Fundamentals of Microelectronics

1

Chapter 2 Basic Physics of Semiconductors

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

2

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.**

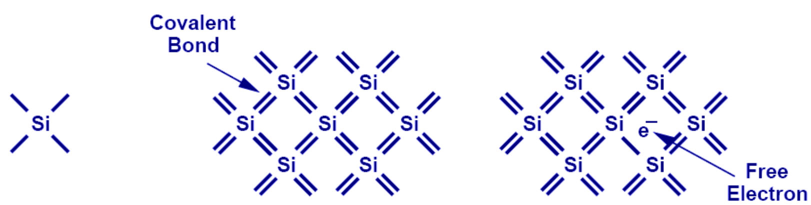
Periodic Table

	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.

CH2 Basic Physics of Semiconductors 5

Silicon

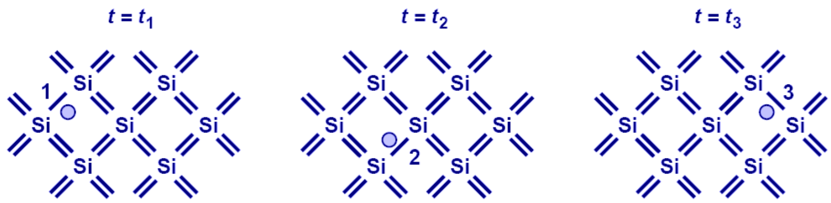


(a) (b) (c)

- 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.

CH2 Basic Physics of Semiconductors 6

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.

CH2 Basic Physics of Semiconductors 7

Free Electron Density at a Given Temperature

$$n_i = 5.2\times10^{15} T^{3/2} \exp\frac{-E_g}{2kT}\ electrons / cm^3$$

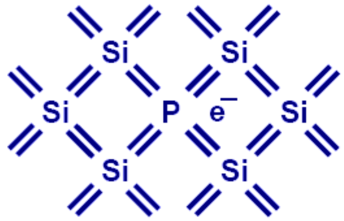
$$n_i(T = 300^0 K) = 1.08\times10^{10}\ electrons / cm^3$$

$$n_i(T = 600^0 K) = 1.54\times10^{15}\ electrons / cm^3$$

- Eg, 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.

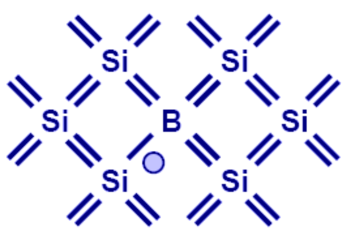
CH2 Basic Physics of Semiconductors 8

Doping (N type)



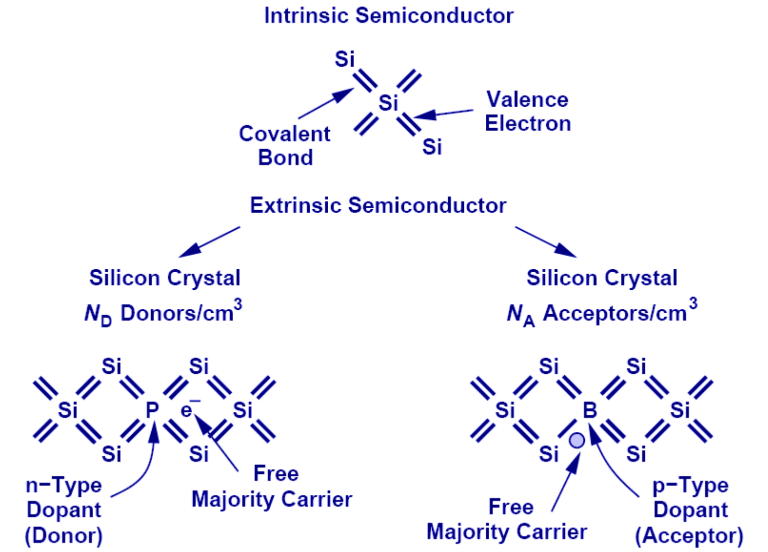
- Pure Si can be doped with other elements to change its electrical properties.
- For example, if Si is doped with P (phosphorous), then it has more electrons, or becomes type N (electron).

