

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

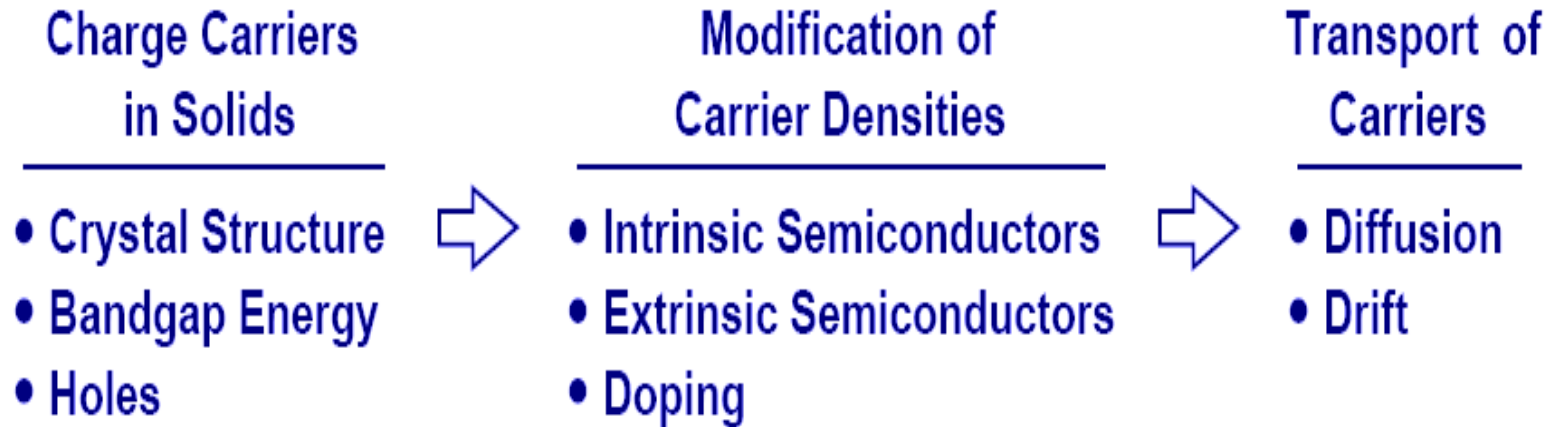
- Charge Carriers
- Doping
- Transport of Carriers

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



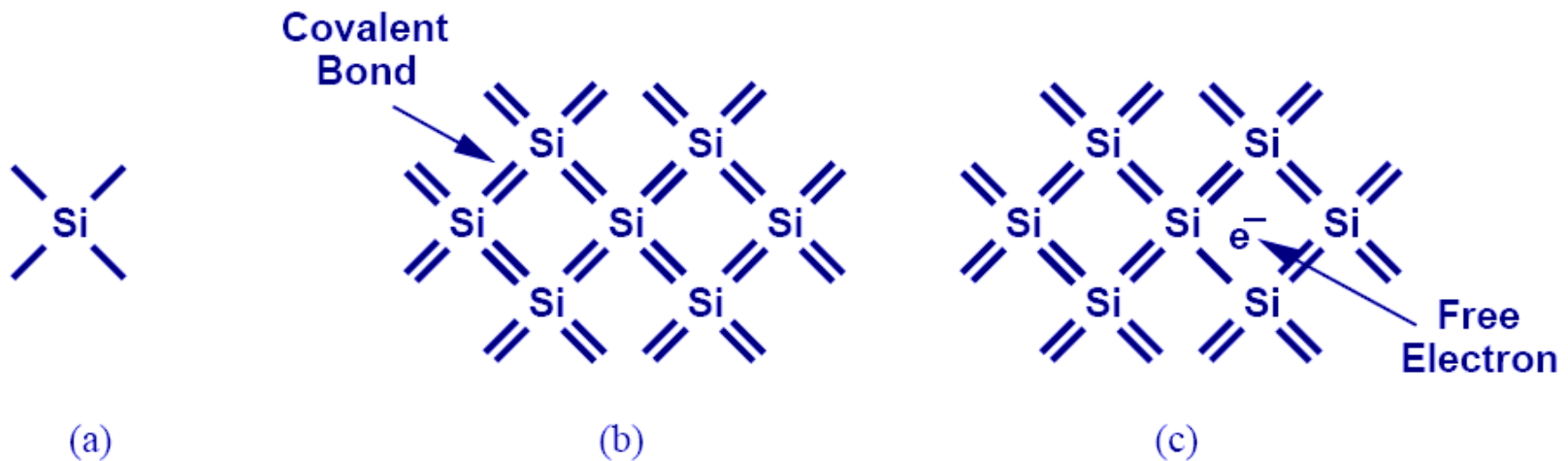
➤ **To understand PN junction's IV characteristics, it is important to understand charge carriers' behavior in solids, how to modify carrier densities, and different mechanisms of charge flow.**

Periodic Table

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

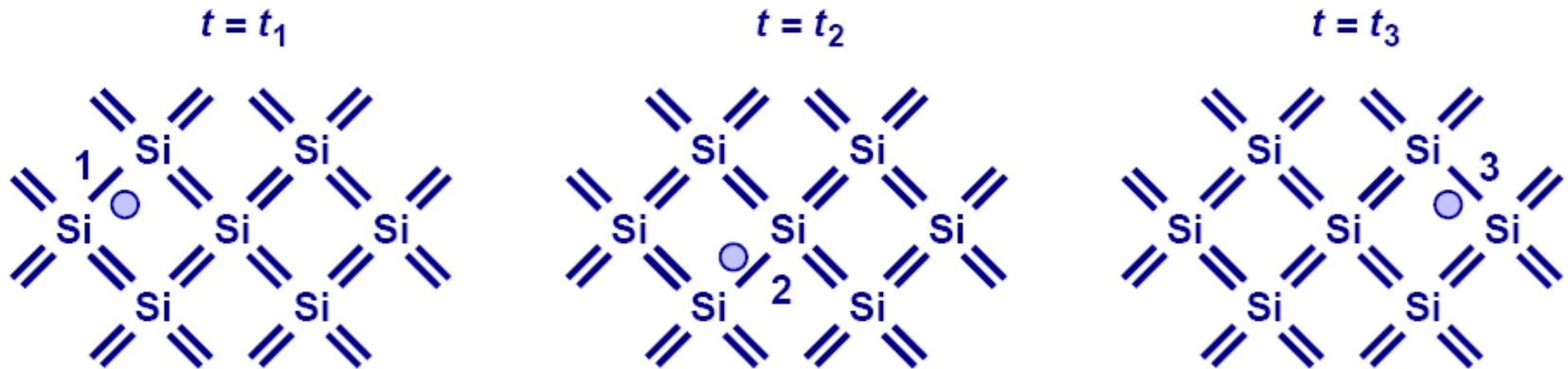
➤ This abridged table contains elements with three to five valence electrons, with Si being the most important.

