Chapter 3   Basic Physics of Semiconductors

- 1 Semiconductor materials and their properties
- 2 PN-junction diodes
- 3 Reverse Breakdown

Semiconductor Physics

Semiconductors

- Charge Carriers
- Doping
- Transport of Carriers

PN Junction

- Structure
- Reverse and Forward Bias Conditions
- I/V Characteristics
- Circuit Models

- **Semiconductor devices serve as heart of microelectronics.**
- **PN junction is the most fundamental semiconductor device.**

Charge Carriers in Semiconductor

Charge Carriers in Solids

- Crystal Structure
- Bandgap Energy
- Holes

⇨

Modification of Carrier Densities

- Intrinsic Semiconductors
- Extrinsic Semiconductors
- Doping

⇨

Transport of Carriers

- Diffusion
- Drift

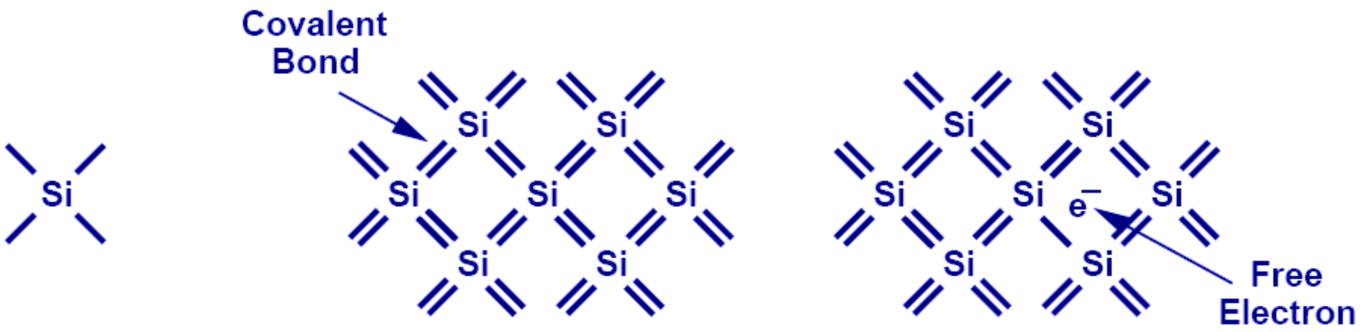
➢ **To understand PN junction's IV characteristics, it is important to understand charge carriers' behavior in solids, how to modify carrier densities, and different mechanisms of charge flow.**

Periodic Table

III	IV	V
Boron (B)	Carbon (C)	
Aluminum (Al)	Silicon (Si)	Phosphorous (P)
Galium (Al)	Germanium (Ge)	Arsenic (As)

- **This abridged table contains elements with three to five valence electrons, with Si being the most important.**

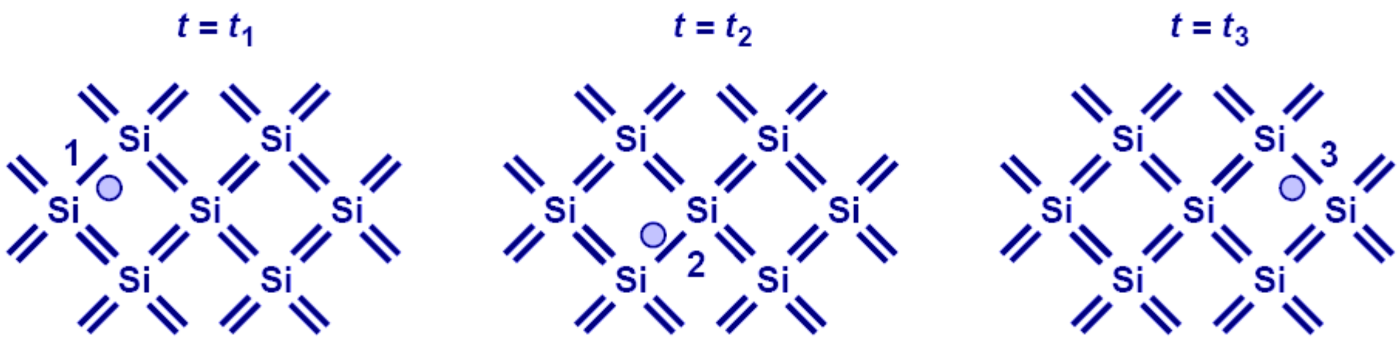
Silicon



(a) (b) (c)

- Si has four valence electrons. Therefore, it can form covalent bonds with four of its neighbors.
- When temperature goes up, electrons in the covalent bond can become free.

