Chapter 2 Basic Physics of Semiconductors

- 2.1 Semiconductor materials and their properties
- 2.2 PN-junction diodes
- 2.3 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

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Modification of Carrier Densities

- Intrinsic Semiconductors
- Extrinsic Semiconductors
- Doping

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Transport of Carriers

- Diffusion
- Drift

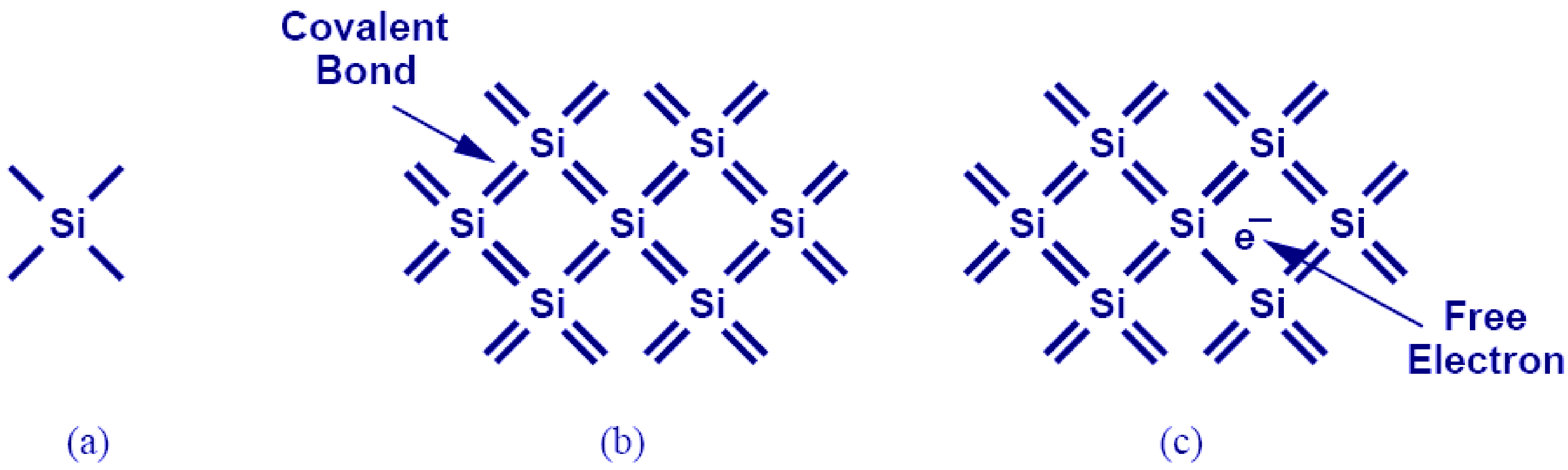
➢ **To understand PN junction's IV characteristics, it is important to understand charge carriers' behavior in solids, how to modify carrier densities, and different mechanisms of charge flow.**

Periodic Table

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

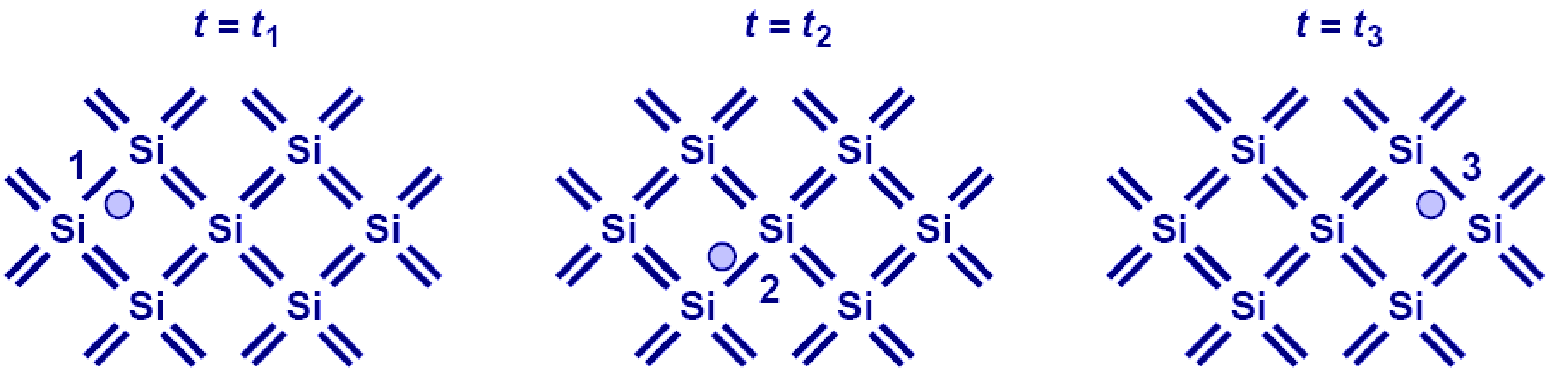
- This abridged table contains elements with three to five valence electrons, with Si being the most important.

