Helwan University - Faculty of Engineering (Helwan)
Electronics and Communications Engineering Department

Electronics

Lec-1 Semiconductor Basics

Presented By:

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Course Basic Information

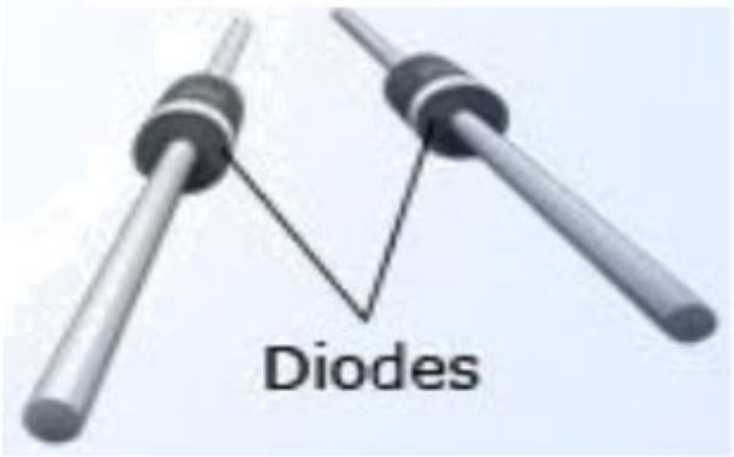
- **Semester Works** 50/100
  - Reports/Sections/Labs 20/100
  - Mid-Term Exam 30/100
- **Final-Term Exam** 50/100

Course Contents

❑ Semiconductor Basics

❑ Semiconductor Devices

- Diodes
- Transistors



Reference

❑ Thomas L. Floyd. Electronic Devices (Conventional Current Version). 7th Edition, Pearson Prentice Hall, 2005.

Classification of Materials

In terms of electrical properties, materials can be classified into three groups that are:

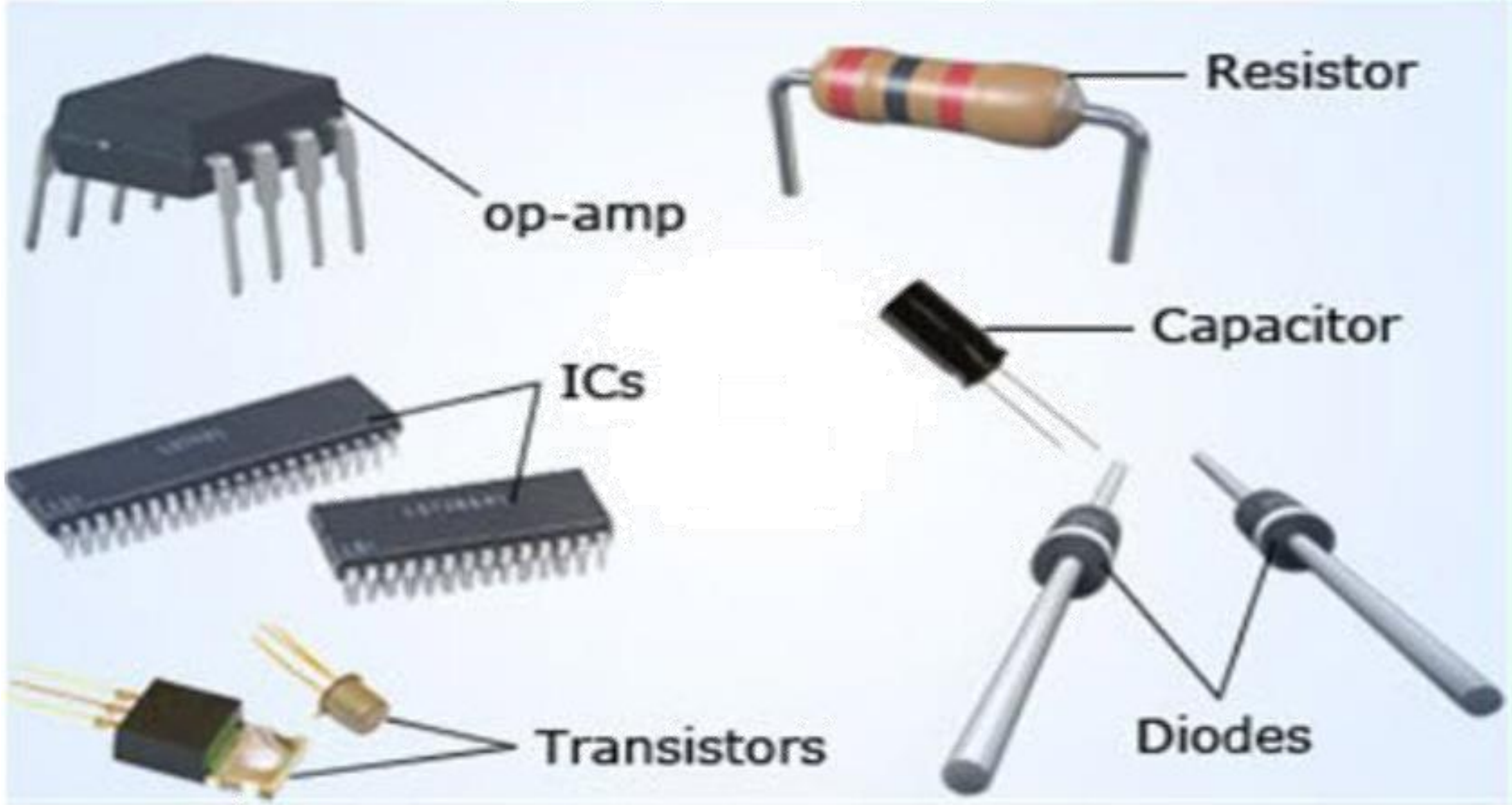
- Conductors: Copper, Aluminum, Iron, Silver, …..

- Semiconductors: Silicon, Germanium, Gallium-Arsenide, Indium-Gallium-Arsenide, …..

- Insulators: Paper, Rubber, Wood, Plastic, Glass, ….

Semiconductors

- Semiconductors are found everywhere around us: communication, computing, healthcare, transportation, clean energy, and in several other applications.



- Semiconductors are in the form of **devices** or **integrated circuits** (ICs).

Why Are Semiconductors Important?

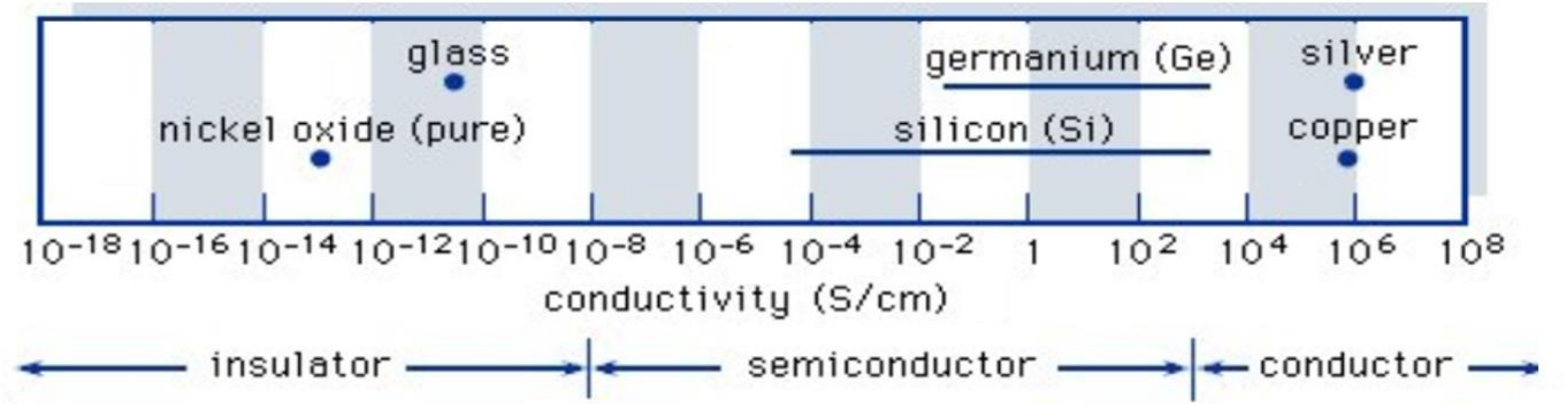
- ❑ The most used semiconductor material (silicon) is extracted from desert sand (**cheap**).

- ❑ Semiconductors act as **insulators** at low temperatures and **conductors** at higher temperatures.

- ❑ **Electrical properties of semiconductors** can be changed by introducing external atoms (impurities).

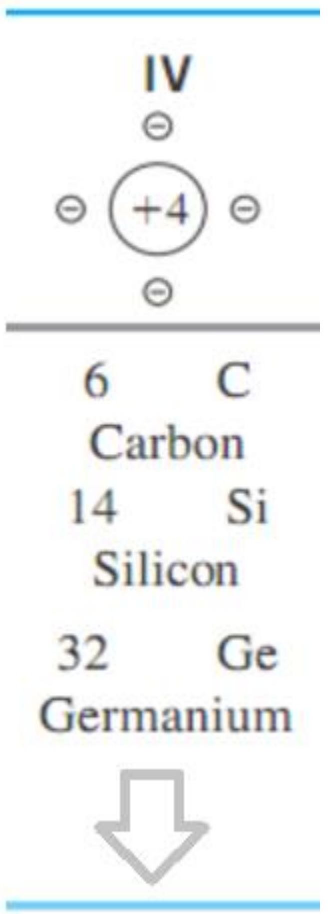
What are Semiconductors?