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 : $p \approx N_A$

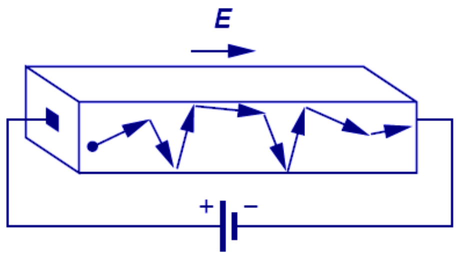
Minority Carriers : $n \approx \dfrac{n_i^2}{N_A}$

Majority Carriers : $n \approx N_D$

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

- **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

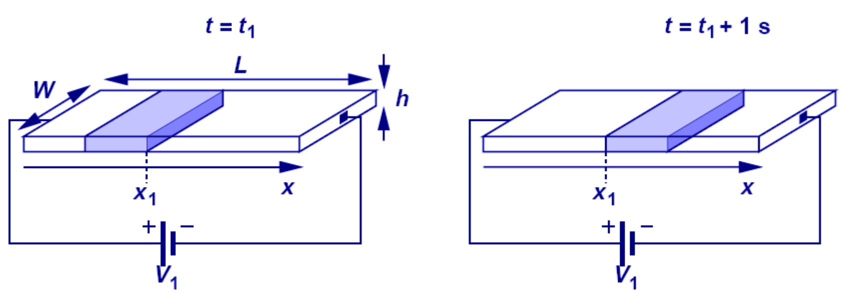


$$\vec{v}_h = \mu_p \vec{E}$$

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

- 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

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

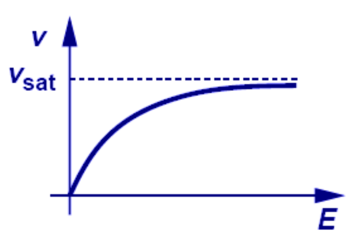
$$J_{tot} = \mu_n E \cdot n \cdot q + \mu_p E \cdot p \cdot q$$

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

- 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.

CH2 Basic Physics of Semiconductors 15

Velocity Saturation



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

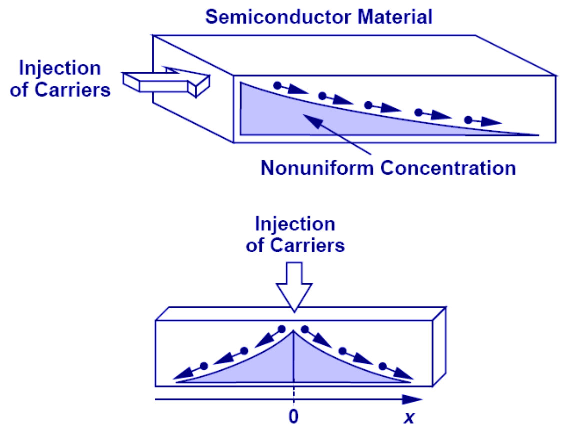
$$v_{sat} = \frac{\mu_0}{b}$$

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

- 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.

CH2 Basic Physics of Semiconductors 16

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.

CH2 Basic Physics of Semiconductors 17

Current Flow: Diffusion

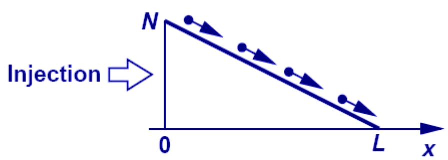
$$I = AqD_n \frac{dn}{dx} \qquad J_p = -qD_p \frac{dp}{dx}$$

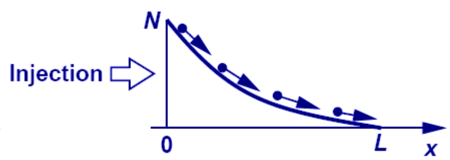
$$J_n = qD_n \frac{dn}{dx} \qquad J_{tot} = q(D_n \frac{dn}{dx} - D_p \frac{dp}{dx})$$

- 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.

CH2 Basic Physics of Semiconductors 18

Example: Linear vs. Nonlinear Charge Density Profile





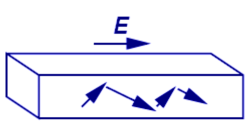
$$J_n = qD_n \frac{dn}{dx} = -qD_n \cdot \frac{N}{L}$$