Silicon



- 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

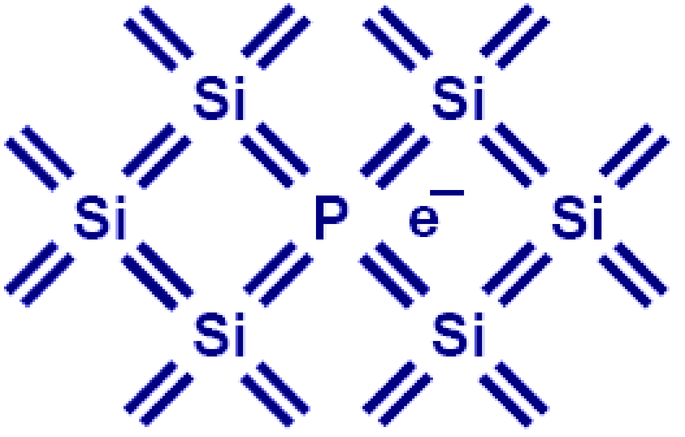
$$n_i = 5.2 \times 10^{15} T^{3/2} \exp\frac{-E_g}{2kT} \, electrons/cm^3$$

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

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

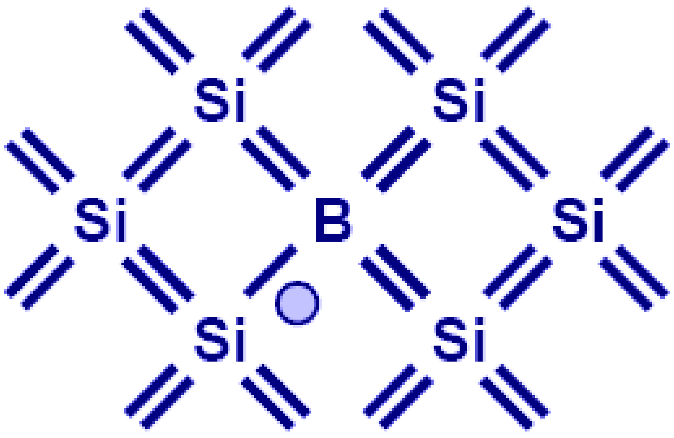
- ***E_g*, or bandgap energy determines how much effort is needed to break off an electron from its covalent bond.**
- **There exists an exponential relationship between the free-electron density and bandgap energy.**

Doping (N type)



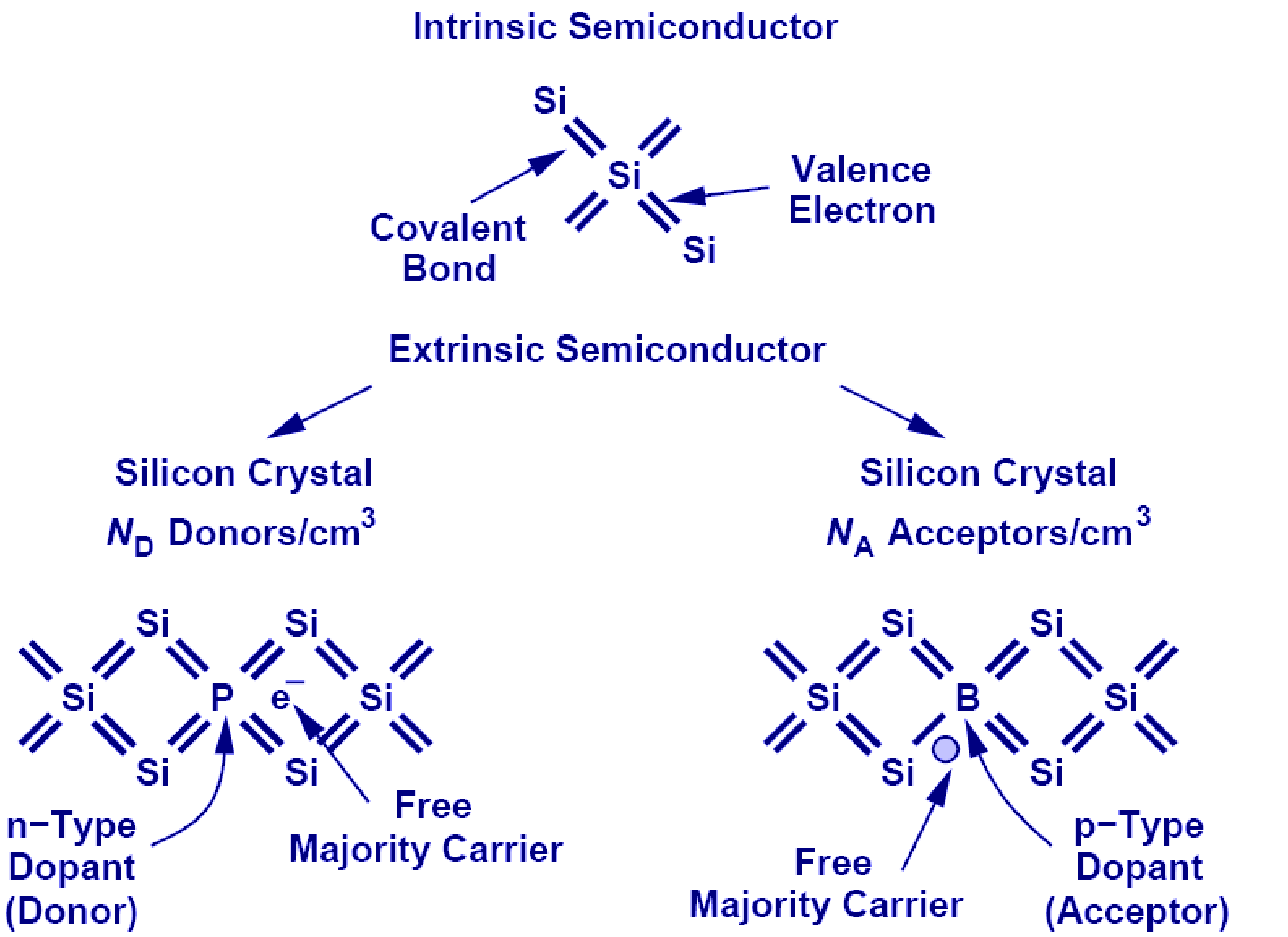
- Pure Si can be doped with other elements to change its electrical properties.
- For example, if Si is doped with P (phosphorous), then it has more electrons, or becomes type N (electron).