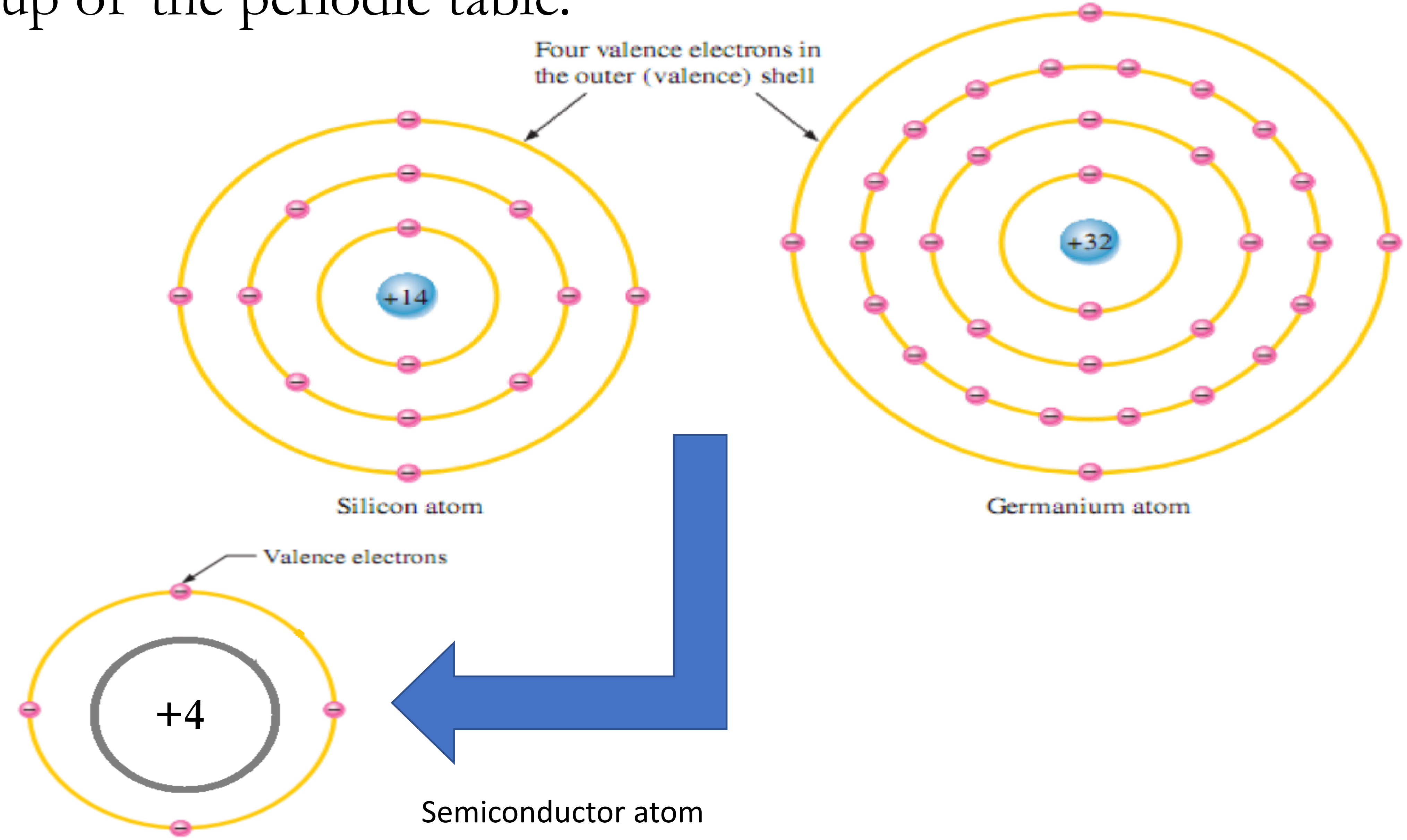
❑ **Semiconductors** are materials whose **electrical properties** between insulators and conductors.



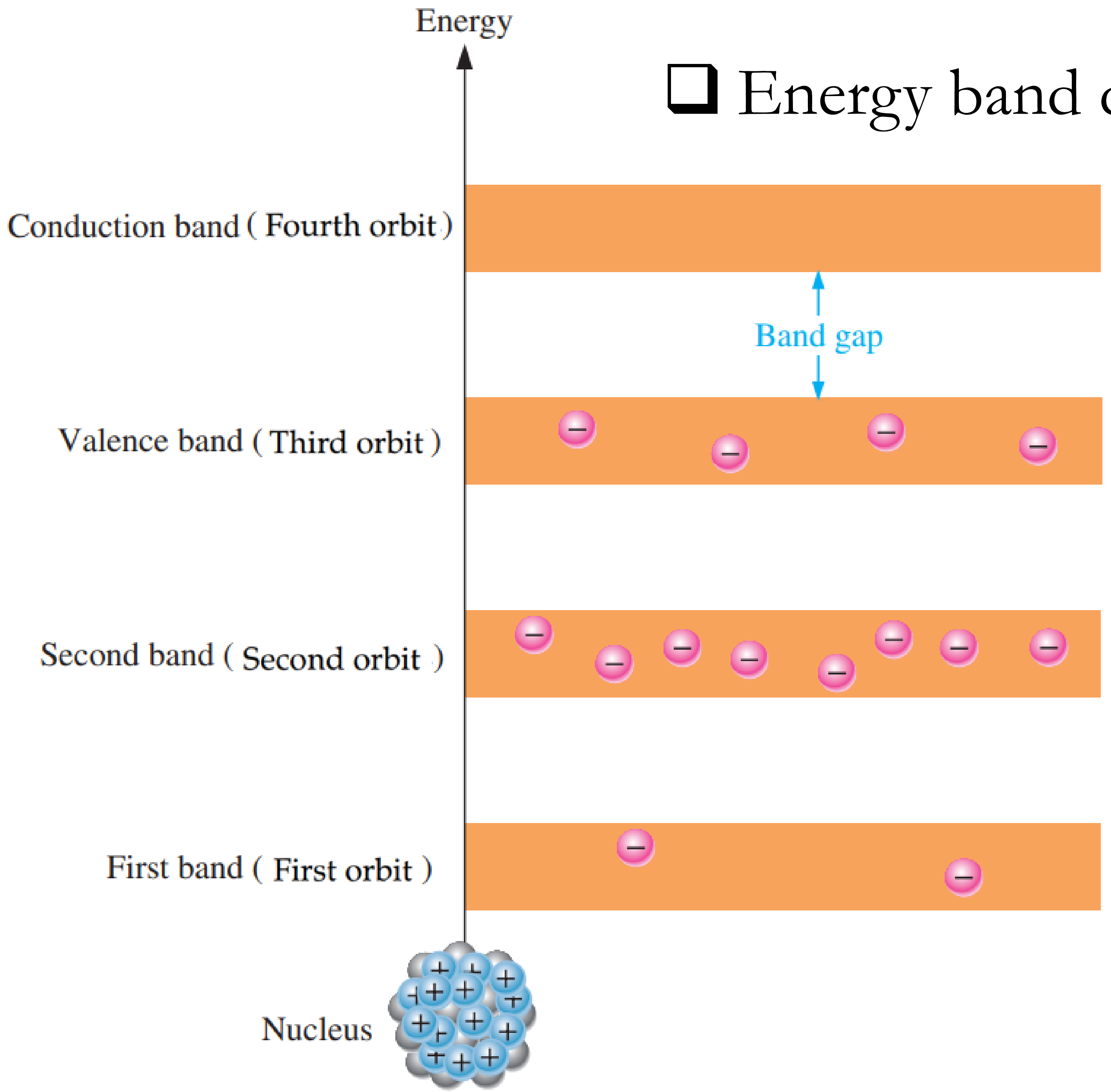
❑ **Conductivity** is the ability of a material to conduct electric current through it.

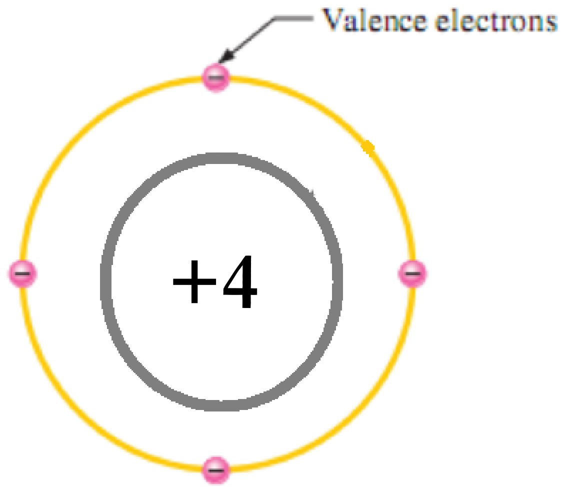
❑ Common **semiconductors** are **silicon** (Si) and **germanium** (Ge) in the fourth group of the periodic table.



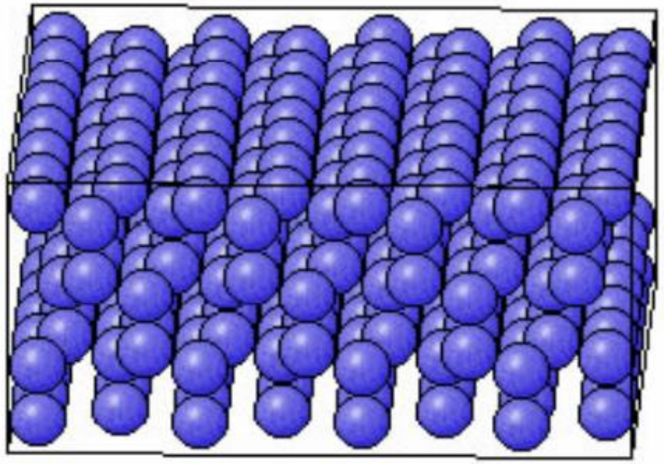


❑ Energy band diagram for **silicon atom.**





Semiconductor atom



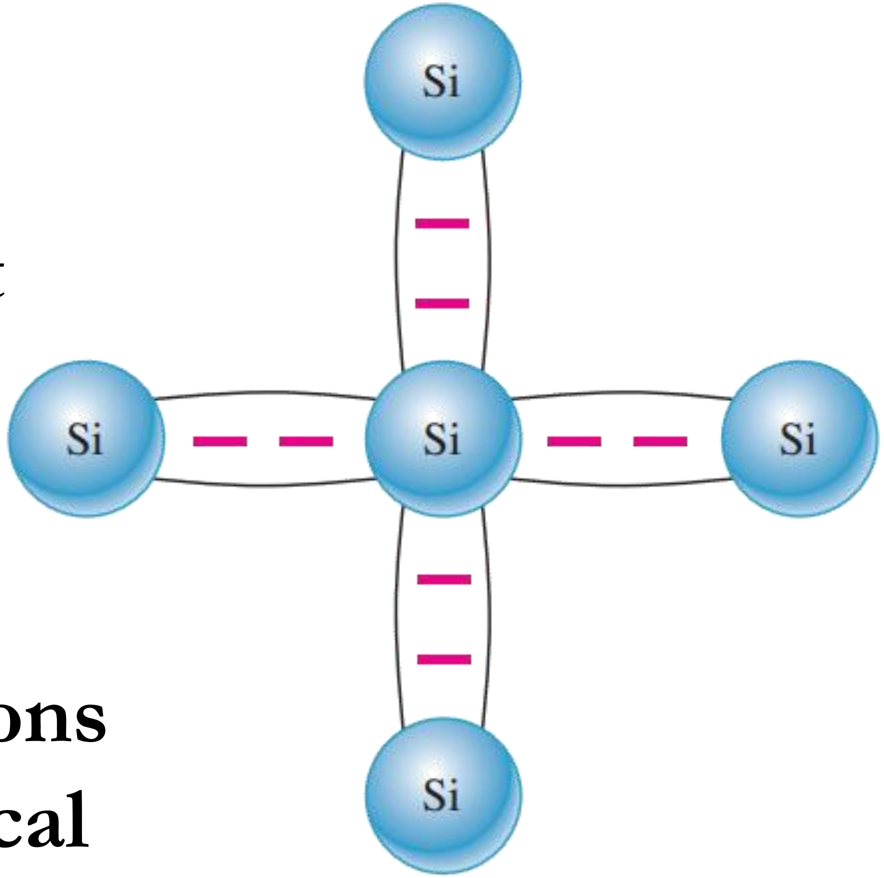
Three-dimensional semiconductor crystal

- Number of Si atoms per cm^3 equals $5x10^{22}$ atoms.
- Number of Ge atoms per cm^3 equals $4.4x10^{22}$ atoms.

- **Semiconductor crystal** is made up of **atoms bonded together** in a regular structure.

- Semiconductor **atom has four valence electrons** which are shared, forming covalent bonds with four atoms.