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

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

Einstein's Relation

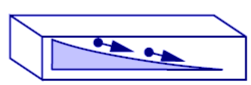
Drift Current



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

$$J_p = q\,\mu_p$$

Diffusion Current



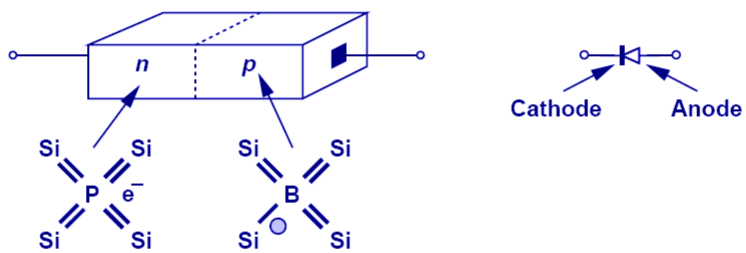
$$J_n = q\,D_n \frac{dn}{dx}$$

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

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

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

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

⇨

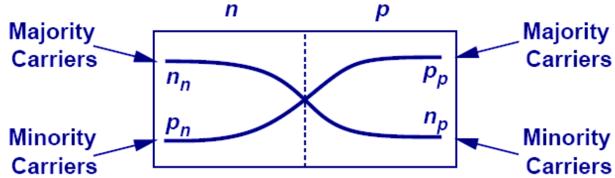
PN Junction Under Reverse Bias
- Junction Capacitance

⇨

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

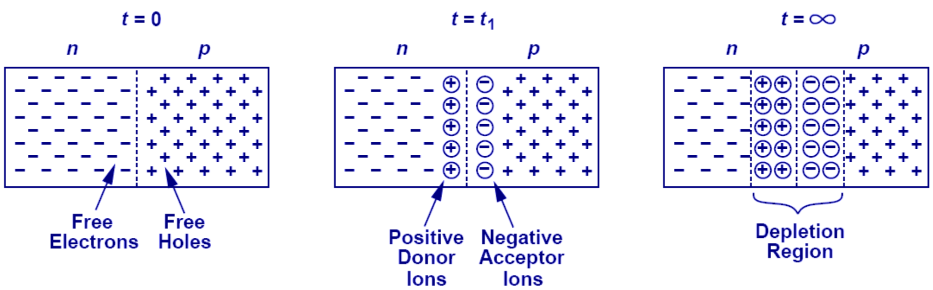
p_n : Concentration of holes on n side

p_p : Concentration of holes on p side

n_p : Concentration of electrons on p side

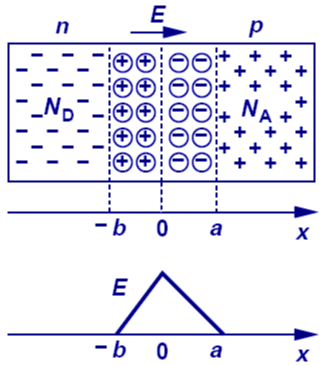
- Because each side of the junction contains an excess of holes or electrons compared to the other side, there exists a large concentration gradient. Therefore, a diffusion current flows across the junction from each side.

Depletion Region



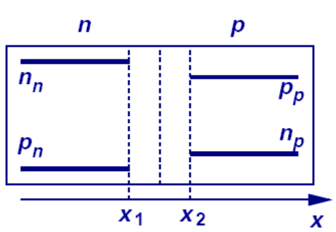
- As free electrons and holes diffuse across the junction, a region of fixed ions is left behind. This region is known as the "depletion region."

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

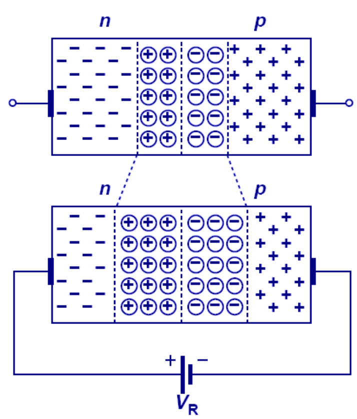
$$q\mu_p pE = -qD_p \frac{dp}{dx} \qquad -\mu_p p \frac{dV}{dx} = -D_p \frac{dp}{dx}$$