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

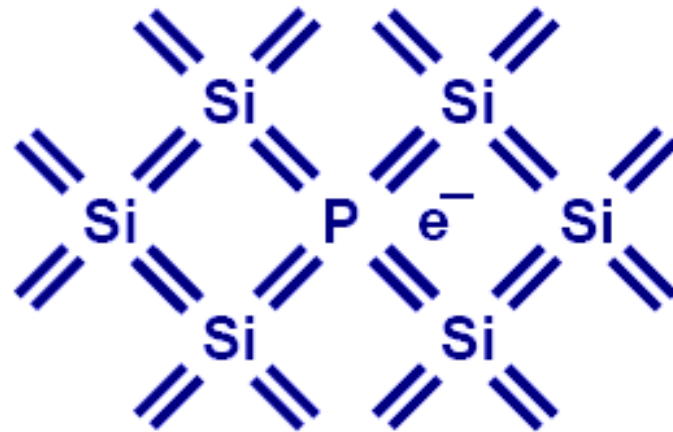
$$n_i = 5.2 \times 10^{15} T^{3/2} \exp \frac{-E_g}{2kT} \text{ electrons/cm}^3$$

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

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

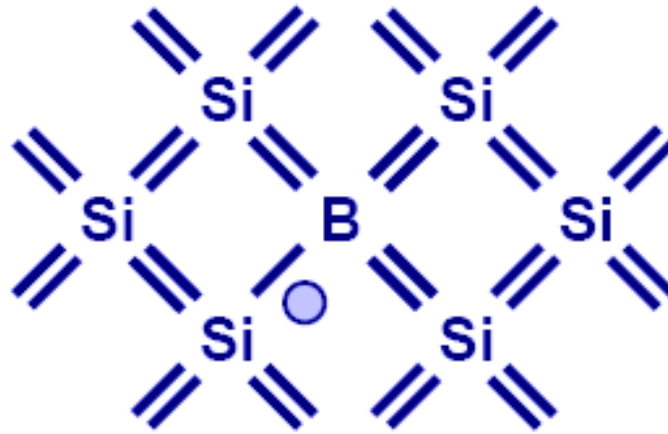
- E_g , or bandgap energy determines how much effort is needed to break off an electron from its covalent bond.
- There exists an exponential relationship between the free-electron density and bandgap energy.

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).

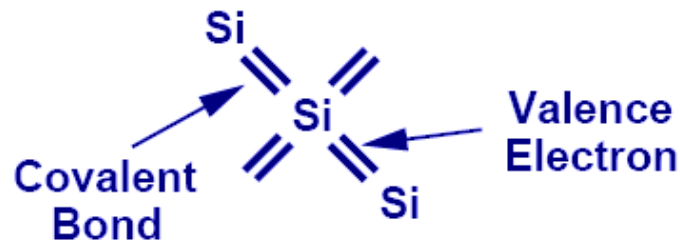
Doping (P type)



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

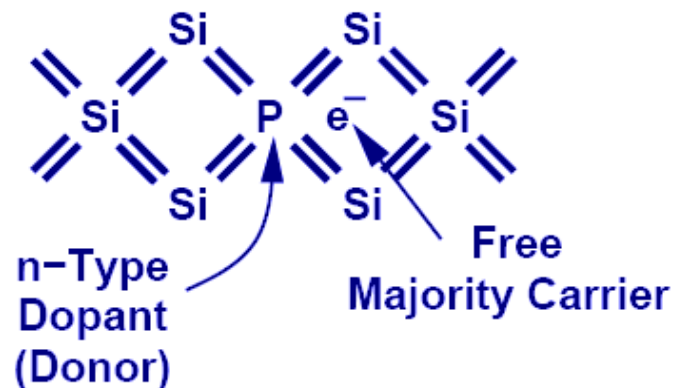
Summary of Charge Carriers

Intrinsic Semiconductor

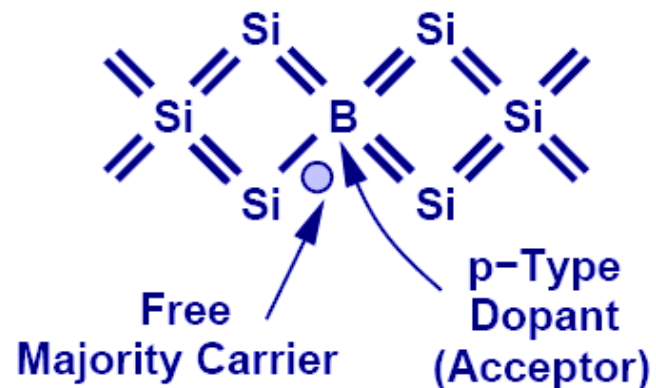


Extrinsic Semiconductor

Silicon Crystal
 N_D Donors/cm³



Silicon Crystal
 N_A Acceptors/cm³



Electron and Hole Densities

$$np = n_i^2$$

Majority Carriers : $p \approx N_A$

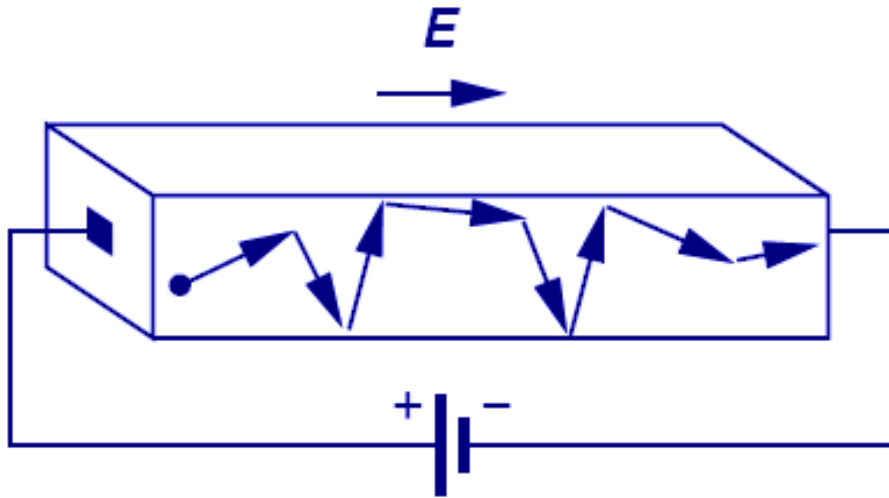
Minority Carriers : $n \approx \frac{n_i^2}{N_A}$

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.

First Charge Transportation Mechanism: Drift

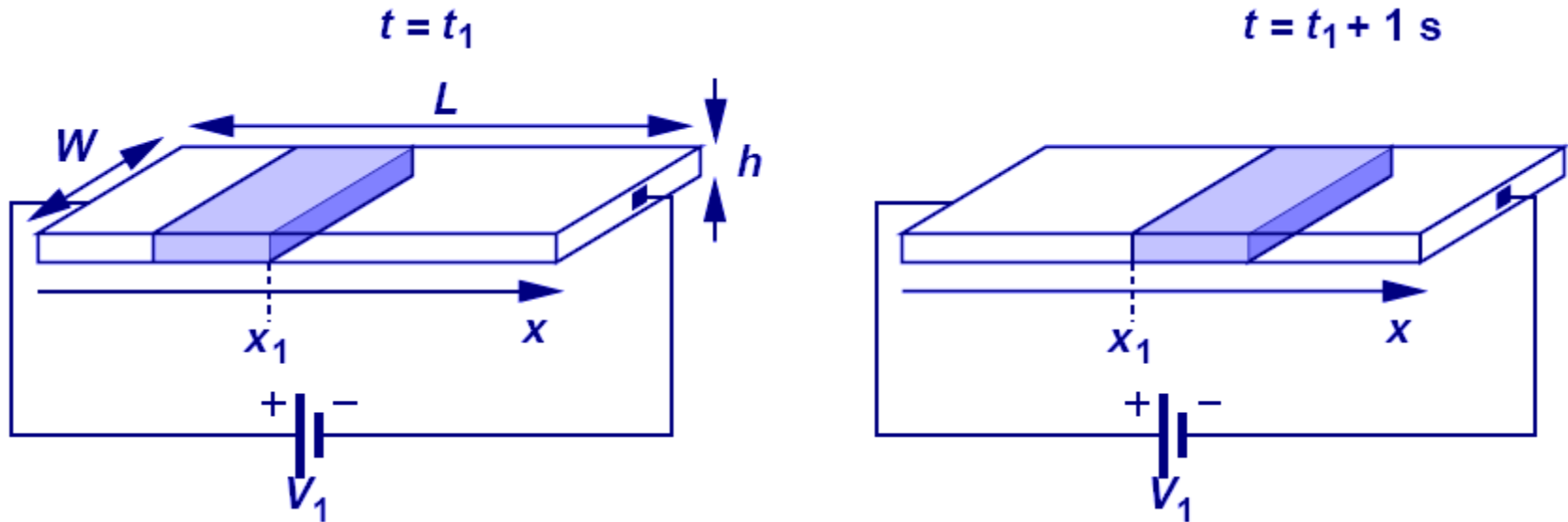


$$\vec{v}_h = \mu_p \vec{E}$$

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

- 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

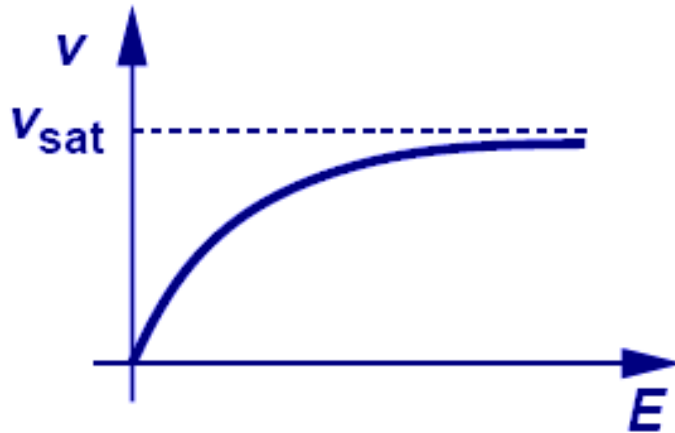
$$J_n = \mu_n E \cdot n \cdot q$$

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

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

- 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.