- This **creates eight shared valence electrons** for each atom and produces a state of **chemical stability.**

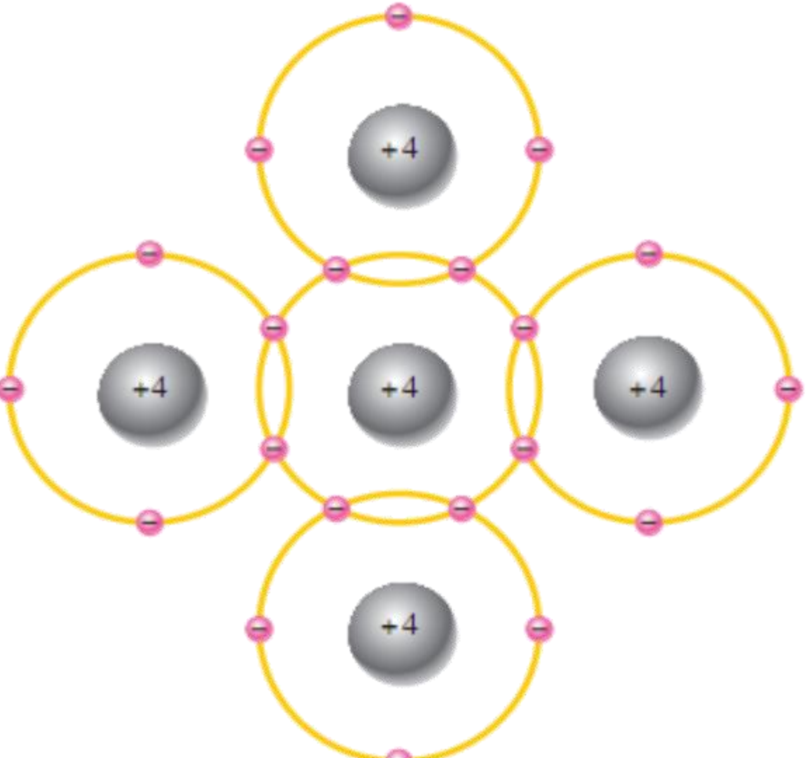


Two-dimensional semiconductor crystal

Semiconductors Types

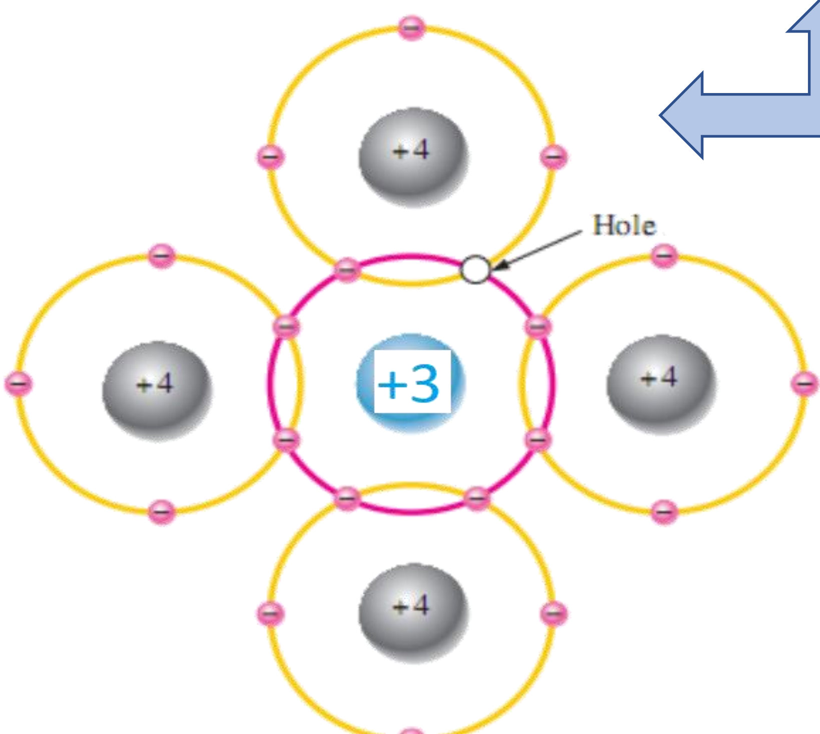
1-<u>Intrinsic</u> Semiconductors

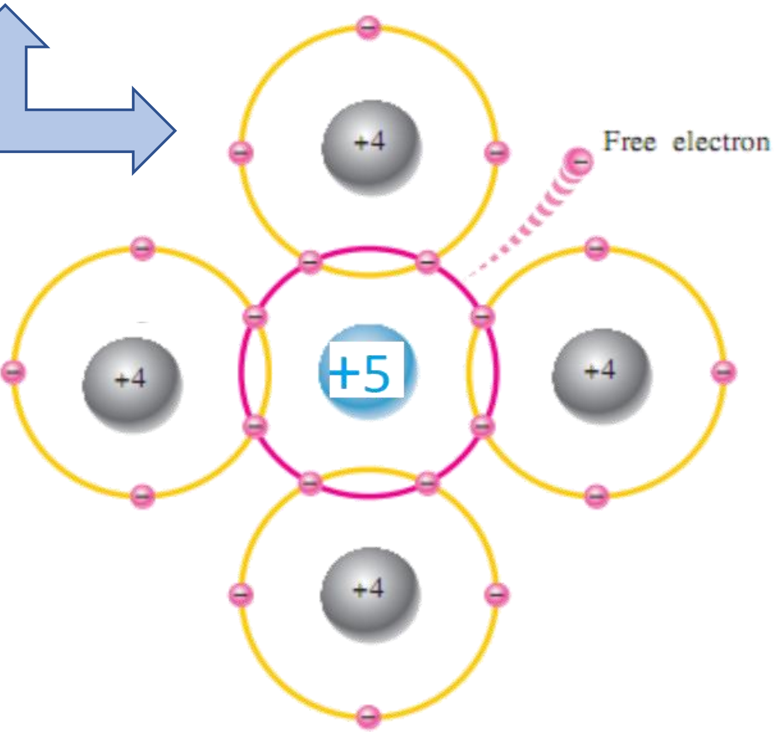
crystal contains **Si or Ge** atoms **only**.



2-<u>Extrinsic</u> Semiconductors

crystal contains **Si or Ge** atoms **plus impurities.**

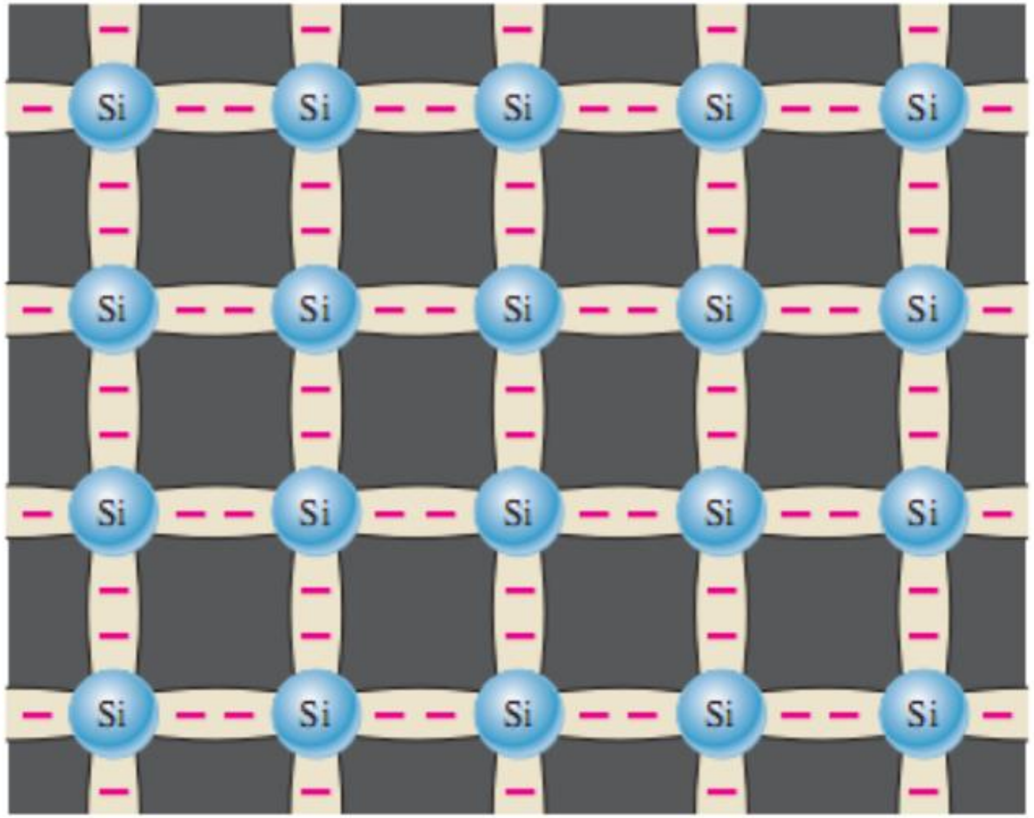




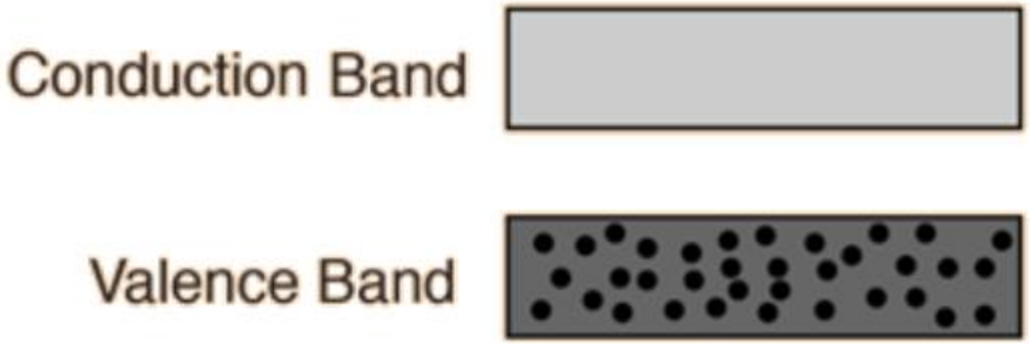
1-Intrinsic Semiconductors

- Intrinsic (pure) semiconductor crystal contains Si or Ge atoms only (no impurities).

- At temperature = zero kelvin (0K), **the valence band** is fully **occupied** by the **valence electrons** and **the conduction band** is completely **empty of electrons**.