Doping (P 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

$$np = n_i^2$$

Majority Carriers : $p \approx N_A$

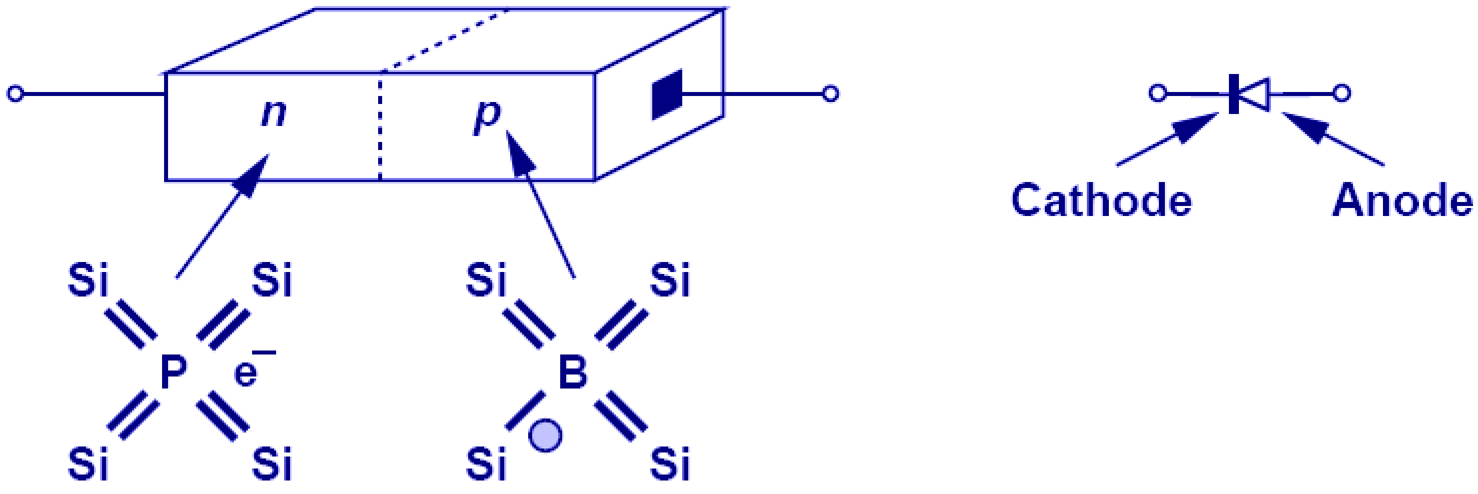
Minority Carriers : $n \approx \frac{n_i^2}{N_A}$

Majority Carriers : $n \approx N_D$

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

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

PN Junction (Diode)



(a) (b)

- When N-type and P-type dopants are introduced side-by-side in a semiconductor, a PN junction or a diode is formed.

Diode's Three Operation Regions

PN Junction in Equilibrium

- Depletion Region
- Built−in Potential

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PN Junction Under Reverse Bias

- Junction Capacitance

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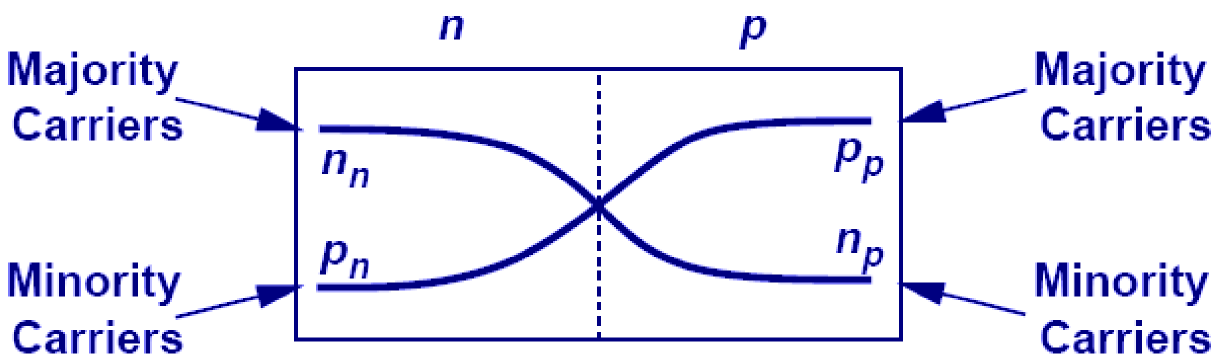
PN Junction Under Forward Bias