Velocity Saturation



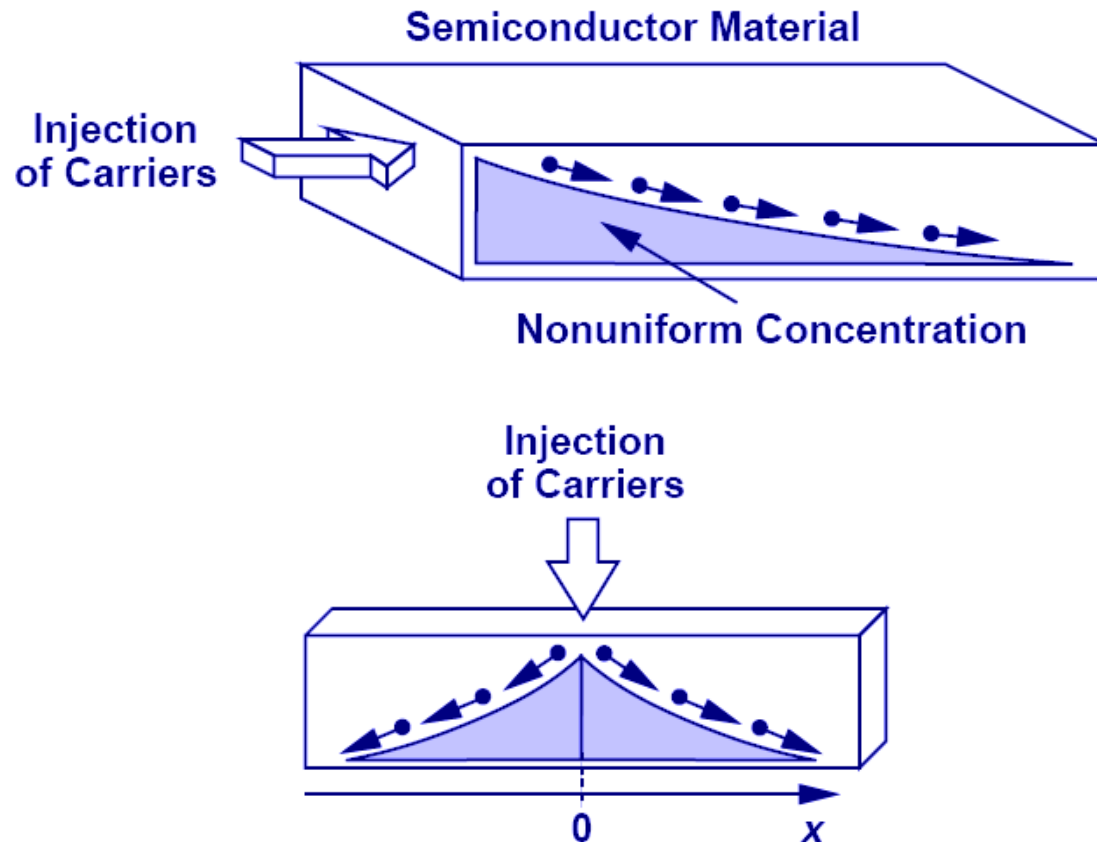
$$\mu = \frac{\mu_0}{1 + bE}$$

$$v_{sat} = \frac{\mu_0}{b}$$

$$v = \frac{\mu_0}{1 + \frac{\mu_0 E}{v_{sat}}} E$$

- A topic treated in more advanced courses is velocity saturation.
- In reality, velocity does not increase linearly with electric field. It will eventually saturate to a critical value.

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

$$I = AqD_n \frac{dn}{dx}$$

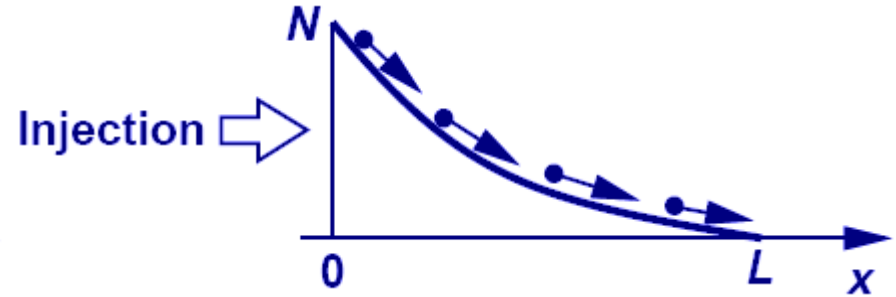
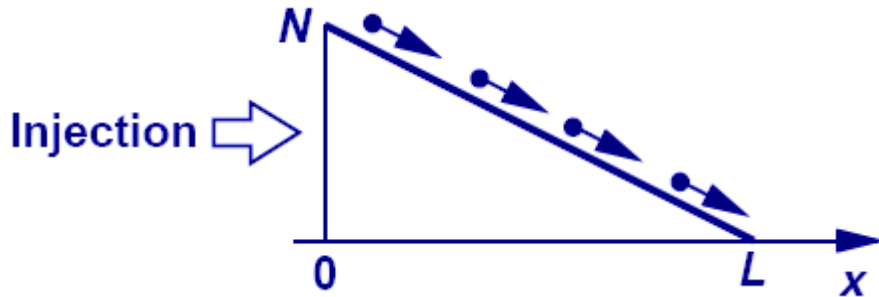
$$J_p = -qD_p \frac{dp}{dx}$$

$$J_n = qD_n \frac{dn}{dx}$$

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

- 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



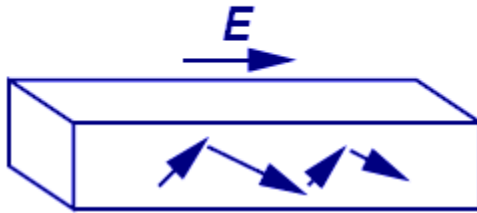
$$J_n = qD_n \frac{dn}{dx} = -qD_n \cdot \frac{N}{L}$$