Electron-Hole Pair Interaction



- With free electrons breaking off covalent bonds, holes are generated.
- Holes can be filled by absorbing other free electrons, so effectively there is a flow of charge carriers.

Free Electron Density at a Given Temperature

$$n_i = 5.2 \times 10^{15} T^{3/2} \exp \frac{-E_g}{2kT} \, electrons / cm^3$$

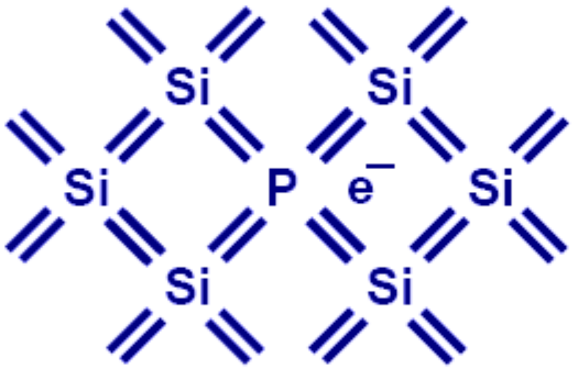
$$n_i (T = 300^0 K) = 1.08 \times 10^{10} \, electrons / cm^3$$

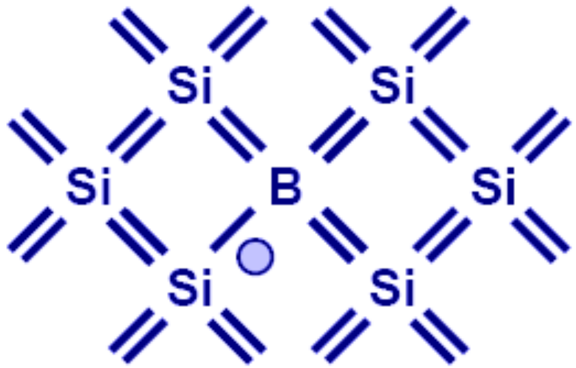
$$n_i (T = 600^0 K) = 1.54 \times 10^{15} \, electrons / cm^3$$

- **E_g, or bandgap energy determines how much effort is needed to break off an electron from its covalent bond.**
- **There exists an exponential relationship between the free-electron density and bandgap energy.**

Doping (N type and P type)

- Pure Si can be doped with other elements to change its electrical properties.