- I/V Characteristics

➢ **In order to understand the operation of a diode, it is necessary to study its three operation regions: equilibrium, reverse bias, and forward bias.**

Current Flow Across Junction: Diffusion



n_n : Concentration of electrons on n side

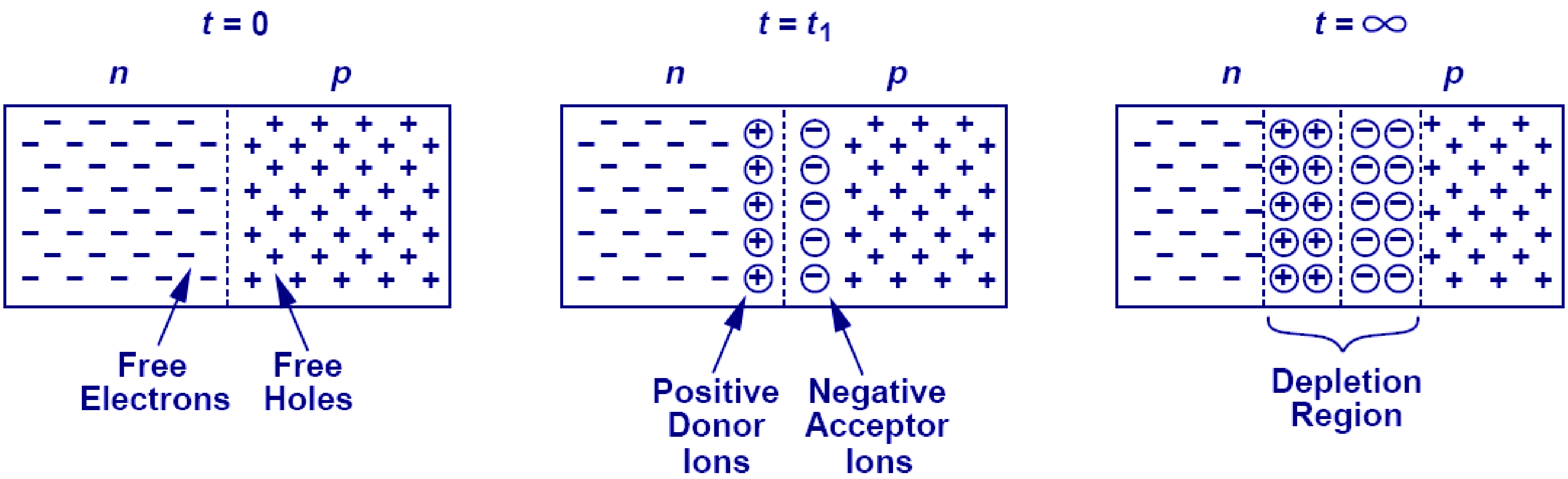
p_n : Concentration of holes on n side

p_p : Concentration of holes on p side

n_p : Concentration of electrons on p side

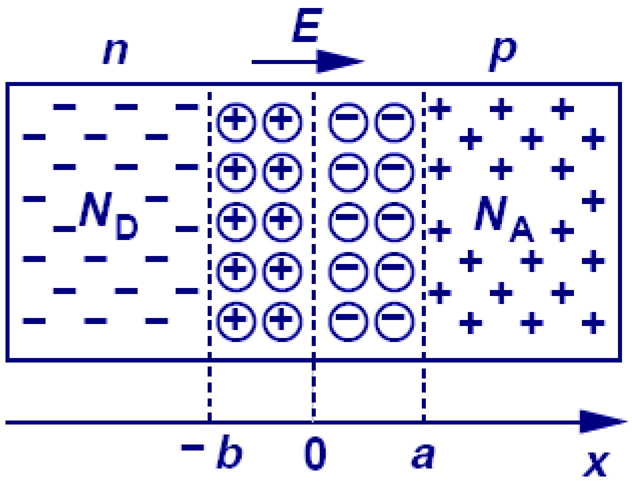
- **Because each side of the junction contains an excess of holes or electrons compared to the other side, there exists a large concentration gradient. Therefore, a diffusion current flows across the junction from each side.**

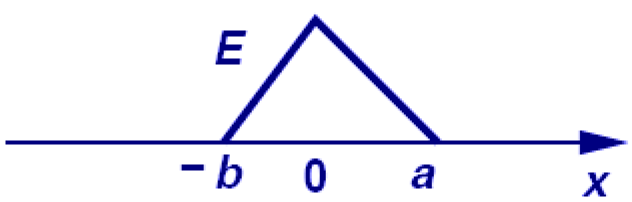
Depletion Region



- **As free electrons and holes diffuse across the junction, a region of fixed ions is left behind. This region is known as the "depletion region."**