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

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

Einstein's Relation

Drift Current



$$J_n = q \mu_n E$$

$$J_p = q \mu_p E$$

Diffusion Current



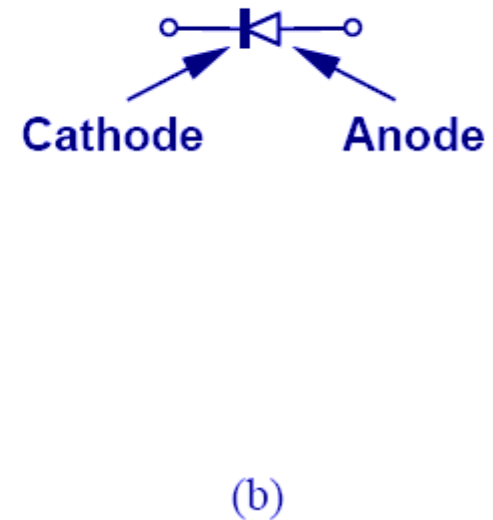
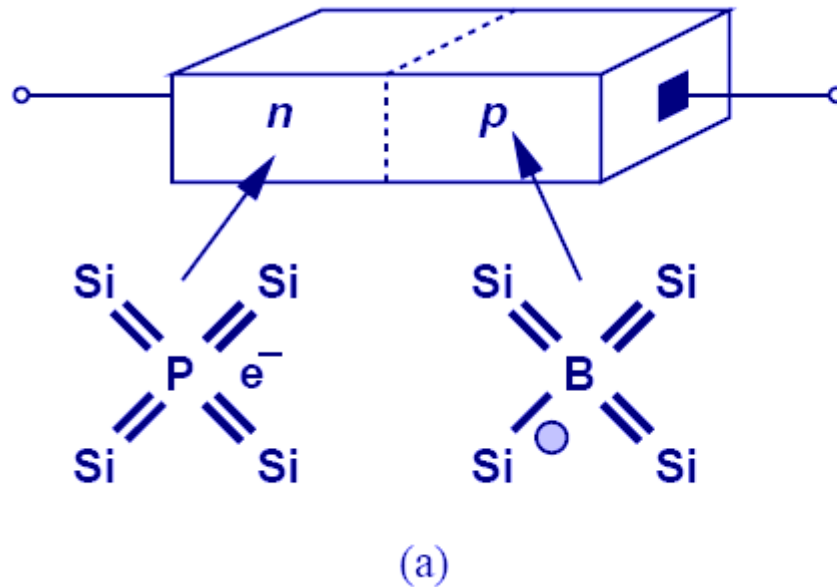
$$J_n = q D_n \frac{dn}{dx}$$

$$J_p = -q D_p \frac{dp}{dx}$$

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

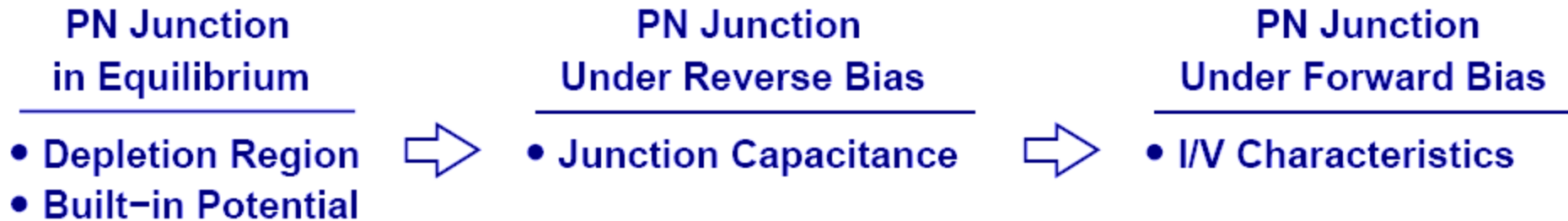
➤ While the underlying physics behind drift and diffusion currents are totally different, Einstein's relation provides a mysterious link between the two.

PN Junction (Diode)



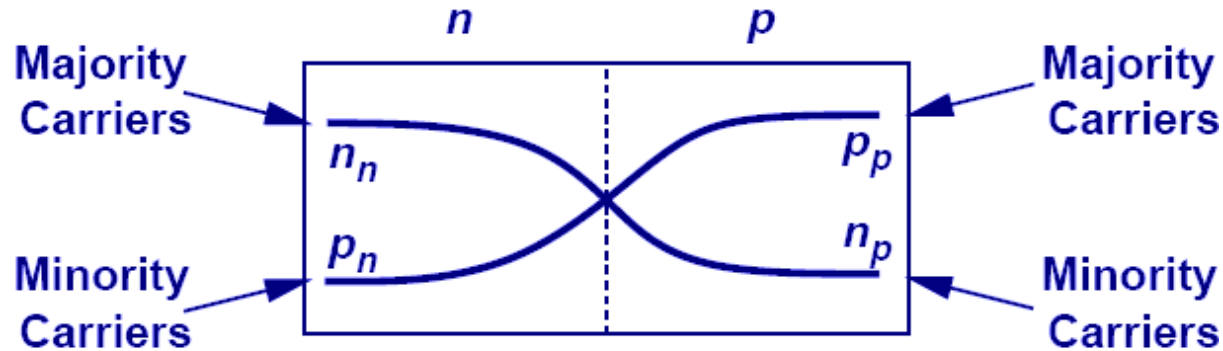
➤ When N-type and P-type dopants are introduced side-by-side in a semiconductor, a PN junction or a diode is formed.

Diode's Three Operation Regions



➤ 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

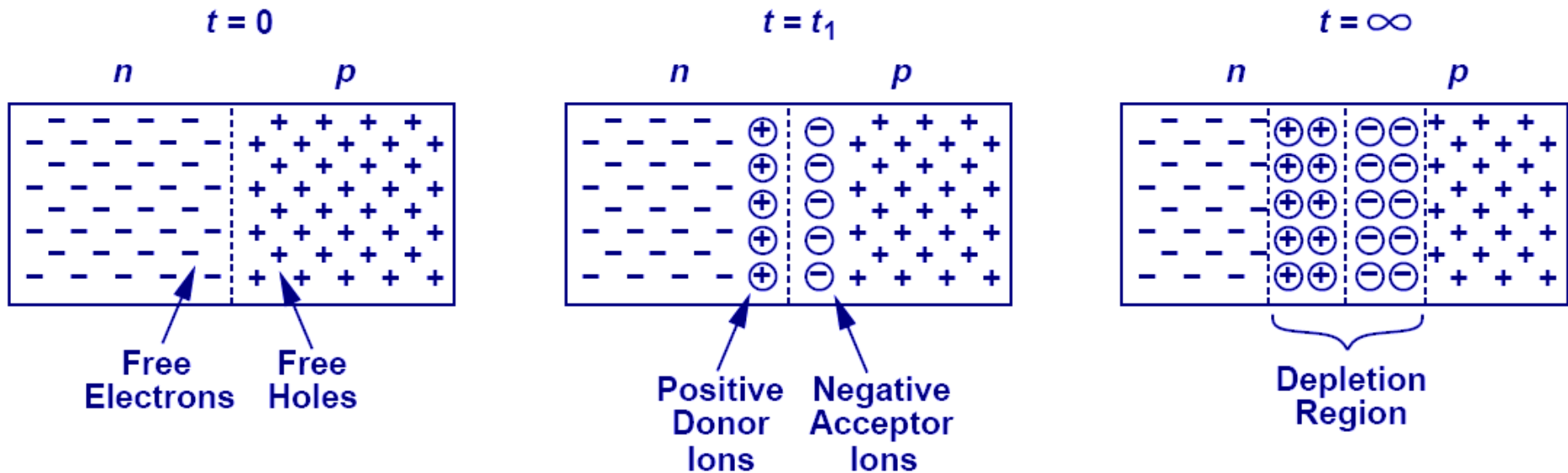
p_n : Concentration of holes
on n side

p_p : Concentration of holes
on p side

n_p : Concentration of electrons
on p side

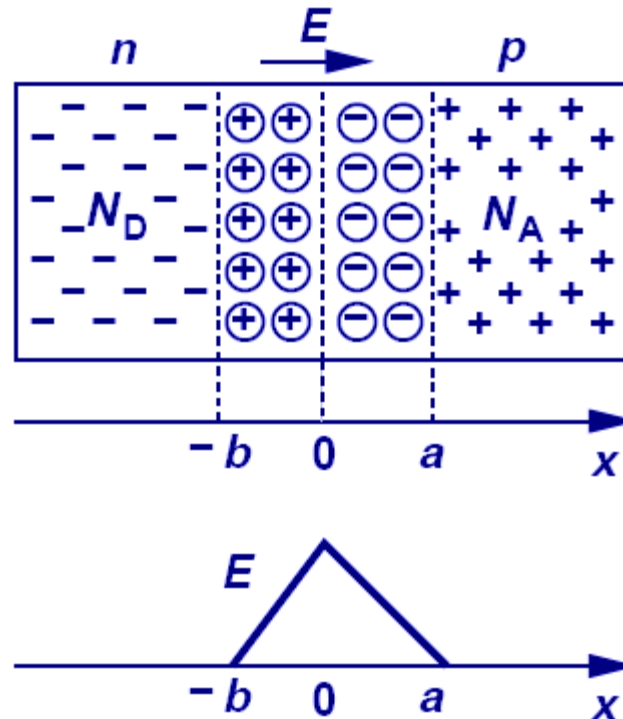
➤ Because each side of the junction contains an excess of holes or electrons compared to the other side, there exists a large concentration gradient. Therefore, a diffusion current flows across the junction from each side.