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

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

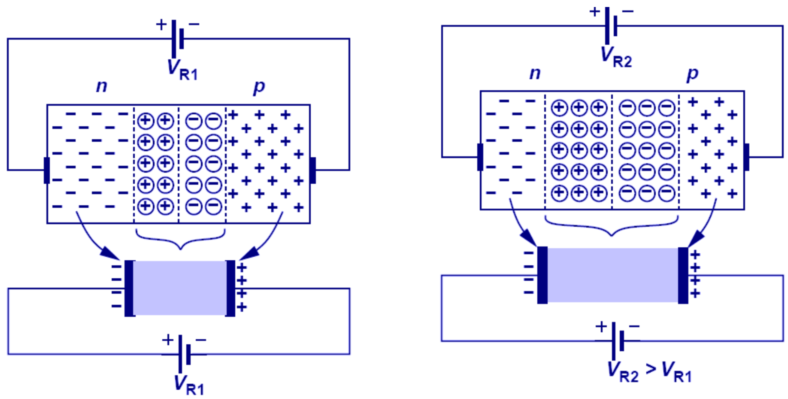
- **Because of the electric field across the junction, there exists a built-in potential. Its derivation is shown above.**

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.**

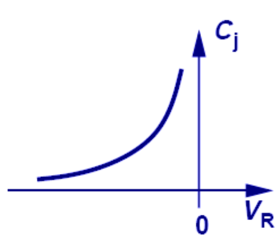
Reverse Biased Diode's Application: Voltage-Dependent Capacitor



(a) (b)

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

Voltage-Dependent Capacitance

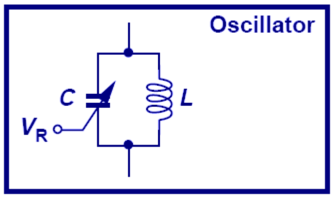


$$C_j = \frac{C_{j0}}{\sqrt{1+\frac{V_R}{V_0}}}$$

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

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

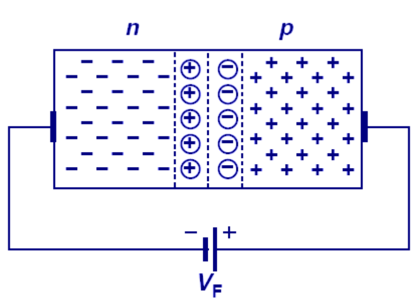
Voltage-Controlled Oscillator



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

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

Diode in Forward Bias

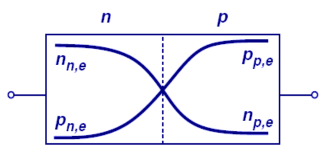


- When the N-type region of a diode is at a lower potential than the P-type region, the diode is in forward bias.
- The depletion width is shortened and the built-in electric field decreased.

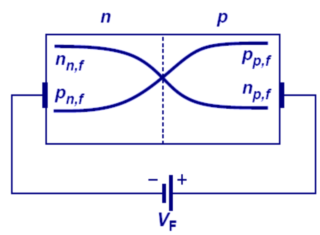
Minority Carrier Profile in Forward Bias

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

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



(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

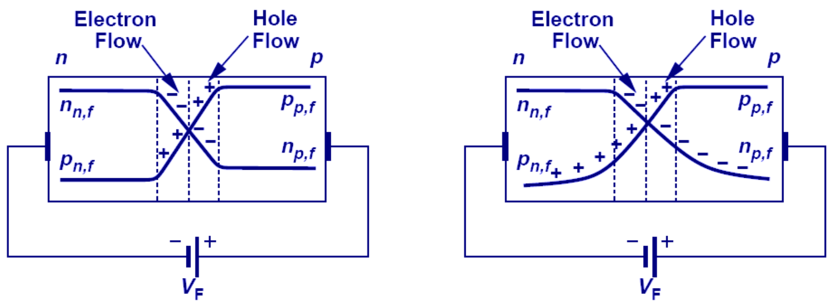
$$\Delta n_p \approx \frac{N_D}{\exp\frac{V_0}{V_T}}(\exp\frac{V_F}{V_T} - 1) \qquad \Delta p_n \approx \frac{N_A}{\exp\frac{V_0}{V_T}}(\exp\frac{V_F}{V_T} - 1)$$

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

$$I_{tot} = I_s(\exp\frac{V_F}{V_T} - 1) \qquad I_s = Aqn_i^2(\frac{D_n}{N_A L_n} + \frac{D_p}{N_D L_p})$$

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

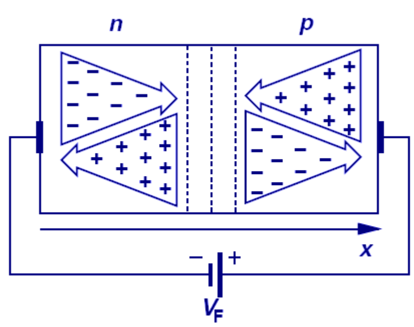
Minority Charge Gradient



(a) (b)