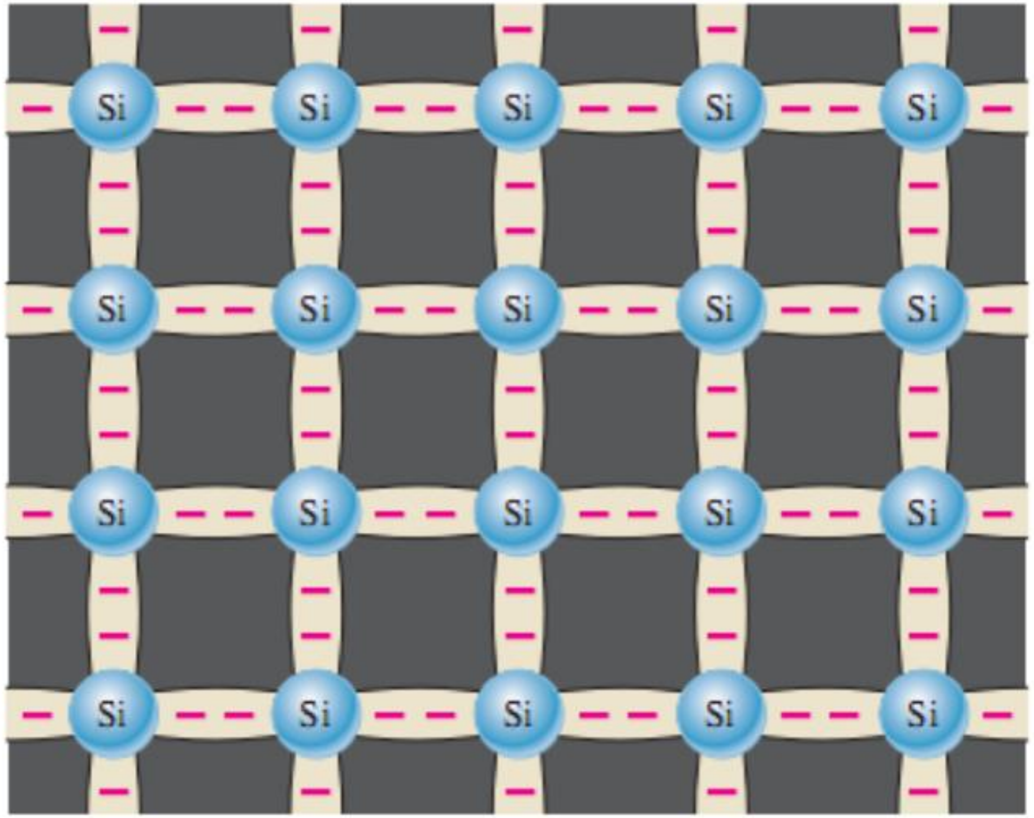


Silicon crystal at 0K

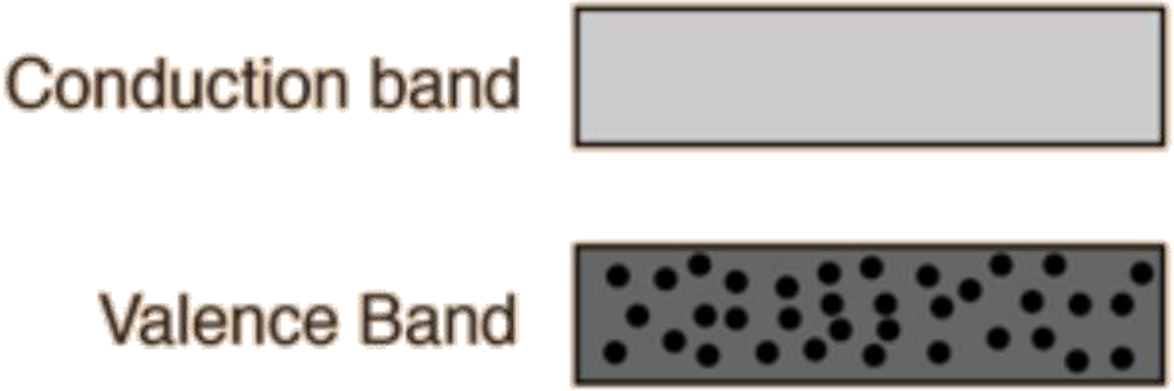


❑ Because of **no electrons** are available **in the conduction band**; the **<u>intrinsic semiconductor crystal act as an insulator at 0K</u>**.

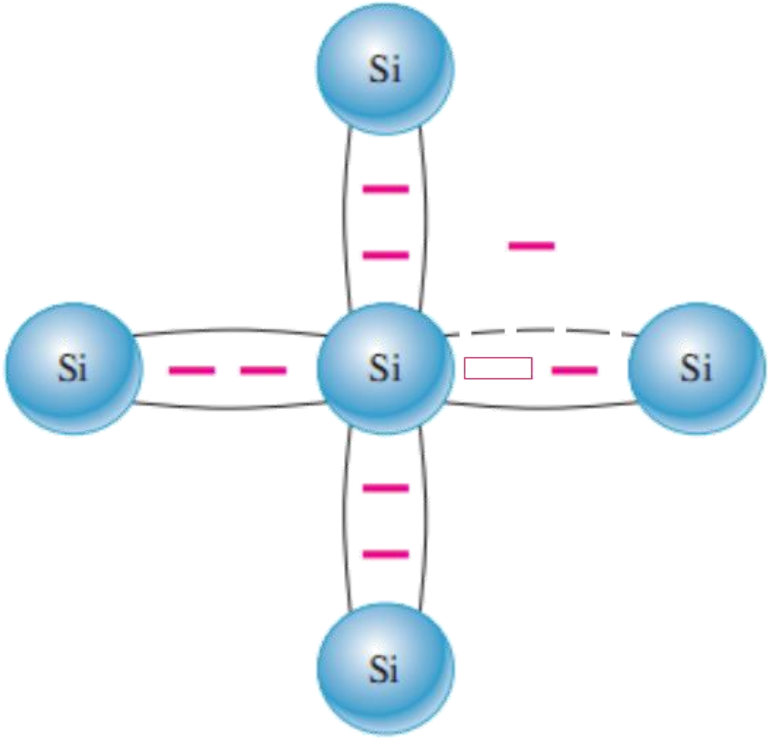
❑ **<u>Conductivity (σ) of intrinsic semiconductor equals zero at 0K</u>**.

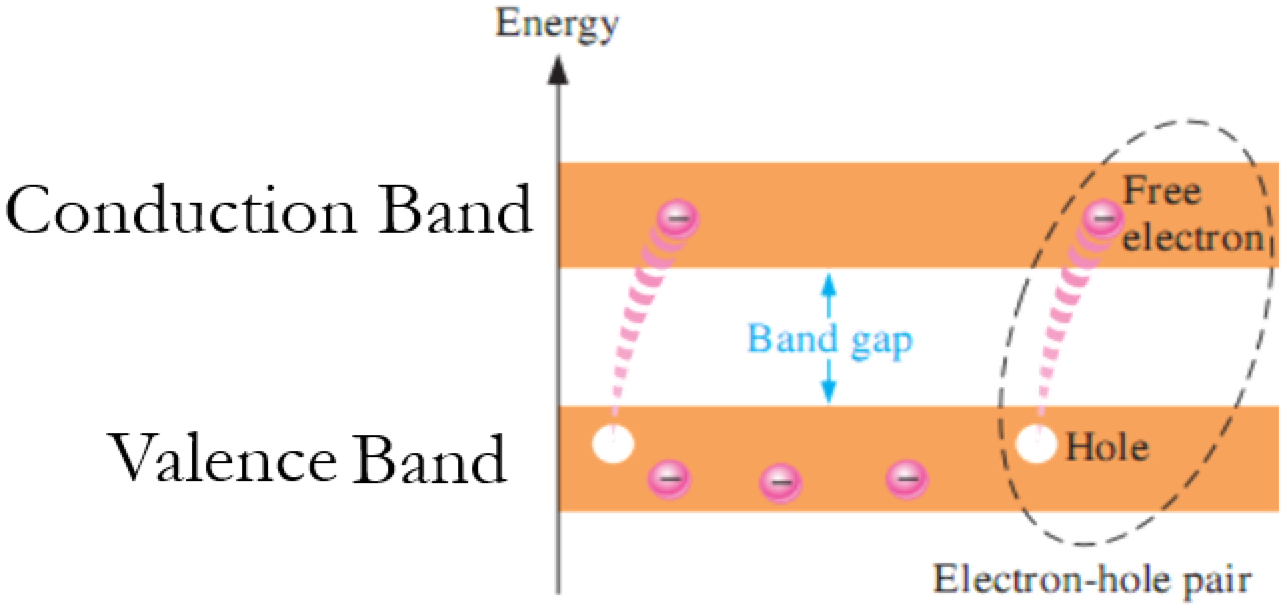


Silicon crystal at 0K

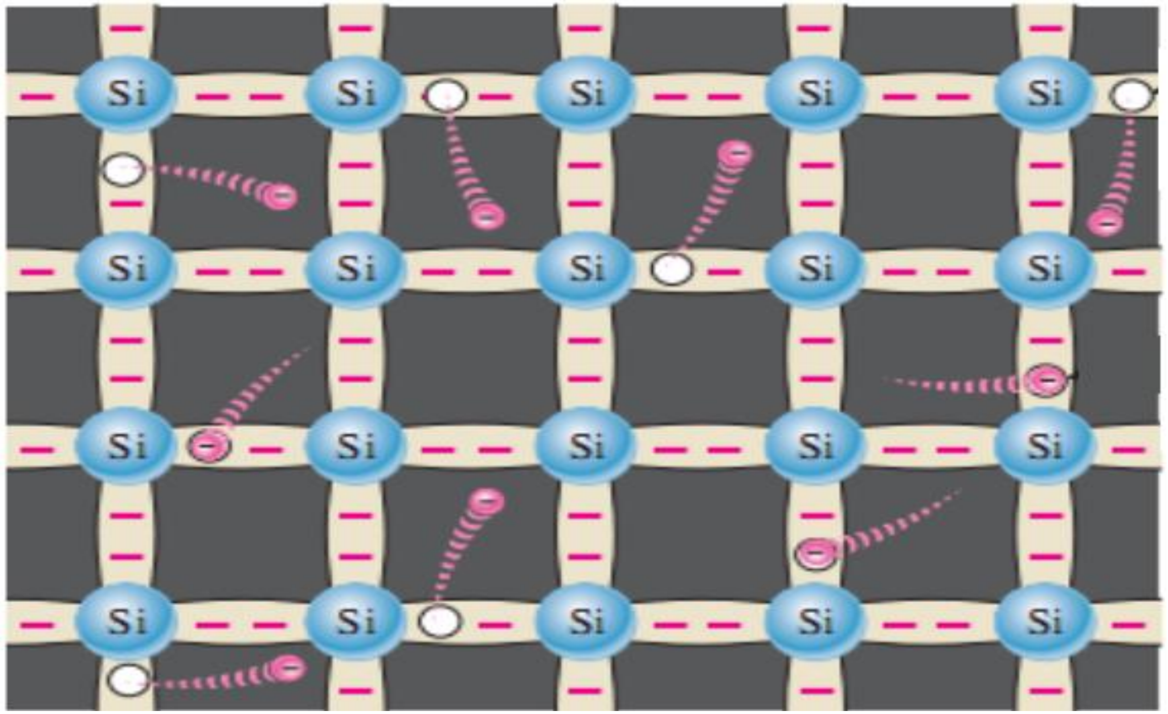


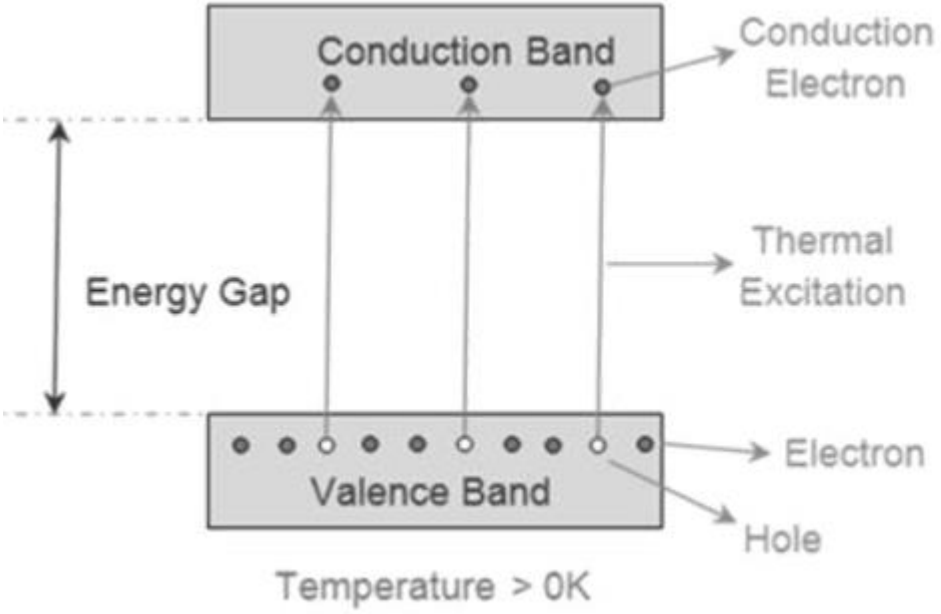
❑ As **temperature increase above 0K**, a few valence electrons gain enough **thermal energy** to break the bond and jump into the conduction band.