Depletion Region



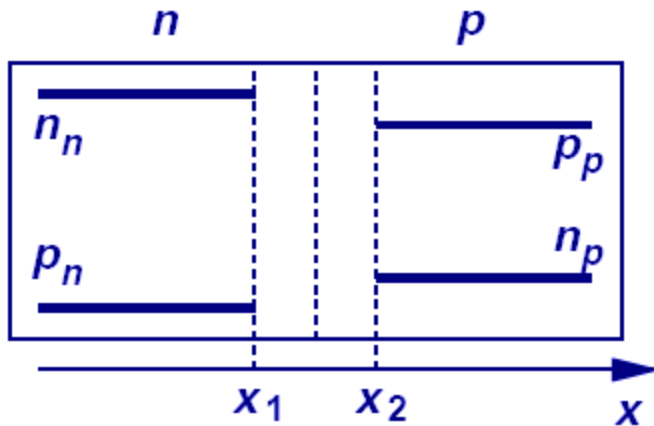
➤ As free electrons and holes diffuse across the junction, a region of fixed ions is left behind. This region is known as the “depletion region.”

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

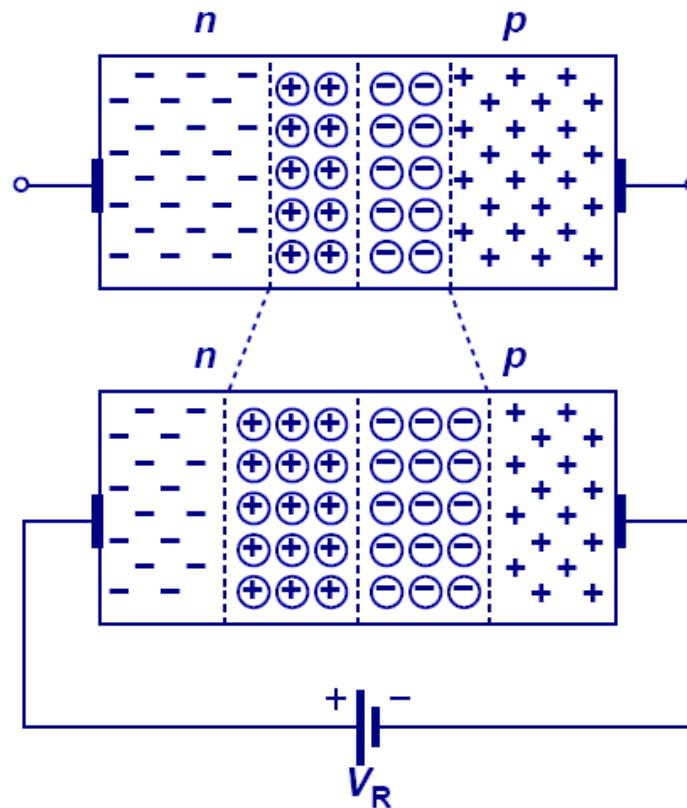
$$q\mu_p pE = -qD_p \frac{dp}{dx} \quad -\mu_p p \frac{dV}{dx} = -D_p \frac{dp}{dx}$$

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

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

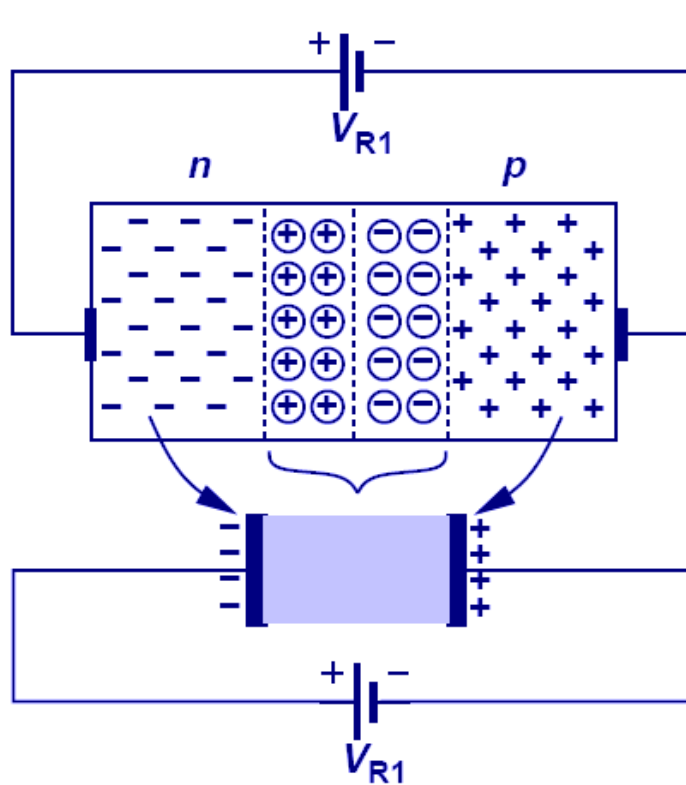
➤ Because of the electric field across the junction, there exists a built-in potential. Its derivation is shown above.

Diode in Reverse Bias

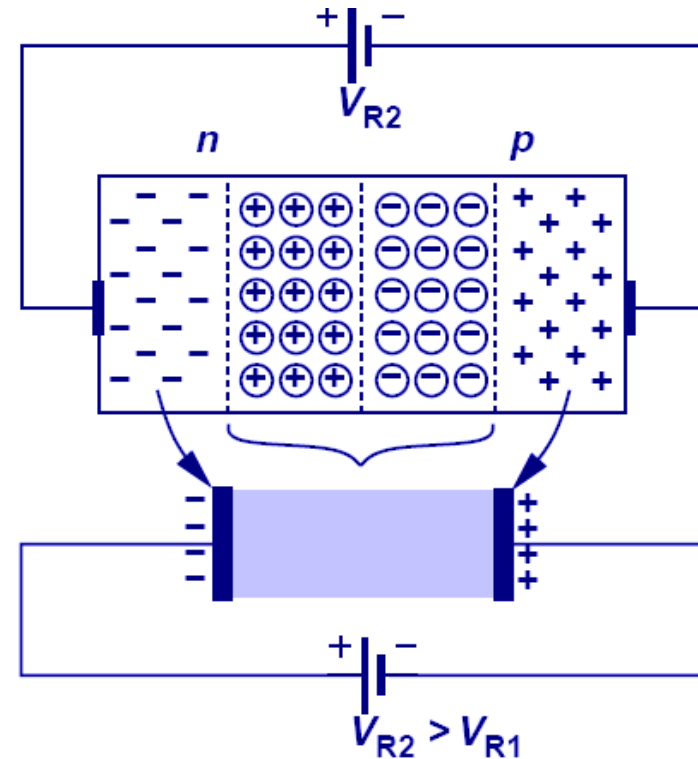


- When the N-type region of a diode is connected to a higher potential than the P-type region, the diode is under reverse bias, which results in wider depletion region and larger built-in electric field across the junction.