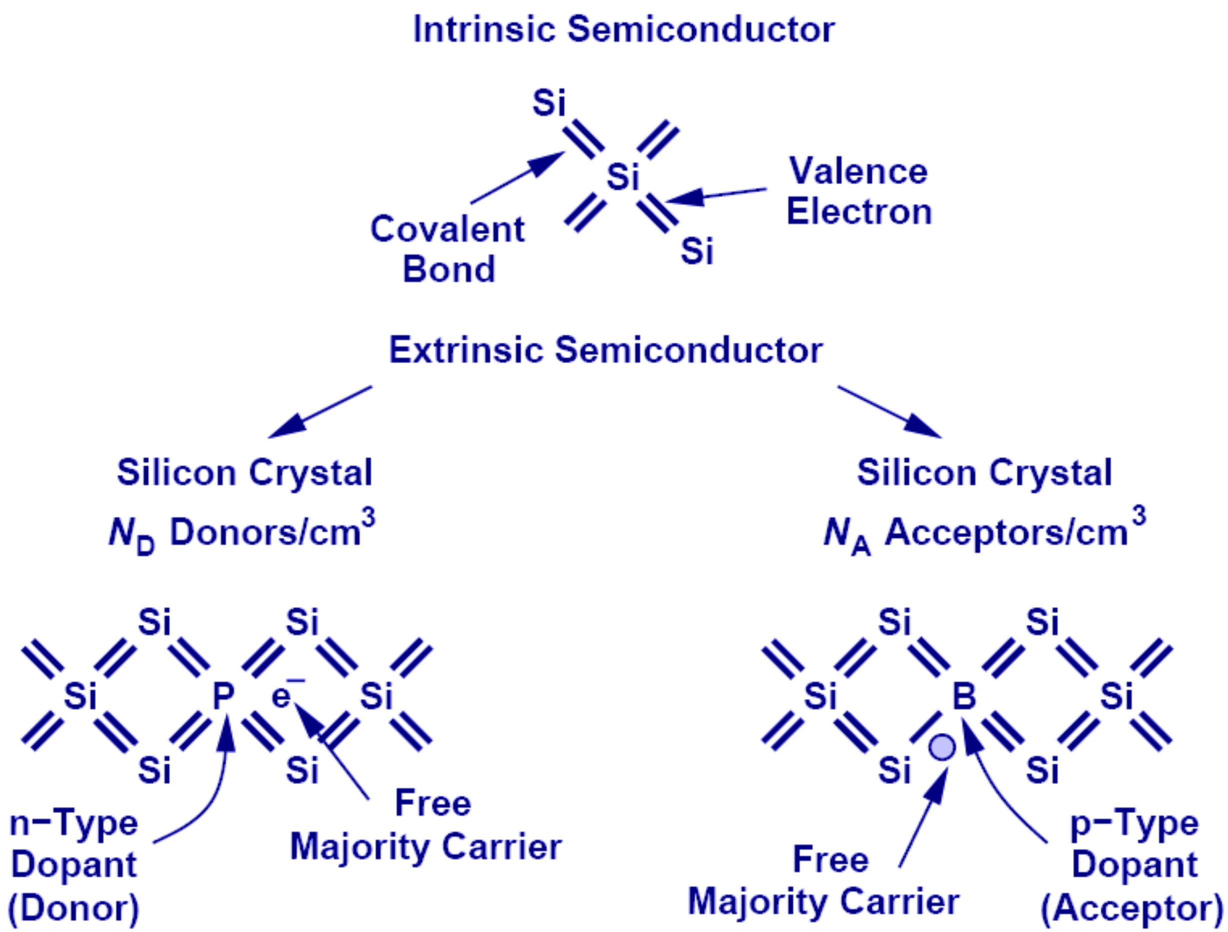




- If Si is doped with P (phosphorous), then it has more electrons, or becomes type N type.

- If Si is doped with B (boron), then it has more holes, or becomes type P.

Summary of Charge Carriers



Electron and Hole Densities

$$np = n_i^2$$

$$\text{Majority Carriers}: \quad p \approx N_A$$

$$\text{Minority Carriers}: \quad n \approx \frac{n_i^2}{N_A}$$

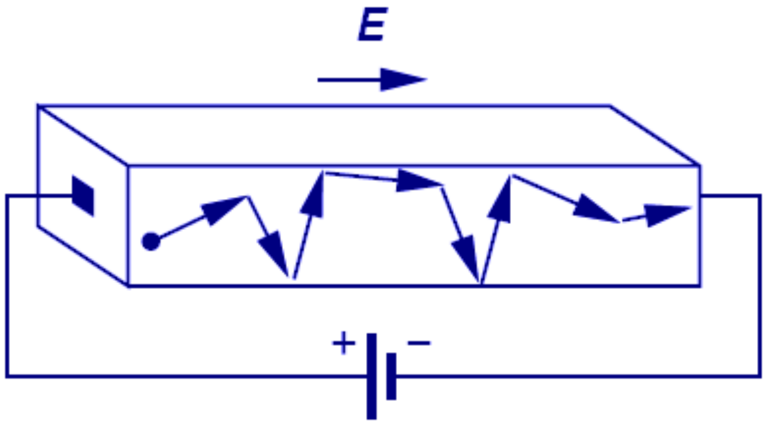
$$\text{Majority Carriers}: \quad n \approx N_D$$