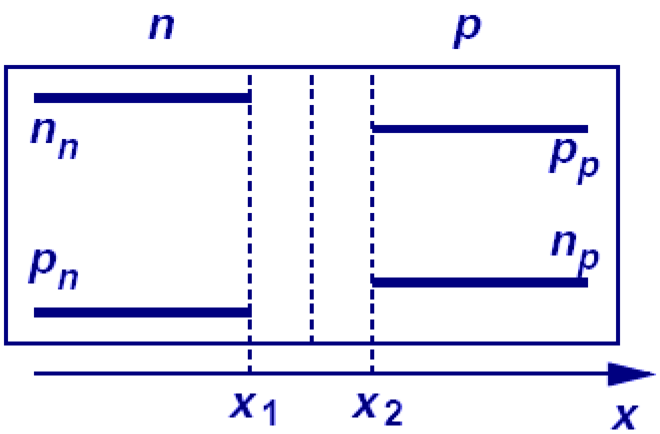
Current Flow Across Junction: Drift





- **The fixed ions in depletion region create an electric field that results in a drift current.**

Current Flow Across Junction: Equilibrium



$$I_{drift,p} = I_{diff,p}$$
$$I_{drift,n} = I_{diff,n}$$

- **At equilibrium, the drift current flowing in one direction cancels out the diffusion current flowing in the opposite direction, creating a net current of zero.**
- **The figure shows the charge profile of the PN junction.**

Built-in Potential

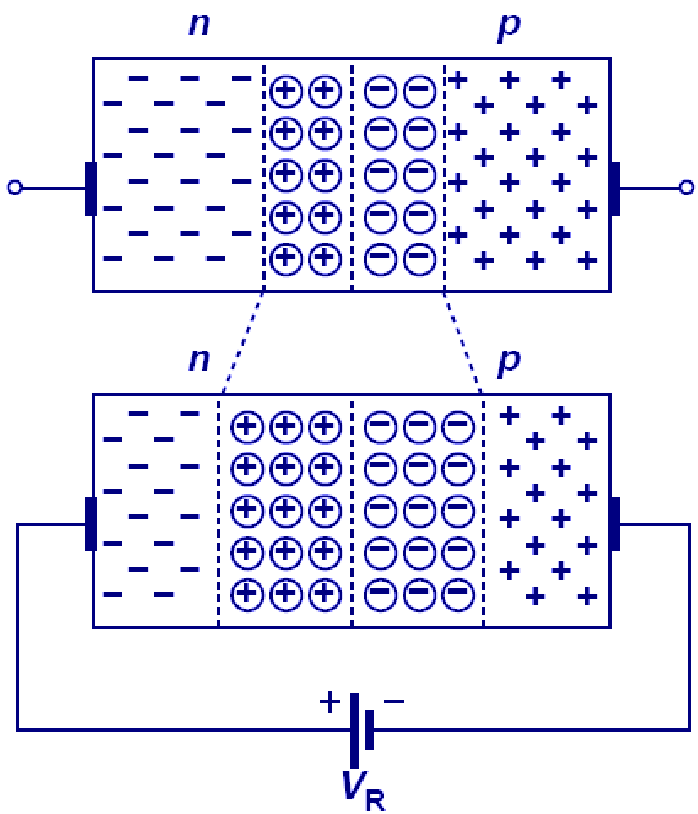
$$q\mu_p pE = -qD_p \frac{dp}{dx} \qquad -\mu_p p \frac{dV}{dx} = -D_p \frac{dp}{dx}$$

$$\mu_p \int_{x_1}^{x_2} dV = D_p \int_{p_p}^{p_n} \frac{dp}{p} \qquad V(x_2) - V(x_1) = \frac{D_p}{\mu_p} \ln \frac{p_p}{p_n}$$

$$V_0 = \frac{kT}{q} \ln \frac{p_p}{p_n}, V_0 = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2}$$