Reverse Biased Diode's Application: Voltage-Dependent Capacitor



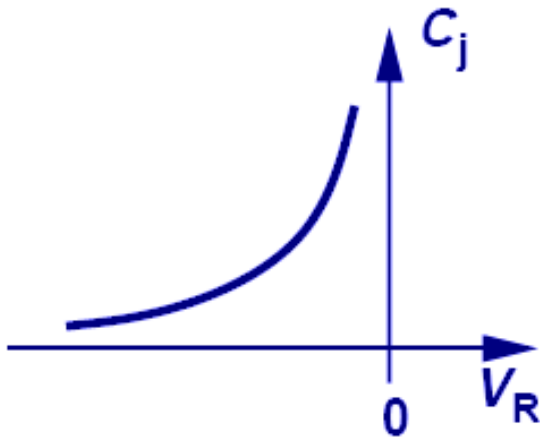
(a)



(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

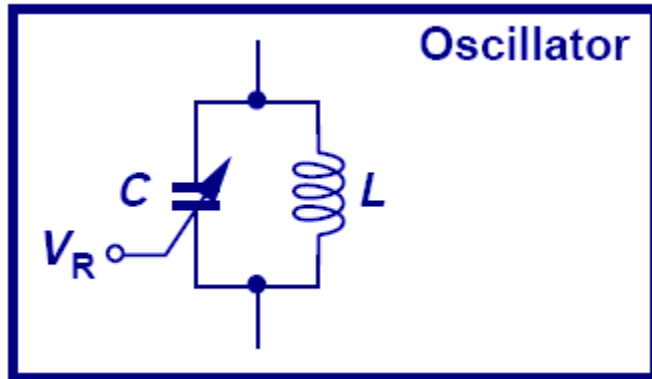


$$C_j = \frac{C_{j0}}{\sqrt{1 + \frac{V_R}{V_0}}}$$

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

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

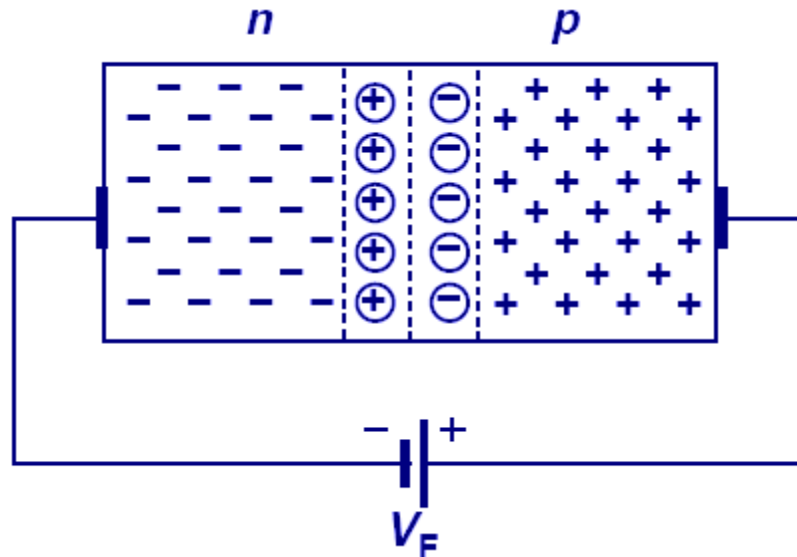
Voltage-Controlled Oscillator



$$f_{res} = \frac{1}{2\pi} \frac{1}{\sqrt{LC}}$$

- A very important application of a reverse-biased PN junction is VCO, in which an LC tank is used in an oscillator. By changing V_R , we can change C , which also changes the oscillation frequency.

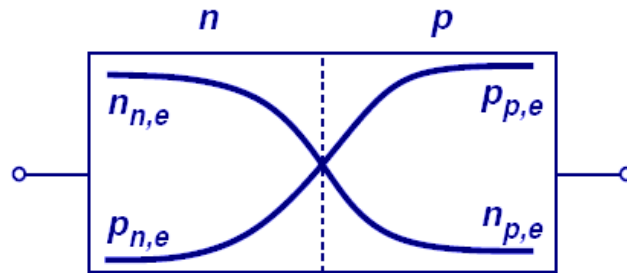
Diode in Forward Bias



- 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.

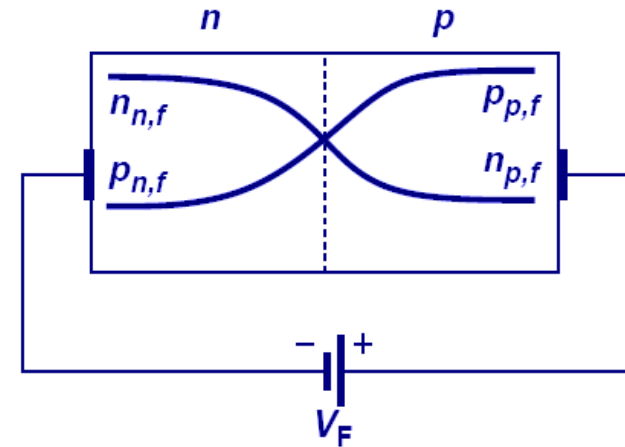
Minority Carrier Profile in Forward Bias

$$p_{n,e} = \frac{p_{p,e}}{\exp \frac{V_0}{V_T}}$$



$$p_{n,f} = \frac{p_{p,f}}{\exp \frac{V_0 - V_F}{V_T}}$$

(a)



(b)

- Under forward bias, minority carriers in each region increase due to the lowering of built-in field/potential. Therefore, diffusion currents increase to supply these minority carriers.

Diffusion Current in Forward Bias

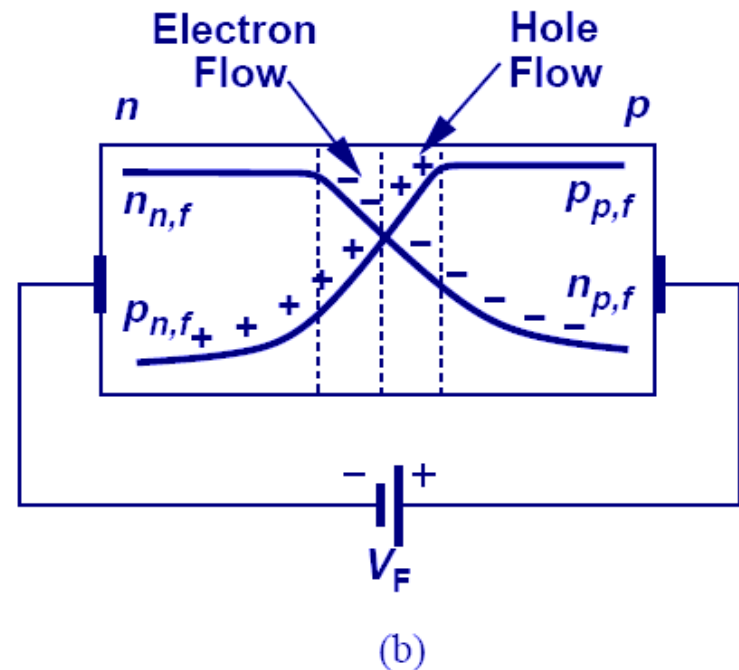
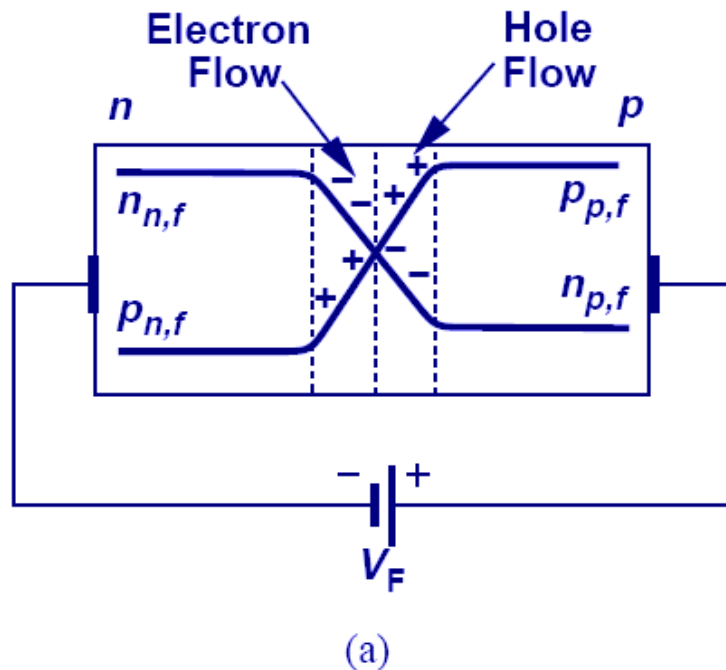
$$\Delta n_p \approx \frac{N_D}{\exp \frac{V_0}{V_T}} (\exp \frac{V_F}{V_T} - 1) \quad \Delta p_n \approx \frac{N_A}{\exp \frac{V_0}{V_T}} (\exp \frac{V_F}{V_T} - 1)$$