$$\text{Minority Carriers}: \quad p \approx \frac{n_i^2}{N_D}$$

- **The product of electron and hole densities is ALWAYS equal to the square of intrinsic electron density regardless of doping levels.**

$$np = n_i^2$$

First Charge Transportation Mechanism: Drift

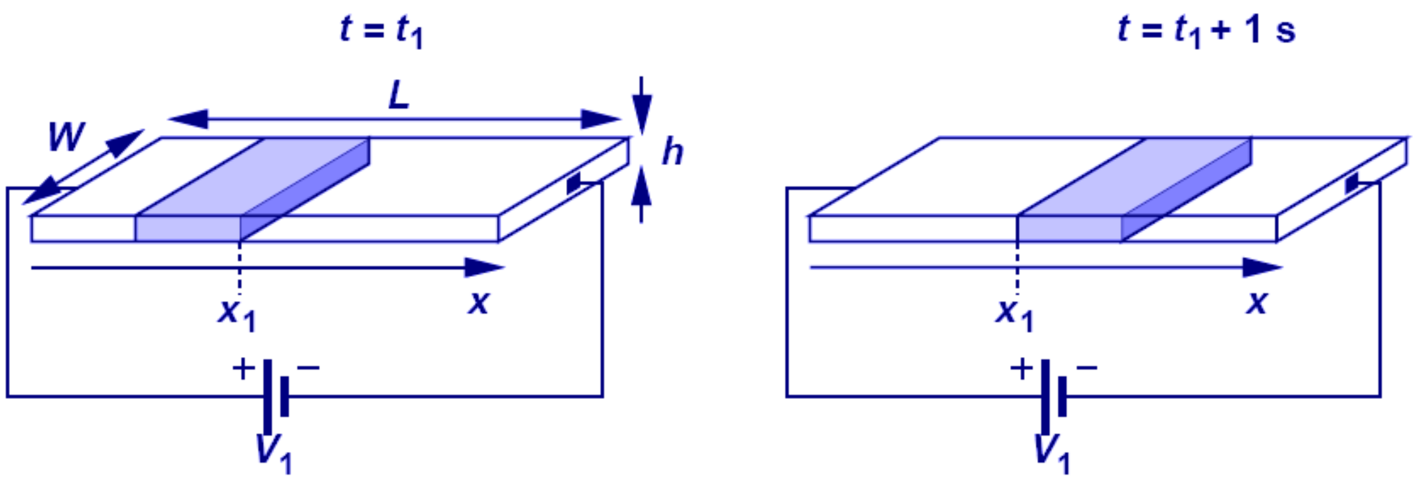


$$\vec{v}_h = \mu_p \vec{E}$$

$$\vec{v}_e = -\mu_n \vec{E}$$

- The process in which charge particles move because of an electric field is called drift.
- Charge particles will move at a velocity that is proportional to the electric field.

Current Flow: General Case



$$I = -v \cdot W \cdot h \cdot n \cdot q$$

- **Electric current is calculated as the amount of charge in *v* meters that passes thru a cross-section if the charge travel with a velocity of *v* m/s.**