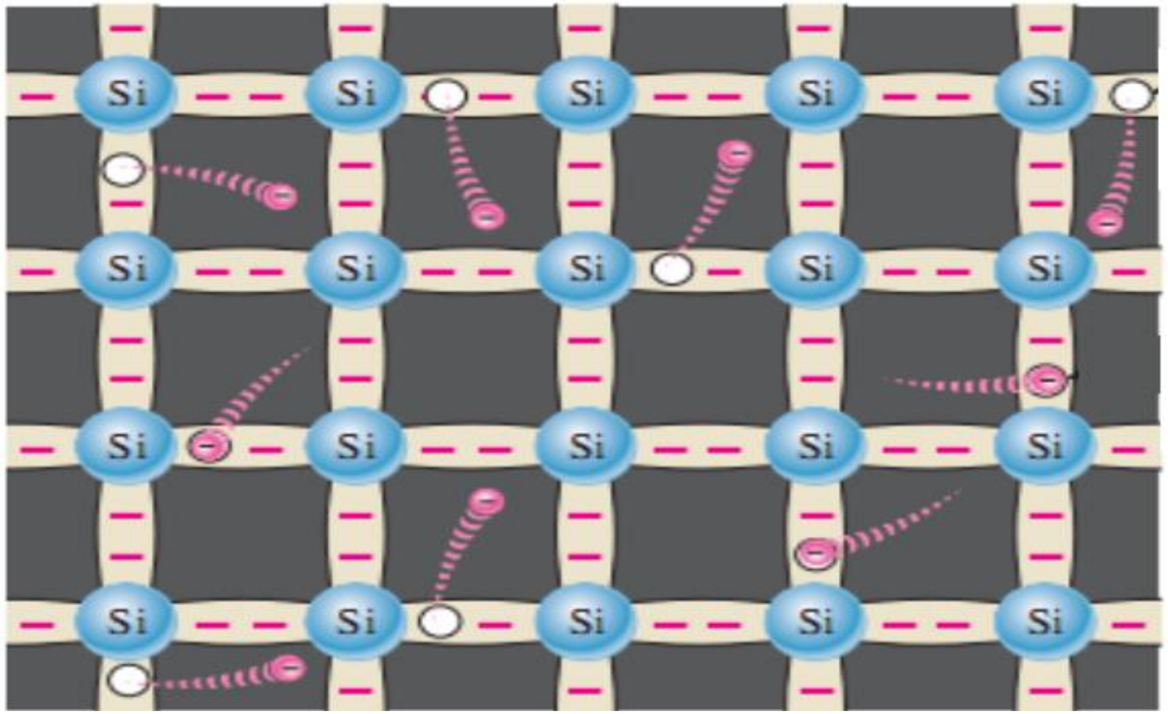


❑ As <u>**temperature increase **</u>**further**, <u>more bonds </u>broken, <u>more electrons</u> jump to the conduction band and <u>more “empty states or holes</u>” created in the valence band.

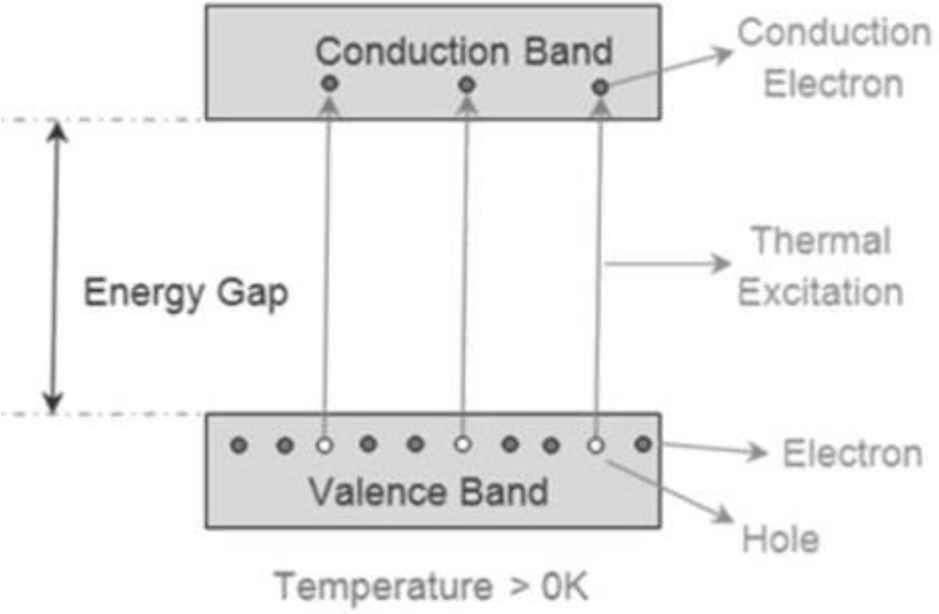




- The <u>number of free electrons</u> in conduction band is <u>equals</u> to the <u>number of holes</u> in the valence band.



Free électrons concentration (n)
= hole concentration (p)
= n_i (intrinsic concentration)
semiconductor atoms
affected by temperature



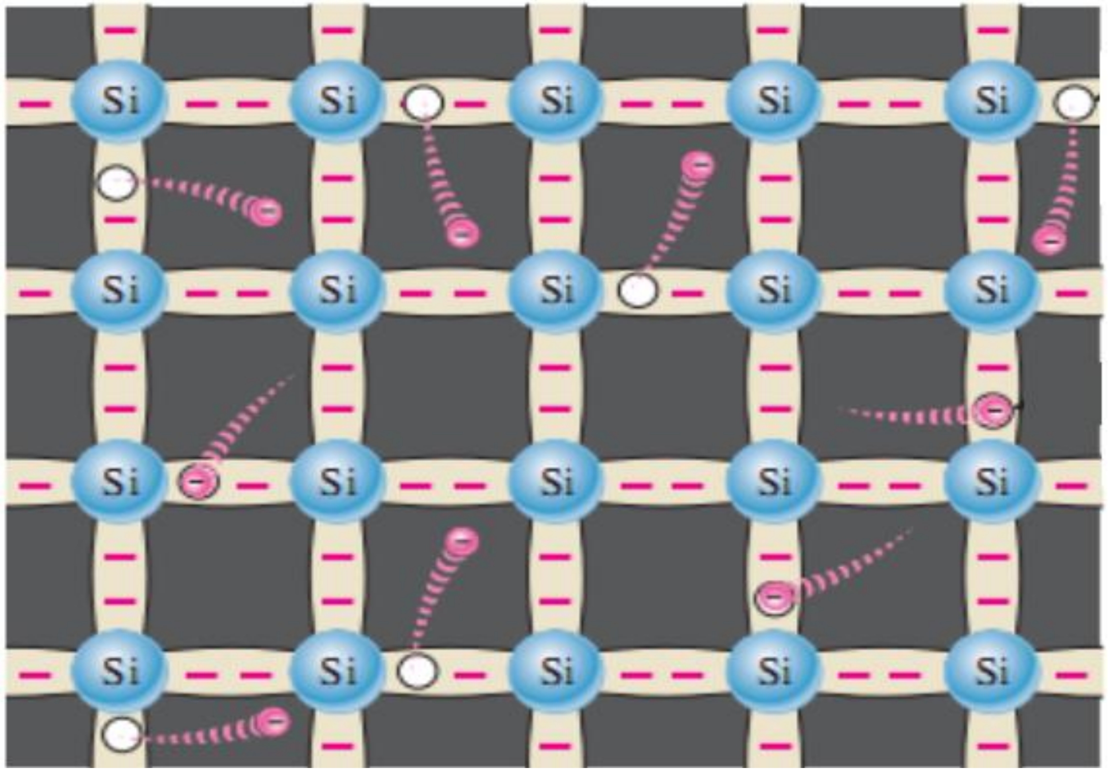
At room temperature (300K),

n_i (Si) = 1.5×10^{10} atoms/cm^3

n_i (Ge) = 2.5×10^{13} atoms/cm^3

= n (free electron concentration)

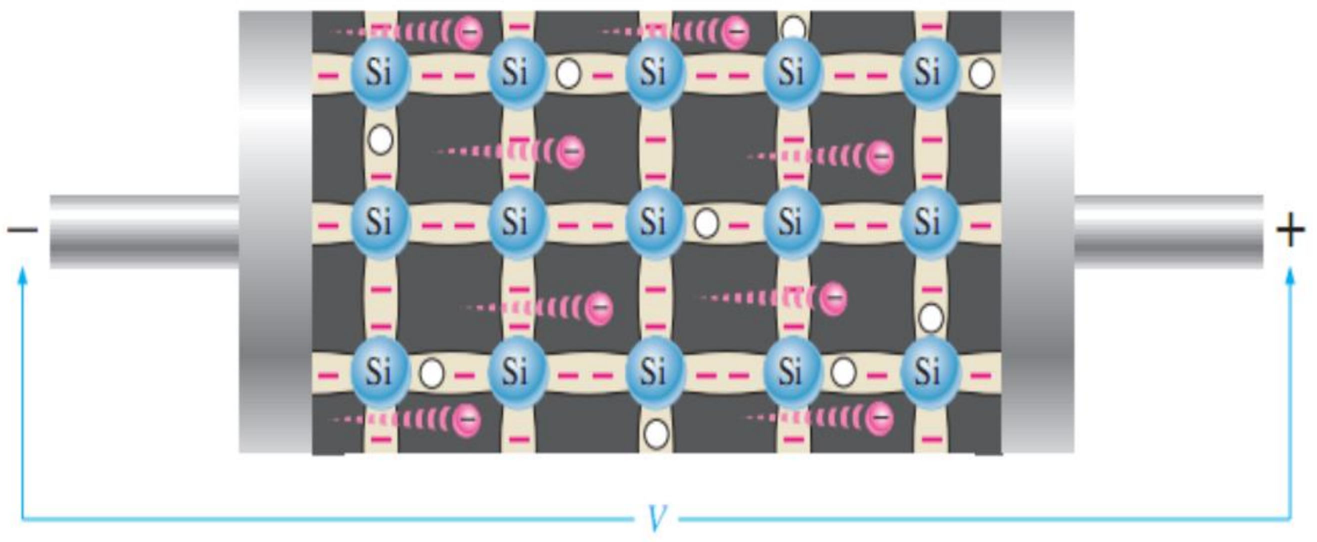
= p (hole concentration)