$$I_{tot} \propto \frac{N_A}{\exp \frac{V_0}{V_T}} (\exp \frac{V_F}{V_T} - 1) + \frac{N_D}{\exp \frac{V_0}{V_T}} (\exp \frac{V_F}{V_T} - 1)$$

$$I_{tot} = I_s (\exp \frac{V_F}{V_T} - 1) \quad I_s = A q n_i^2 \left(\frac{D_n}{N_A L_n} + \frac{D_p}{N_D L_p} \right)$$

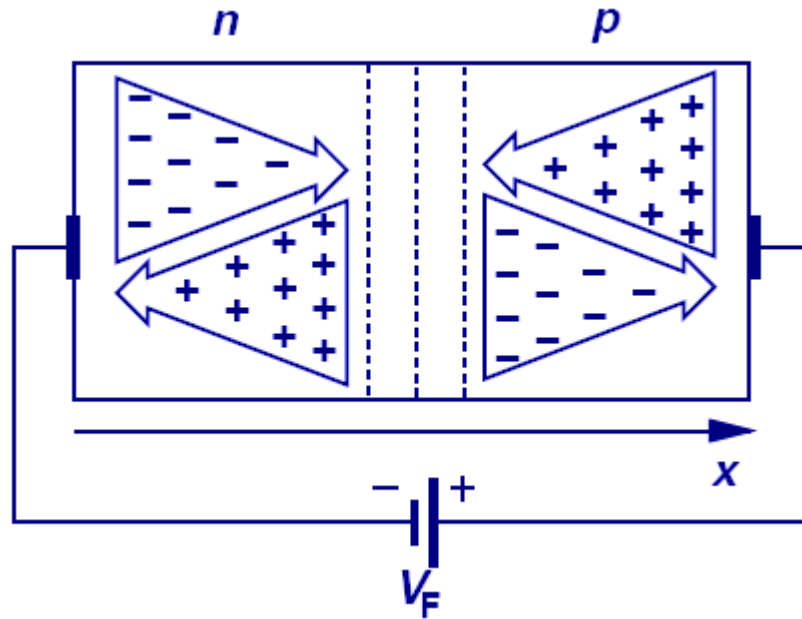
➤ Diffusion current will increase in order to supply the increase in minority carriers. The mathematics are shown above.

Minority Charge Gradient



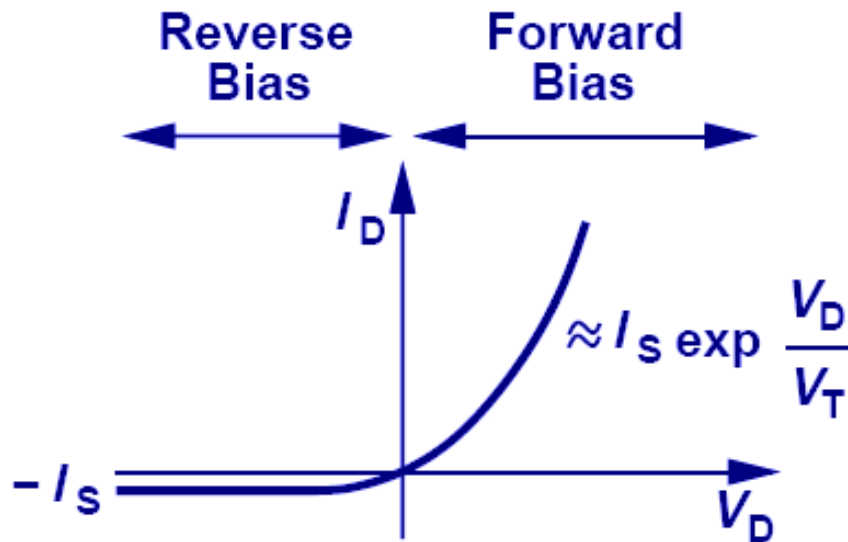
- Minority charge profile should not be constant along the x-axis; otherwise, there is no concentration gradient and no diffusion current.
- Recombination of the minority carriers with the majority carriers accounts for the dropping of minority carriers as they go deep into the P or N region.

Forward Bias Condition: Summary



- In forward bias, there are large diffusion currents of minority carriers through the junction. However, as we go deep into the P and N regions, recombination currents from the majority carriers dominate. These two currents add up to a constant value.

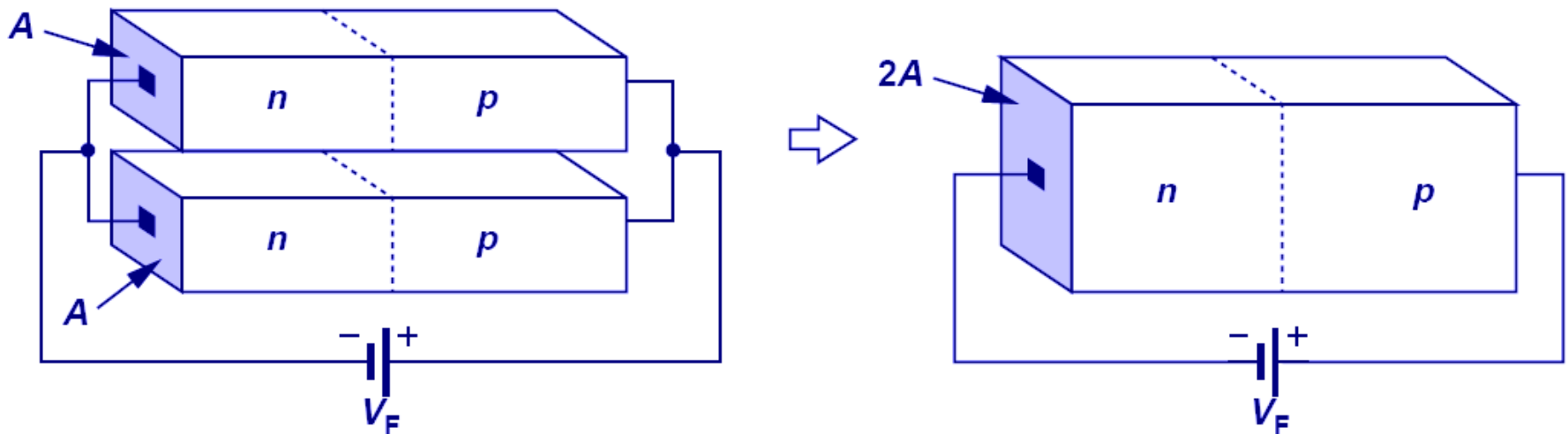
IV Characteristic of PN Junction



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

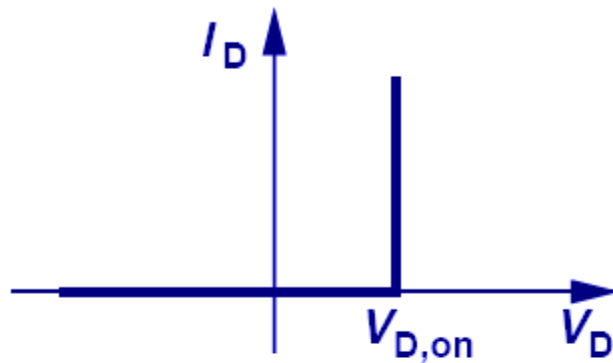
- The current and voltage relationship of a PN junction is exponential in forward bias region, and relatively constant in reverse bias region.