Current Flow: Drift

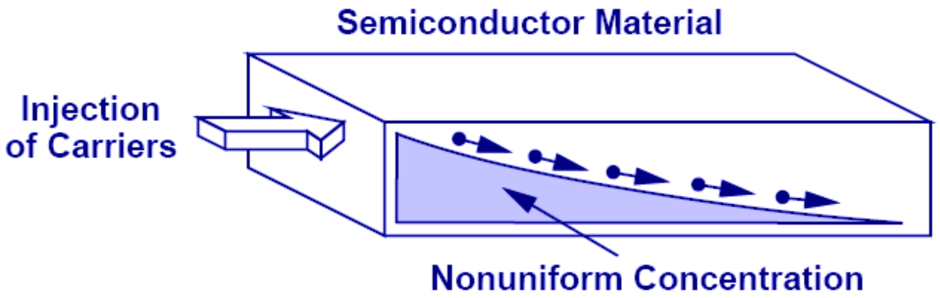
$$J_n = \mu_n E \cdot n \cdot q$$

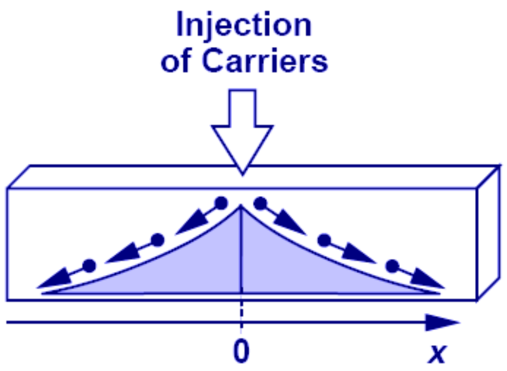
$$J_{tot} = \mu_n E \cdot n \cdot q + \mu_p E \cdot p \cdot q$$

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

- **Since velocity is equal to μE, drift characteristic is obtained by substituting V with μE in the general current equation.**
- **The total current density consists of both electrons and holes.**

Second Charge Transportation Mechanism: Diffusion





- Charge particles move from a region of high concentration to a region of low concentration. It is analogous to an every day example of an ink droplet in water.

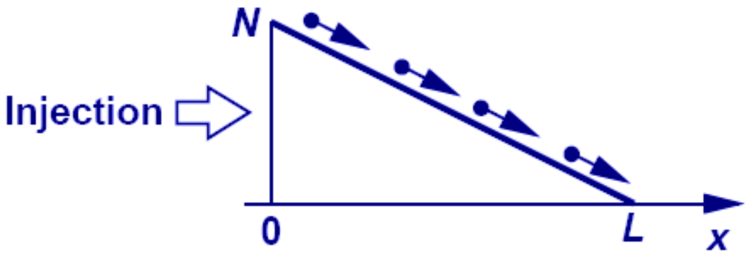
Current Flow: Diffusion

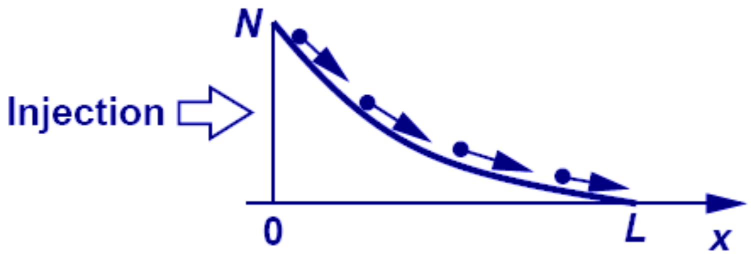
$$I = AqD_n \frac{dn}{dx} \qquad J_p = -qD_p \frac{dp}{dx}$$

$$J_n = qD_n \frac{dn}{dx} \qquad J_{tot} = q(D_n \frac{dn}{dx} - D_p \frac{dp}{dx})$$

- **Diffusion current is proportional to the gradient of charge (dn/dx) along the direction of current flow.**
- **Its total current density consists of both electrons and holes.**

Example: Linear vs. Nonlinear Charge Density Profile





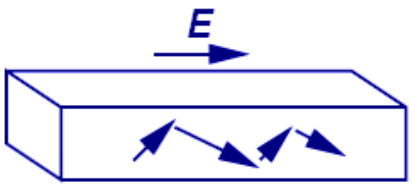
$$J_n = qD_n \frac{dn}{dx} = -qD_n \cdot \frac{N}{L}$$

$$J_n = qD \frac{dn}{dx} = \frac{-qD_n N}{L_d} \exp \frac{-x}{L_d}$$

- **Linear charge density profile means constant diffusion current, whereas nonlinear charge density profile means varying diffusion current.**

Einstein's Relation

Drift Current



$$J_n = q\,\mu_n E$$

$$J_p = q\,\mu_p$$

Diffusion Current

$$J_n = q\,D_n \frac{dn}{dx}$$

$$J_n = -q\,D_p \frac{dp}{dx}$$

$$\frac{D}{\mu} = \frac{kT}{q}$$

- **While the underlying physics behind drift and diffusion currents are totally different, Einstein's relation provides a mysterious link between the two.**