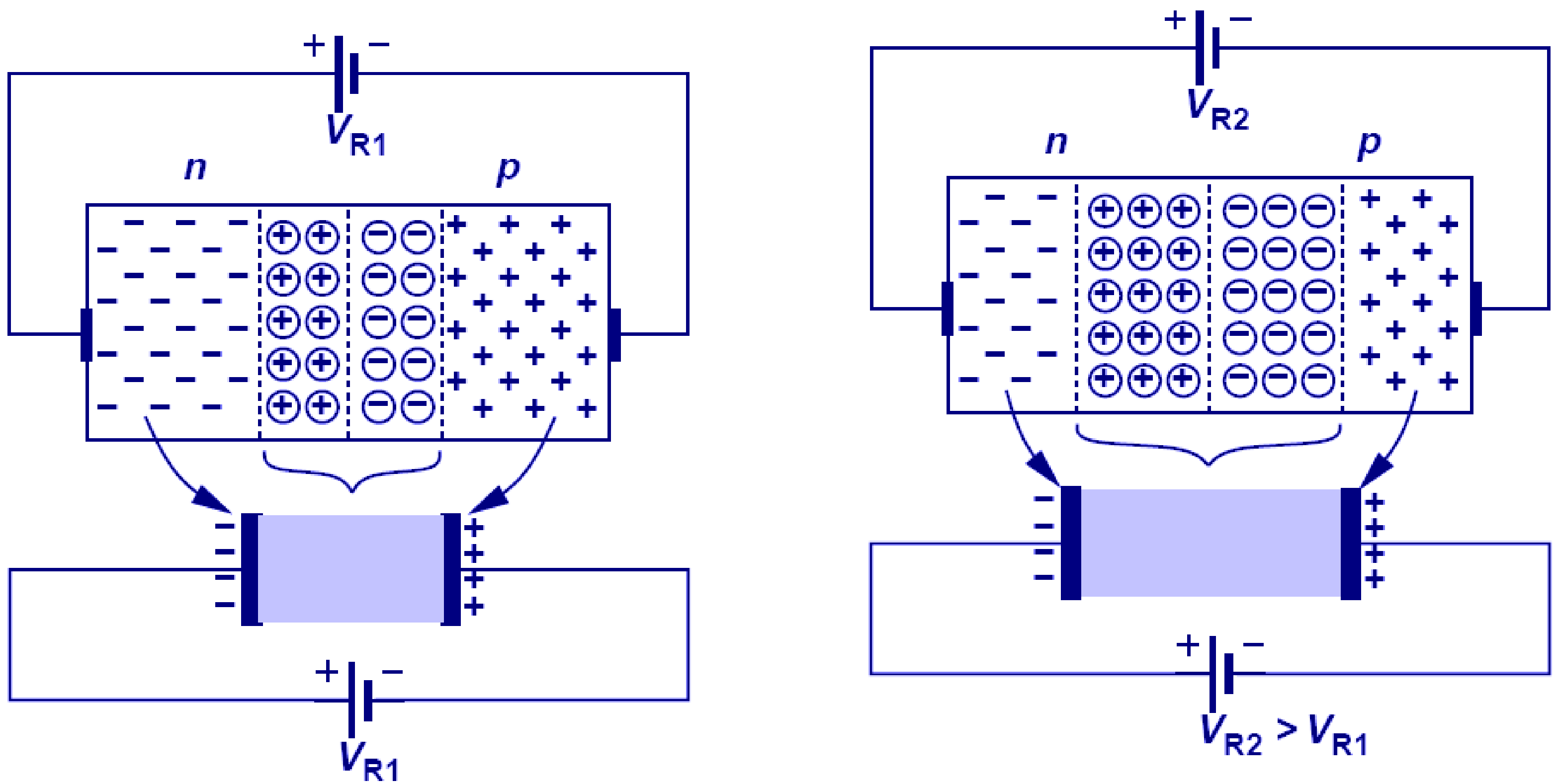
- **Because of the electric field across the junction, there exists a built-in potential. Its derivation is shown above.**

Diode in Reverse Bias



- **When the N-type region of a diode is connected to a higher potential than the P-type region, the diode is under reverse bias, which results in wider depletion region and larger built-in electric field across the junction.**

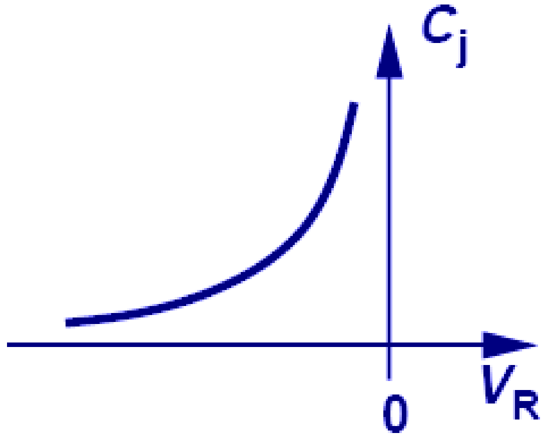
Reverse Biased Diode's Application: Voltage-Dependent Capacitor



(a) (b)

- The PN junction can be viewed as a capacitor. By varying V_R, the depletion width changes, changing its capacitance value; therefore, the PN junction is actually a voltage-dependent capacitor.

Voltage-Dependent Capacitance

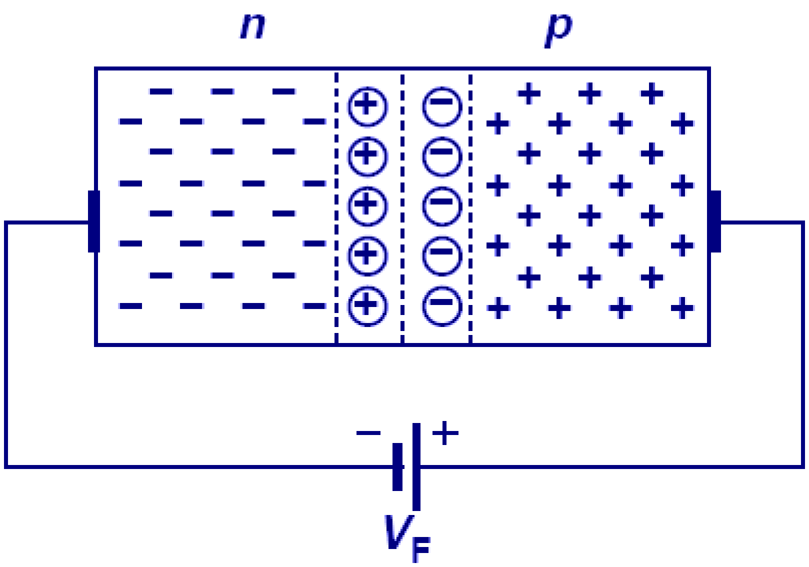


$$C_j = \frac{C_{j0}}{\sqrt{1 + \frac{V_R}{V_0}}}$$

$$C_{j0} = \sqrt{\frac{\varepsilon_{si} q}{2} \frac{N_A N_D}{N_A + N_D} \frac{1}{V_0}}$$