Parallel PN Junctions

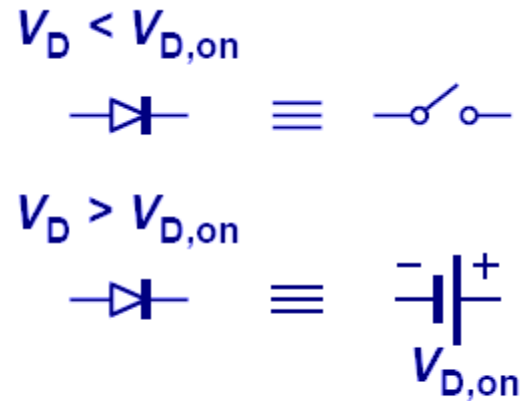


- Since junction currents are proportional to the junction's cross-section area. Two PN junctions put in parallel are effectively one PN junction with twice the cross-section area, and hence twice the current.

Constant-Voltage Diode Model



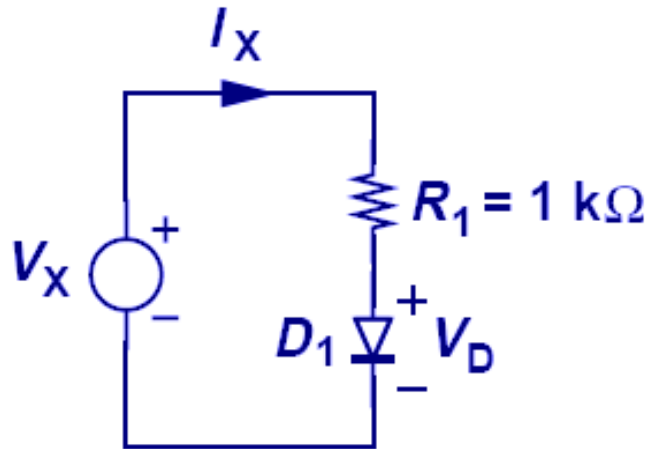
(a)



(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 $V_{D,on}$.

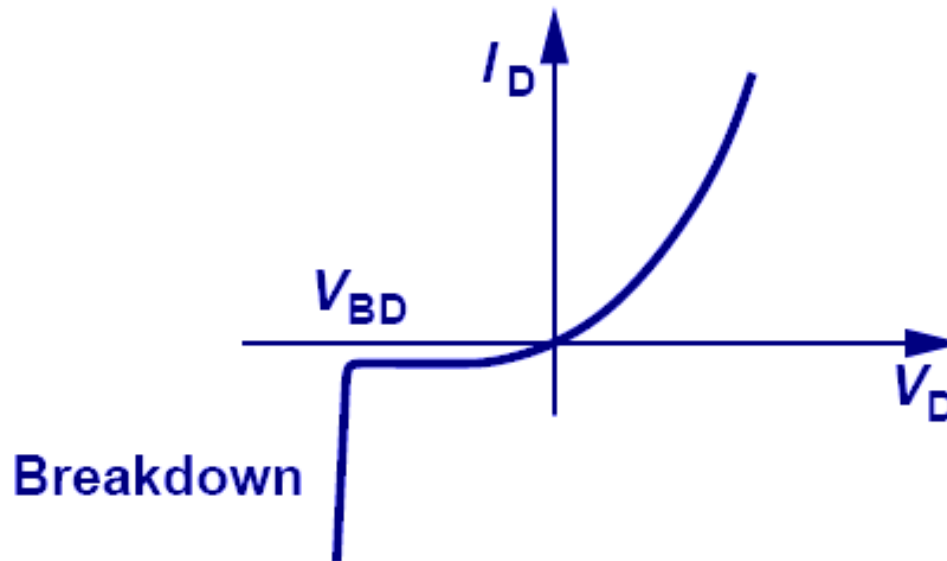
Example: Diode Calculations



$$V_X = I_X R_1 + V_D = I_X R_1 + V_T \ln \frac{I_X}{I_S}$$
$$I_X = 2.2\text{mA} \quad \text{for} \quad V_X = 3\text{V}$$
$$I_X = 0.2\text{mA} \quad \text{for} \quad V_X = 1\text{V}$$

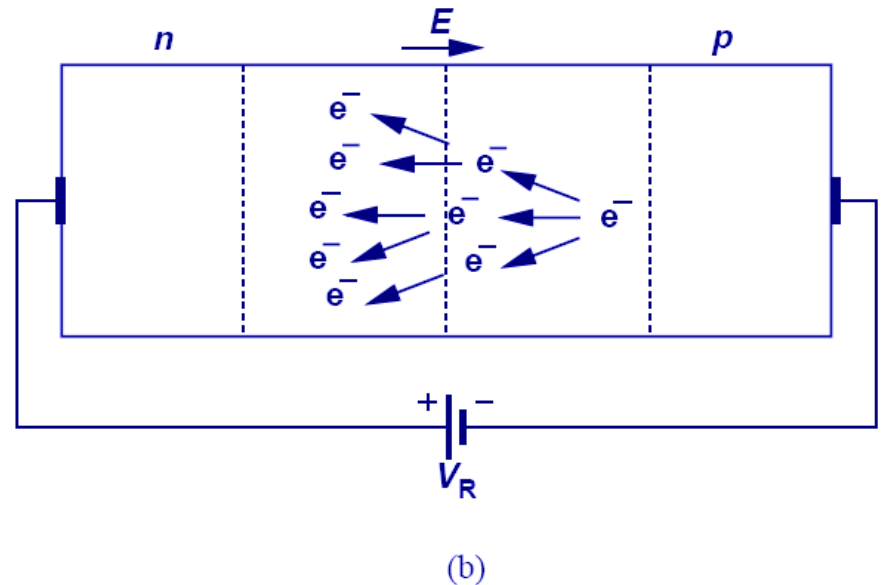
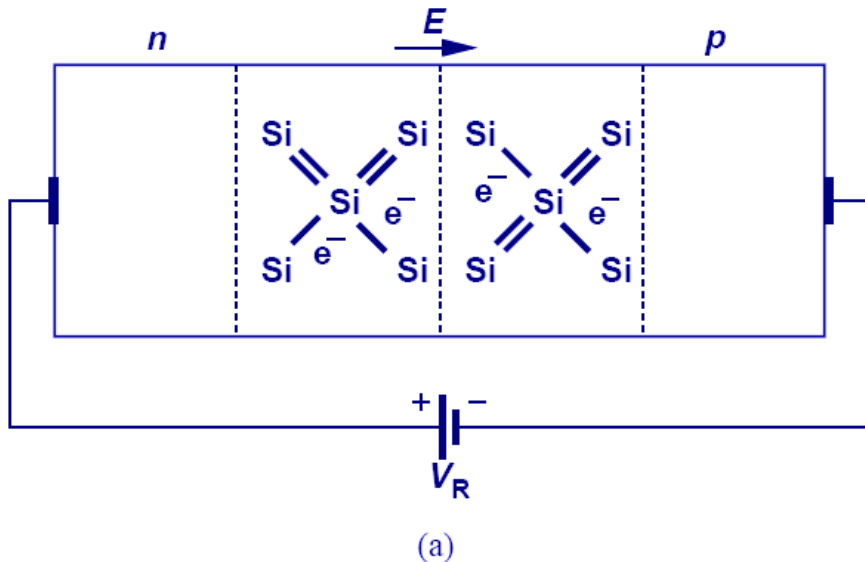
- This example shows the simplicity provided by a constant-voltage model over an exponential model.
- For an exponential model, iterative method is needed to solve for current, whereas constant-voltage model requires only linear equations.

Reverse Breakdown



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

Zener vs. Avalanche Breakdown



- Zener breakdown is a result of the large electric field inside the depletion region that breaks electrons or holes off their covalent bonds.
- Avalanche breakdown is a result of electrons or holes colliding with the fixed ions inside the depletion region.