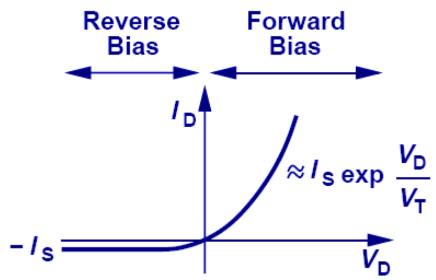
- **Minority charge profile should not be constant along the x-axis; otherwise, there is no concentration gradient and no diffusion current.**
- **Recombination of the minority carriers with the majority carriers accounts for the dropping of minority carriers as they go deep into the P or N region.**

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.**

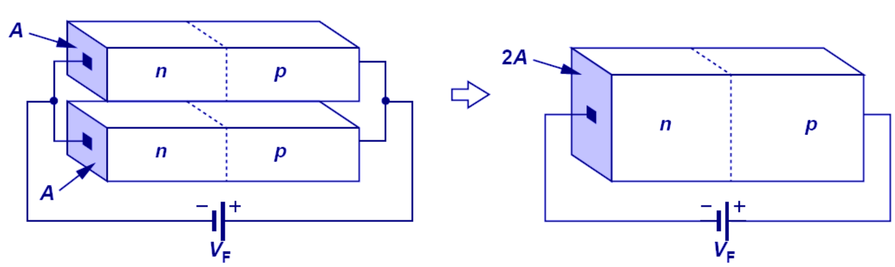
IV Characteristic of PN Junction



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

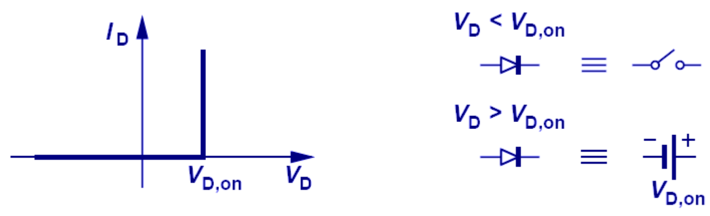
- The current and voltage relationship of a PN junction is exponential in forward bias region, and relatively constant in reverse bias region.

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.

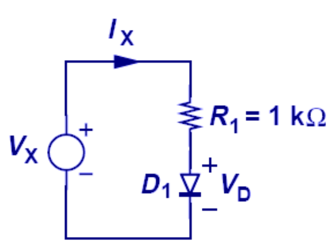
Constant-Voltage Diode Model



(a) (b)

- Diode operates as an open circuit if VD< VD,on and a constant voltage source of VD,on if VD tends to exceed VD,on.

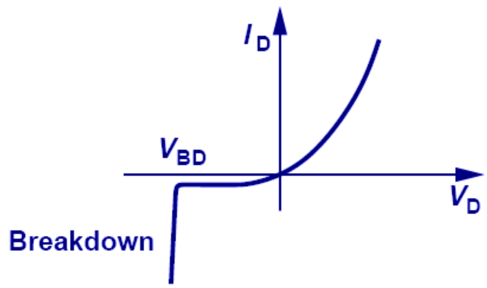
Example: Diode Calculations



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

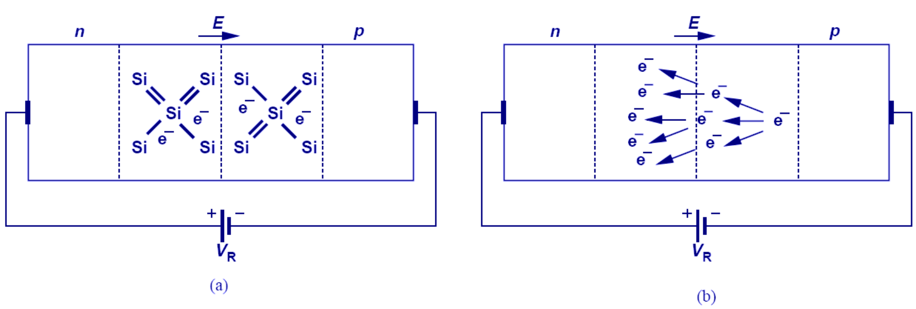
- This example shows the simplicity provided by a constant-voltage model over an exponential model.
- For an exponential model, iterative method is needed to solve for current, whereas constant-voltage model requires only linear equations.

Reverse Breakdown



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

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.