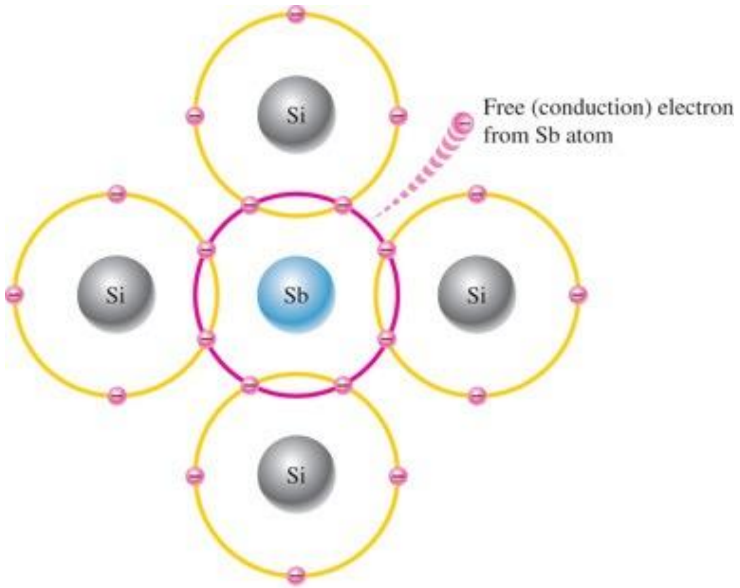


∴ Bound charge → negative

N -Type Semiconductor

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

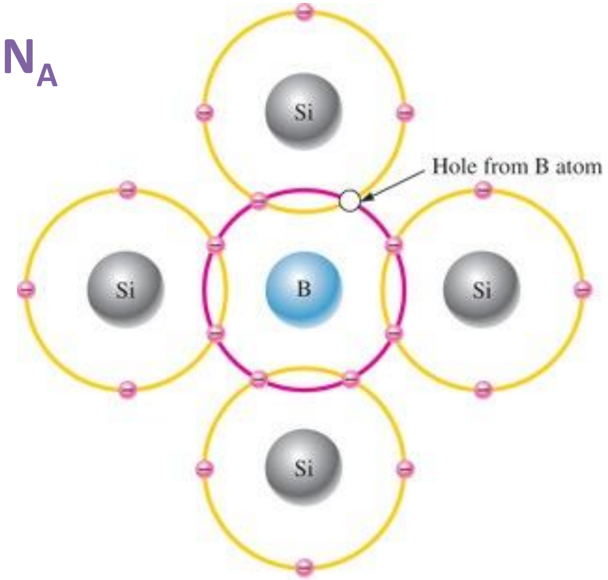
$$\therefore\ p_n \simeq \frac{{n_i}^2}{N_D}$$



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?

$B=7.3\times10^{15}\ cm^{-3}K^{-3/2}$, $E_g=1.12\ eV$, $k=8.62\times10^{-5}\ eV/K$