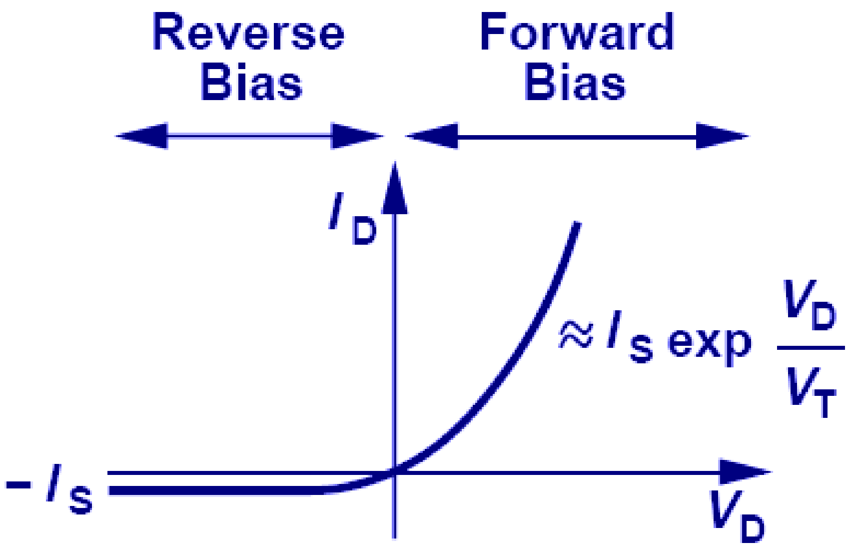
- **The equations that describe the voltage-dependent capacitance are shown above.**

Diode in Forward Bias



- When the N-type region of a diode is at a lower potential than the P-type region, the diode is in forward bias.
- The depletion width is shortened and the built-in electric field decreased.