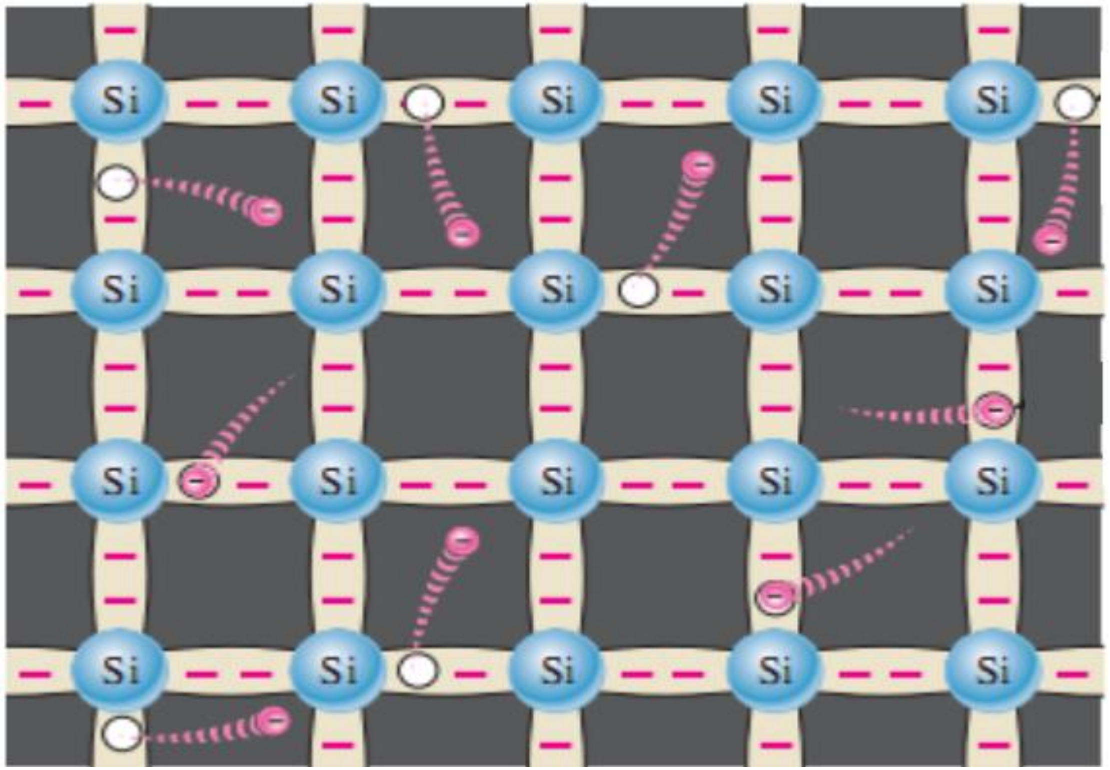


Conductivity of intrinsic semiconductor **at 300K (σ) = $q\,(n\,\mu_n + p\,\mu_p)$**

Conductivity of intrinsic semiconductor **at 300K (σ) = $q\,n_i\,(\mu_n + \mu_p)$**

q is the magnitude of electron charge (1.6×10^{-19} C)



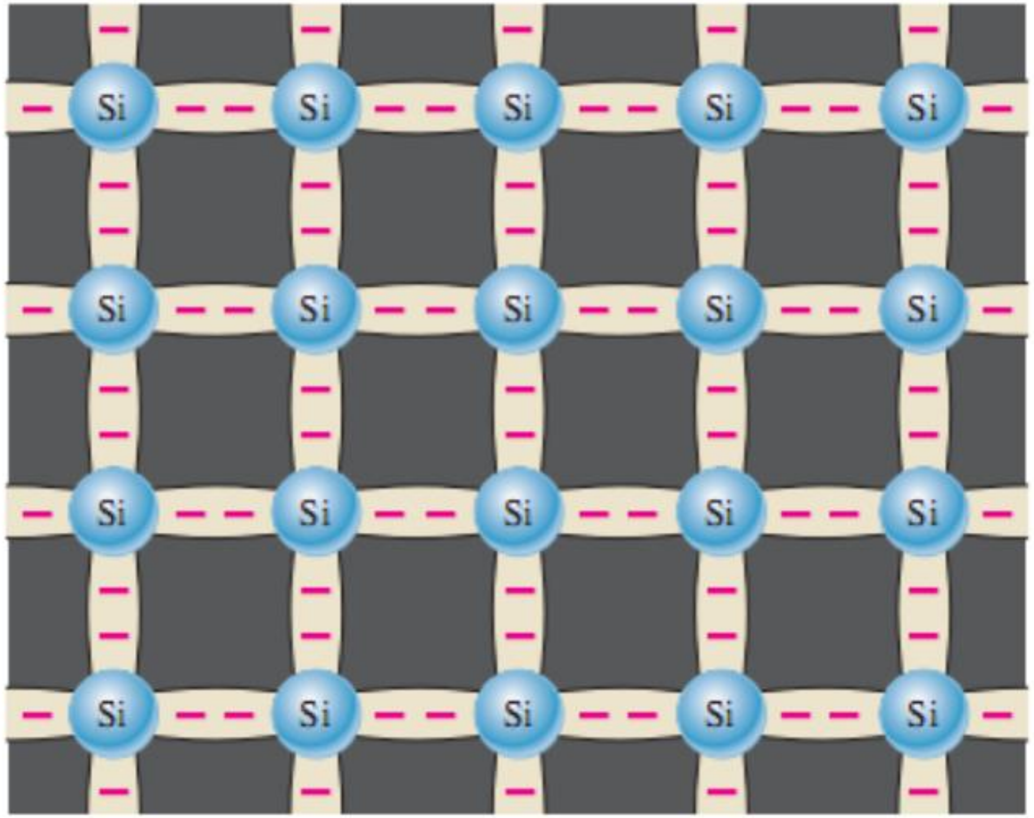


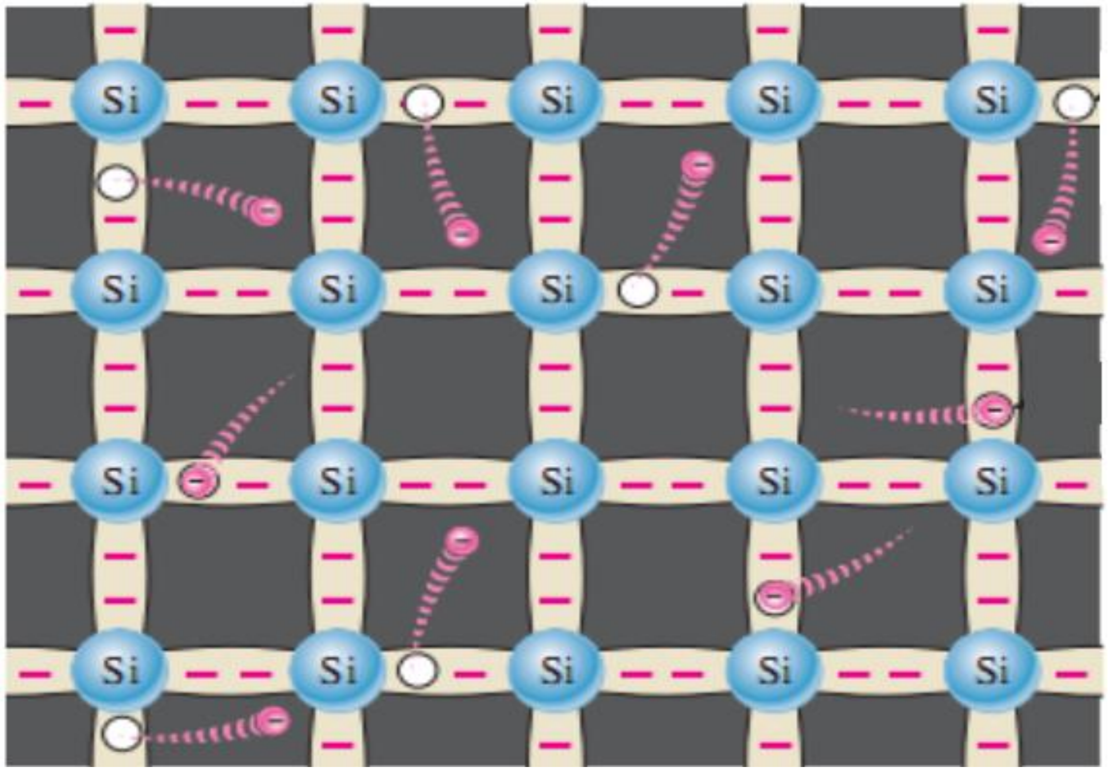
Conductivity (σ) = $q\,(n\,\mu_n + p\,\mu_p) = q\,n_i\,(\mu_n + \mu_p)$

Current Density (J) = Conductivity (σ) x Electric Field (E)

Electric Field (E) = V/L

Finally, for **<u>intrinsic semiconductors:</u>**





<u>At 0K</u>:

$$\sigma = \text{zero}$$

$$J = \text{zero}$$

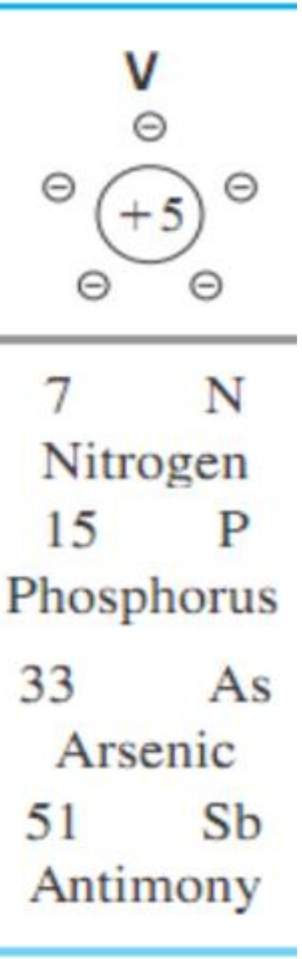
<u>At 300K:</u>

$$\sigma = q\, n_i\, (\mu_n + \mu_p)$$

$$J = q\, n_i\, (\mu_n + \mu_p)\, E$$

2-Extrinsic Semiconductors

Crystal contains **Si or Ge atoms** plus **impurities**.



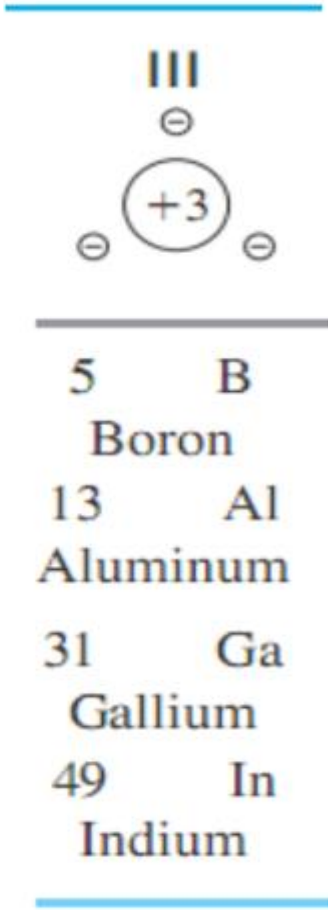
Impurities

Pentavalent atoms

These atoms with **five valence electrons:** such as arsenic (As), phosphorus (P), antimony (Sb).