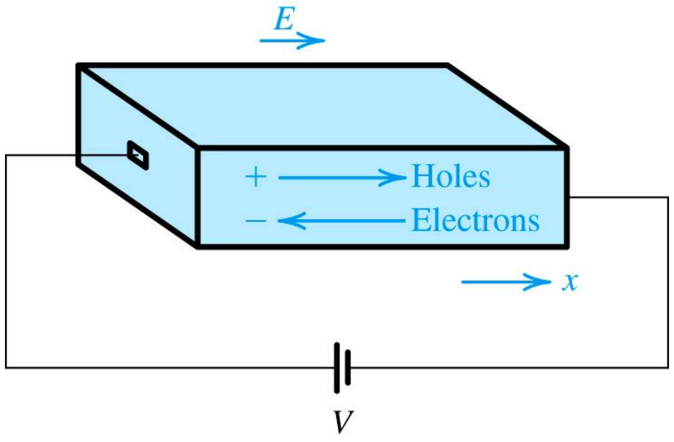
Current Flow in Semiconductors

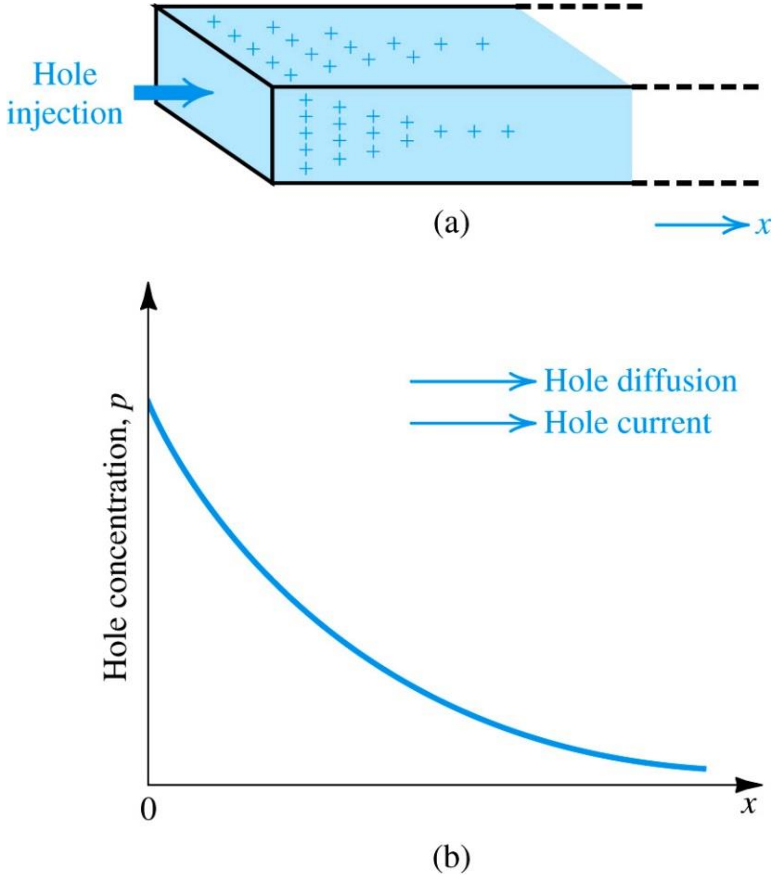
… there are two distinctly different mechanisms for the movement of charge carriers and hence for current flow in semiconductors: ***drift*** and ***diffusion***

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!*



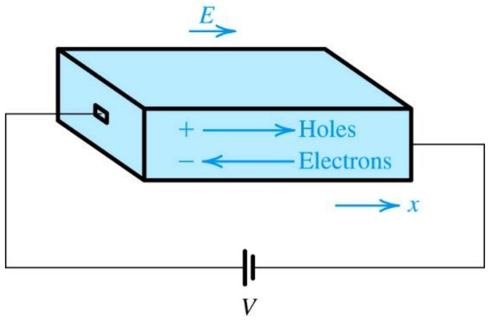


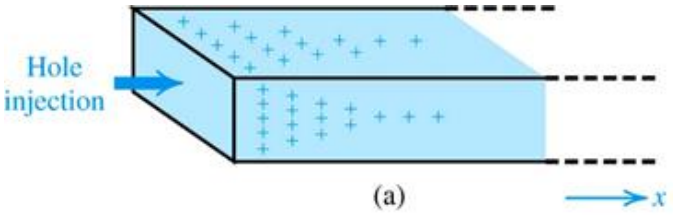
Diffusion Current

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 Density





A= cross-sectional area of silicon, *q*= magnitude of the electron charge,
p= concentration of holes, *n*= concentration of free electrons,
μ_p= hole mobility, μ_n= electron mobility, *E*= electric field

drift current density : $J_{drift} = J_{p-drift} + J_{n-drift} = q(p\mu_p + n\mu_n)E$

diffusion current density : $J_{diff} = J_{p-diff} + J_{n-diff} = -qD_p \dfrac{d\mathbf{p}(x)}{dx} - qD_n \dfrac{d\mathbf{n}(x)}{dx}$

D_p= diffusion constant of holes (12cm^2/s for silicon), D_n= diffusion constant of electrons (35cm^2/s for silicon),
p(*x*)= hole concentration at point *x*, **n**(*x*)= free electron concentration at point *x*,
*d***p** / *dx*= gradient of hole concentration, *d***n** / *dx*= gradient of free electron concentration

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]

- **Ohm's Law [A/cm^2]**

$$J = \sigma \mathrm{E}$$

- **Conductivity [1/ Ω·cm]**

$$\sigma = q(p\mu_p + n\mu_n)$$

- **Resistivity [Ω·cm]**

$$\rho = \frac{1}{q(p\mu_p + n\mu_n)}$$