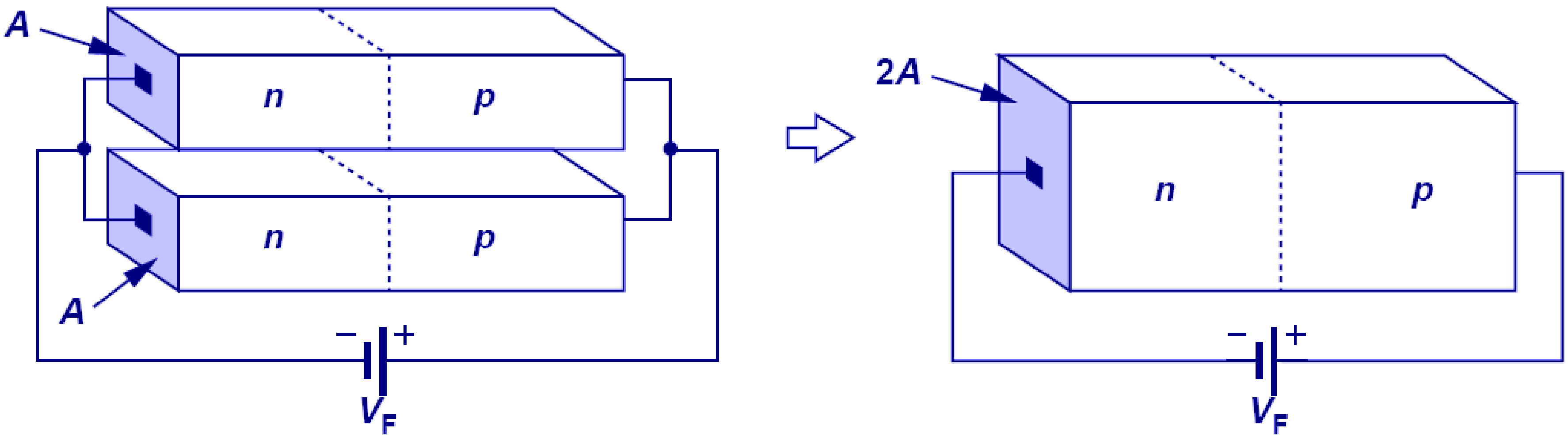
IV Characteristic of PN Junction



$$I_D = I_S\left(\exp\frac{V_D}{V_T} - 1\right)$$

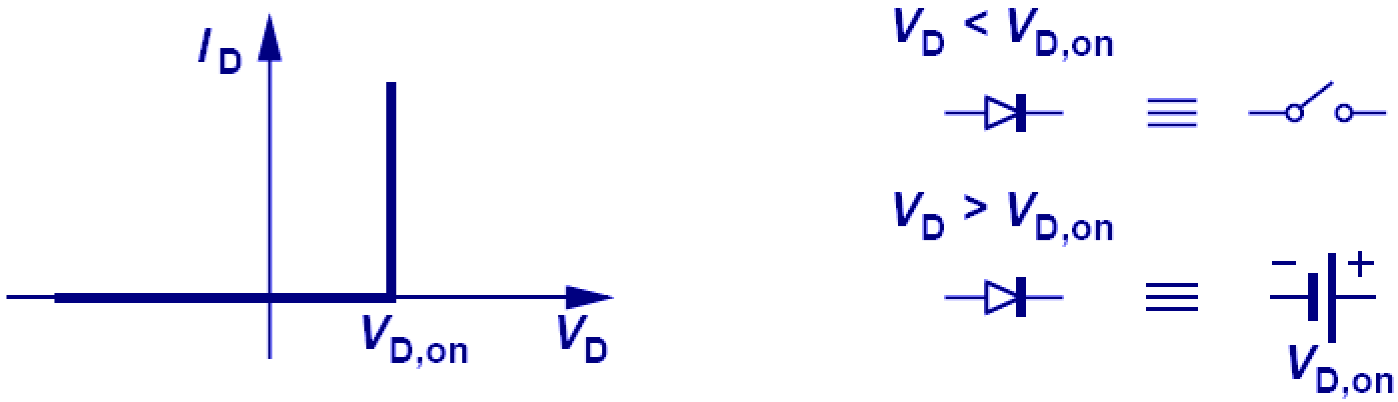
- **The current and voltage relationship of a PN junction is exponential in forward bias region, and relatively constant in reverse bias region.**

Parallel PN Junctions



- Since junction currents are proportional to the junction's cross-section area. Two PN junctions put in parallel are effectively one PN junction with twice the cross-section area, and hence twice the current.

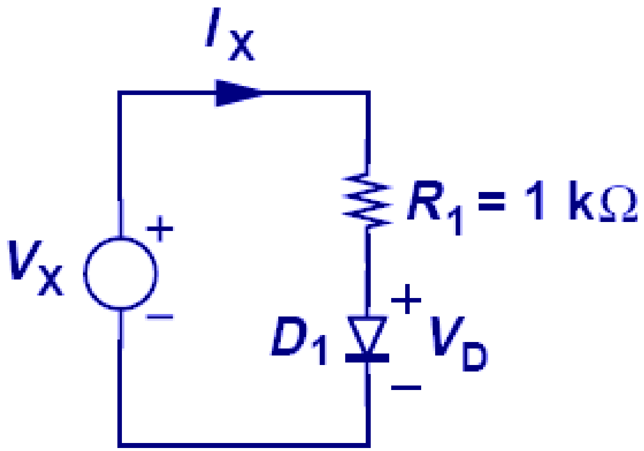
Constant-Voltage Diode Model



(a) (b)

- **Diode operates as an open circuit if $V_D < V_{D,on}$ and a constant voltage source of $V_{D,on}$ if V_D tends to exceed $V_{D,on}$.**

Example: Diode Calculations



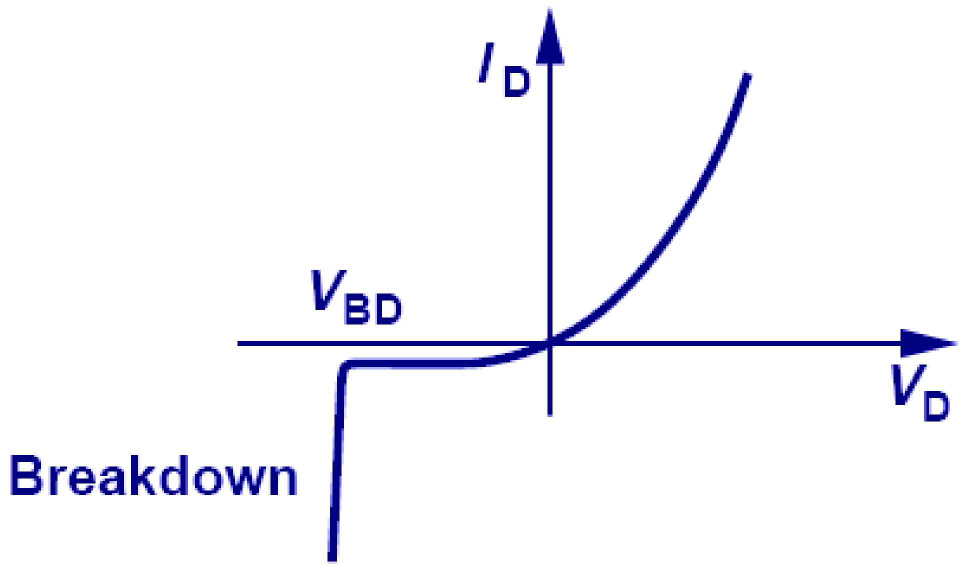
$$V_X = I_X R_1 + V_D = I_X R_1 + V_T \ln \frac{I_X}{I_S}$$

$$I_X = 2.2mA \quad for \quad V_X = 3V$$

$$I_X = 0.2mA \quad for \quad V_X = 1V$$

- This example shows the simplicity provided by a constant-voltage model over an exponential model.
- For an exponential model, iterative method is needed to solve for current, whereas constant-voltage model requires only linear equations.

Reverse Breakdown



- When a large reverse bias voltage is applied, breakdown occurs and an enormous current flows through the diode.