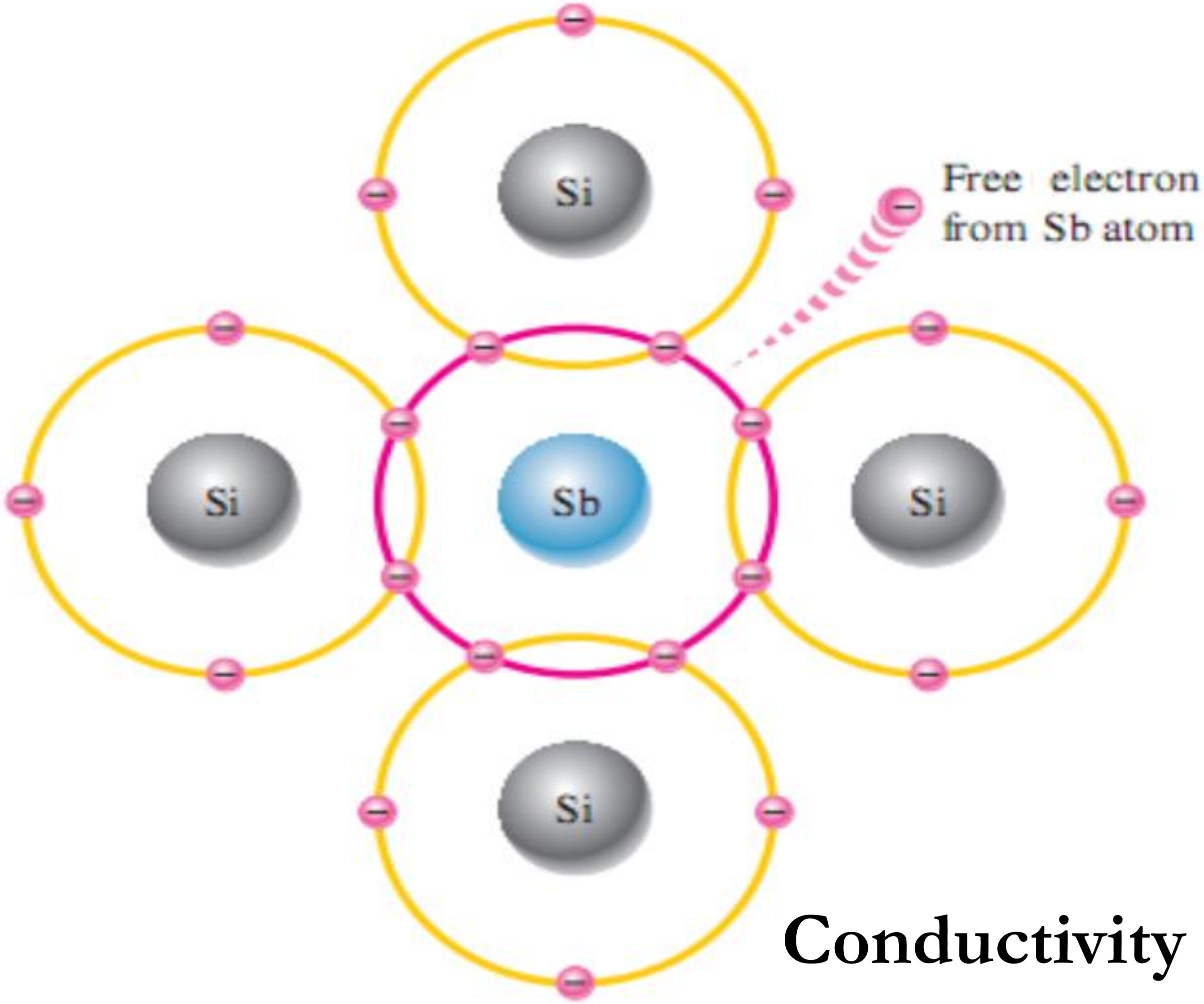
Trivalent atoms

These atoms with **three valence electrons:** such as boron (B), indium (In), gallium (Ga).

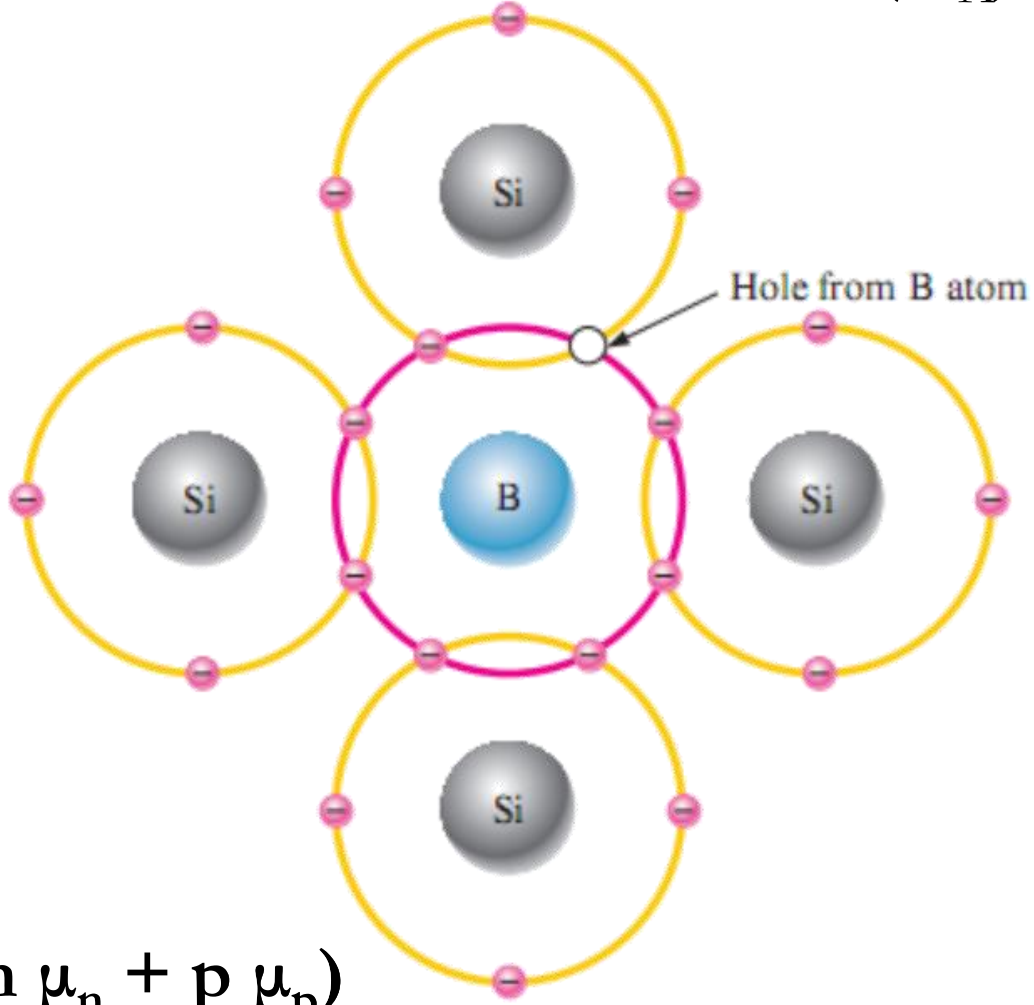


Extrinsic Semiconductors

Si or Ge + **Pentavalent atoms** (N_D)



Si or Ge + **Trivalent atoms** (N_A)

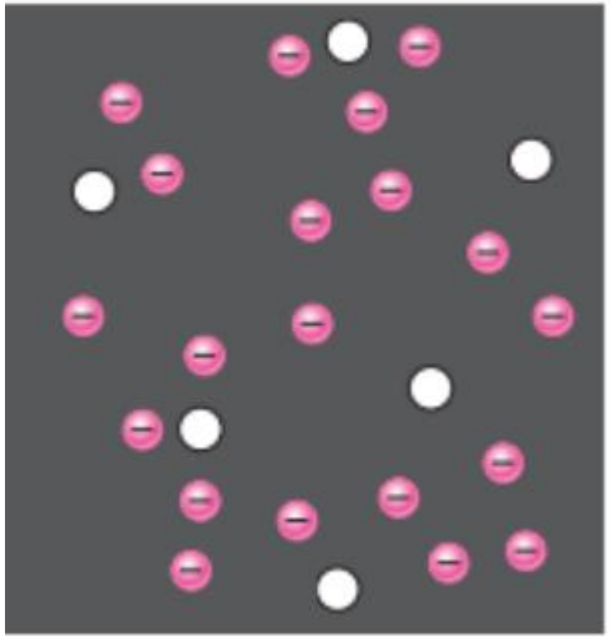


Conductivity (σ) = q (n μ_n + p μ_p)

Extrinsic Semiconductors

Si or Ge + Pentavalent atoms (N_D)

(n-type semiconductors)

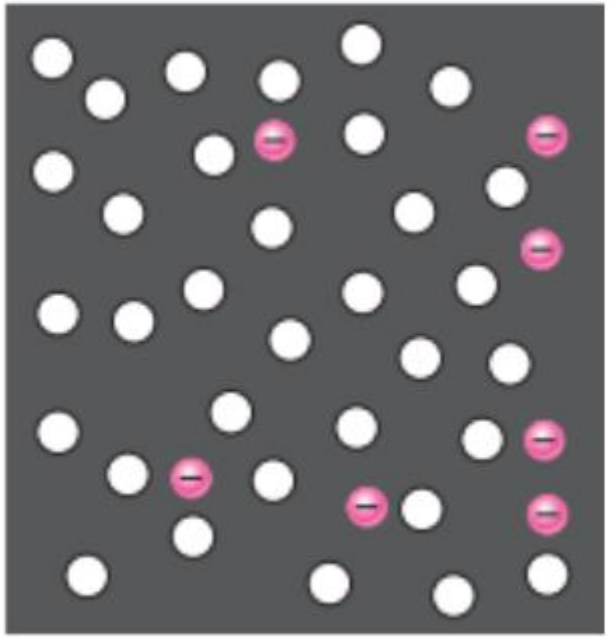


Electrons are majority carriers
Holes are minority carriers

$$n.p = n_i^2$$

Si or Ge + Trivalent atoms (N_A)

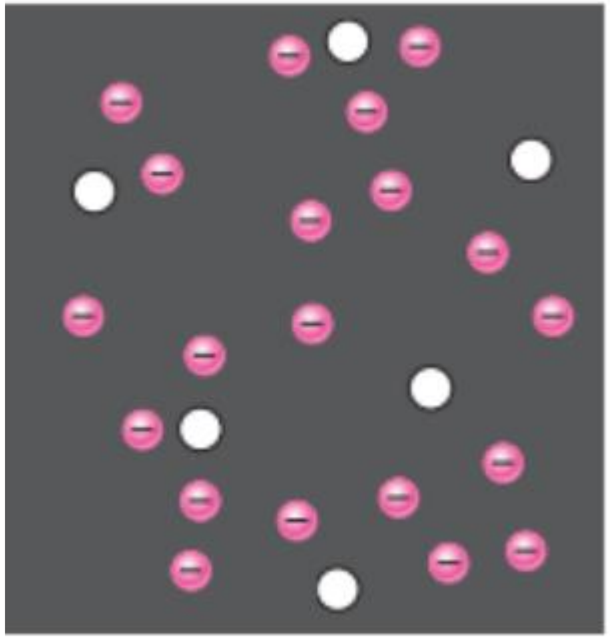
(p-type semiconductors)



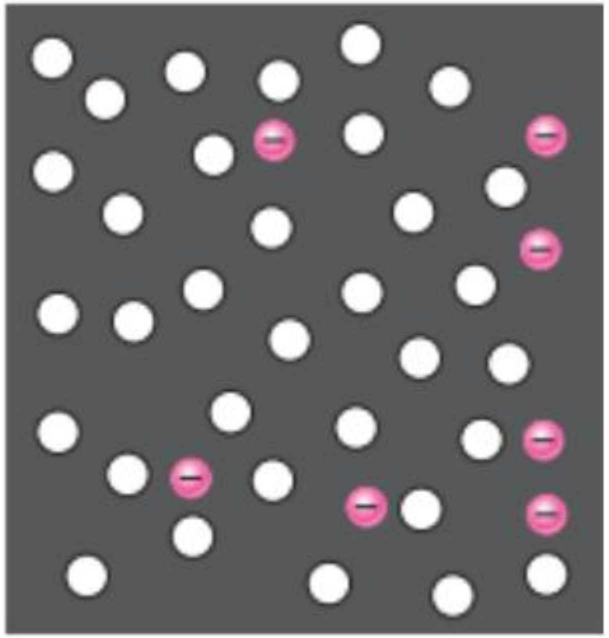
Holes are majority carriers
Electrons are minority carriers

Extrinsic Semiconductors

N-type semiconductors



P-type semiconductors



$$n.p = n_i^2$$

$$n \approx N_D$$

$$p \approx \frac{n_i^2}{N_D}$$

$$\sigma_{(n-type)} \approx q\,n\,\mu_n \approx qN_D\,\mu_n$$

$$J_{(n-type)} \approx q\,n\,\mu_n\,E \approx q\,N_D\,\mu_n\,E$$

$$\sigma_{(p-type)} \approx q\,p\,\mu_p \approx q\,N_A\,\mu_p$$

$$J_{(p-type)} \approx q\,p\,\mu_p\,E \approx q\,N_A\,\mu_p\,E$$

$$p \approx N_A$$

$$n \approx \frac{n_i^2}{N_A}$$

Extrinsic Semiconductors

N-type: Si or Ge + N_D

$$n \approx N_D$$

$$p \approx \frac{n_i^2}{N_D}$$

$$\sigma_{(n-type)} \approx qn\mu_n$$

$$J_{(n-type)} \approx qn\mu_n E$$

P-type: Si or Ge + N_A

$$p \approx N_A$$

$$n \approx \frac{n_i^2}{N_A}$$

$$\sigma_{(p-type)} \approx qp\mu_p$$

$$J_{(p-type)} \approx qp\mu_p E$$

Si or Ge + N_D + N_A

$$n.p = n_i^2$$

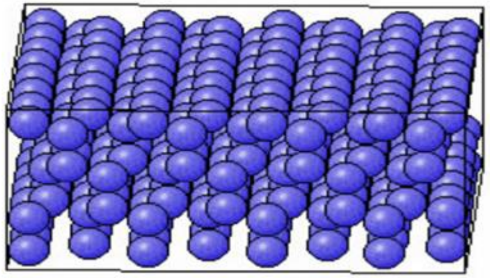
$$p + N_D = n + N_A$$

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

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

Find the resistivity of intrinsic Si and intrinsic Ge at 300K

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



Given at 300K:

n_i (Si) = $1.5x10^{10}$ atoms/cm^3
μ_n (Si) = 1300 cm^2 /V.s
μ_p (Si) = 500 cm^2 /V.s
n_i (Ge) = $2.5x10^{13}$ atoms/cm^3
μ_n (Ge) = 3800 cm^2 /V.s
μ_p (Ge) = 1800 cm^2 /V.s

$$\rho(Si) = \frac{1}{1.6x10^{-19}x1.5\text{x}10^{10}(1300 + 500)}$$

$$\rho(Si) = 2.3\text{x}10^5 \quad \Omega.cm$$

$$\rho(Ge) = \frac{1}{1.6x10^{-19}x2.5\text{x}10^{13}(3800 + 1800)}$$

$$\rho(Ge) = 45 \quad \Omega.cm$$

(a) Determine the concentration of free electrons (n) and holes (p) in a sample of germanium at 300K which has a concentration of donor atoms (N_D) equal to $2x10^{14}$ atoms/cm3 and a concentration of acceptor atoms (N_A) equal to $3x10^{14}$ atoms/cm3. Is this p-type or n-type germanium?

Solution

Sample of Ge atoms + N_D + N_A $\Rightarrow$

$$n.p = n_i^2$$

$$p + N_D = n + N_A$$

Given at 300K:

n_i (Ge) = $2.5x10^{13}$ atoms/cm^3

$$n\,p = n_i^2 \longrightarrow n = n_i^2/p$$

$$P + (N_D - N_A) - (n_i^2/p) = 0$$

$$P + (N_D - N_A) - (n_i^2 / p) = 0$$

Multiplying both sides by p

$$P^2 + (N_D - N_A)p - n_i^2 = 0$$

$$p = \frac{-(N_D - N_A) \pm \sqrt{(N_D - N_A)^2 + 4n_i^2}}{2}$$

$$p = \frac{-(N_D - N_A) \pm \sqrt{(N_D - N_A)^2 + 4\mathrm{n}_\mathrm{i}^2}}{2}$$

Choose the "+" sign since p > 0

$$p = \frac{-(-1 \times 10^{14}) + \sqrt{10^{28} + 2.5 \times 10^{27}}}{2}$$

$$= 1.06 \times 10^{14} holes/cm^3$$

$$n\,p = n_i^2$$

$$\longrightarrow \quad n = n_i^2 / p$$

$= 0.06 \times 10^{14}$ **electrons/cm^3**

$\because\ p > n$

Sample is p-type Ge

(b) Repeat part a for equal donor and acceptor concentration of 10^{15} atoms/cm^3. Is this p- or n-type germanium?

Solution

Sample of Ge atoms + N_D + N_A $\Rightarrow$ $p + N_D = n + N_A$

$$\because N_D = N_A$$

$$P = n$$

The sample is an intrinsic semiconductor

$$n = p = n_i = 2.5 \times 10^{13} \ /cm^3$$

(c) Repeat part a for donor concentration of 10^{16} atoms/cm^3 and acceptor concentration of 10^{14} atoms/cm^3

Since $N_D >> N_A$ The sample is n-type

$$n \approx N_D = 10^{16} \text{ electrons/cm}^3$$

$$p = n_i^2 / n = n_i^2 / N_D = 6.25 \times 10^{10} \text{ holes/cm}^3$$

Sample of germanium is doped to the extent of $2x10^{14}$ donor atoms/cm^3 and $3x10^{14}$ acceptor atoms/cm^3. At the temperature of the sample the resistivity of pure (intrinsic) germanium is 60 Ω-cm.
Assume that the value of the mobility of holes and electrons is approximately the same as at 300K (μp=1800 cm^2/V.s and μn=3800 cm^2/V.s). If the applied electric field intensity is 2V/cm, find the total conduction current density.

Solution:

Sample of Ge atoms + N_D + N_A ⇒

$$n.p = n_i^2$$

$$p + N_D = n + N_A$$

Find n_i from the given <u>intrinsic resistivity</u> by: ⇒

$$\rho_i = \frac{1}{qn_i(\mu_n + \mu_p)}$$

$$n_i = \frac{1}{q\rho_i(\mu_n + \mu_p)}$$

$$= \frac{1}{1.6\times10^{-19}\times60\times(3800+1800)}$$

$$= 1.86\times10^{13}cm^{-3}$$

$$n.p = n_i^2$$

$$p + N_D = n + N_A$$

$$n = n_i^2 / p$$

$$p = \frac{-(N_D - N_A) \pm \sqrt{(N_D - N_A)^2 + 4n_i^2}}{2}$$

$$p = 1.03x10^{14}$$ holes/cm^3

$$n = 3.36x10^{12}$$ electrons/cm^3

$$J = q\left(n\,\mu_n + p\,\mu_p\right)E$$

$$J = 0.032 \quad A/cm^2$$

Sample of silicon is 4 cm long and has square cross section 2x2 mm the current is due to electrons whose mobility is 1300 cm^2 /V.s. Two volts impressed across the bar results in a current of 8mA. Calculate

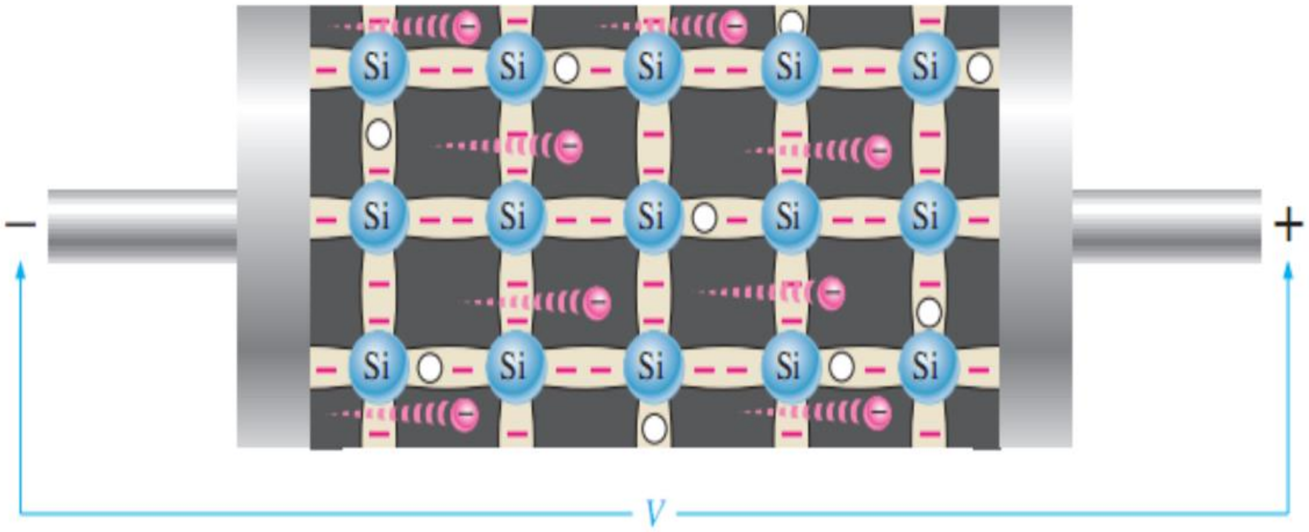
(a) Concentration of free electrons (n)

(b) Drift velocity (v_d).

$$\because J = \frac{I}{A} = \sigma E = q\, n\, \mu_n E = q\, n\, v_d = q\, n\, \mu_n \frac{V}{L} = q\, n\, \mu_n \frac{IR}{L}$$

$$\frac{I}{A} = q\, n\, \mu_n \frac{V}{L}$$

$$n = \frac{L}{q \mu_n V} \cdot \frac{I}{A}$$



$$n = \frac{L}{q\mu_n V} . \frac{I}{A} = \frac{(4x10^{-2}m)(8x10^{-3}A)}{(1.6x10^{-19}C)(1300x10^{-4}m^2/V.s)(2V)(2x10^{-3}mx2x10^{-3}m)}$$

$n = 1.92\text{x}10^{21}$ electrons/m³

$$\because J = \frac{I}{A} = qnv_d = qn\mu_n E = \sigma E = qn\mu_n \frac{V}{L} = qn\mu_n \frac{IR}{L}$$

$$v_d = \mu_n \frac{V}{L} \quad = \frac{(1300x10^{-4}m^2/V.s)(2V)}{(4x10^{-2}m)}$$

$v_d = 6.5$ m/s