Fundamentals of Microelectronics

- **CH1 Why Microelectronics?**
- **CH2 Basic Physics of Semiconductors**
- **CH3 Diode Circuits**
- **CH4 Physics of Bipolar Transistors**
- **CH5 Bipolar Amplifiers**
- **CH6 Physics of MOS Transistors**
- **CH7 CMOS Amplifiers**
- **CH8 Operational Amplifier As A Black Box**

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

Modification of Carrier Densities

- Intrinsic Semiconductors
- Extrinsic Semiconductors
- Doping

Transport of Carriers

- Diffusion
- Drift

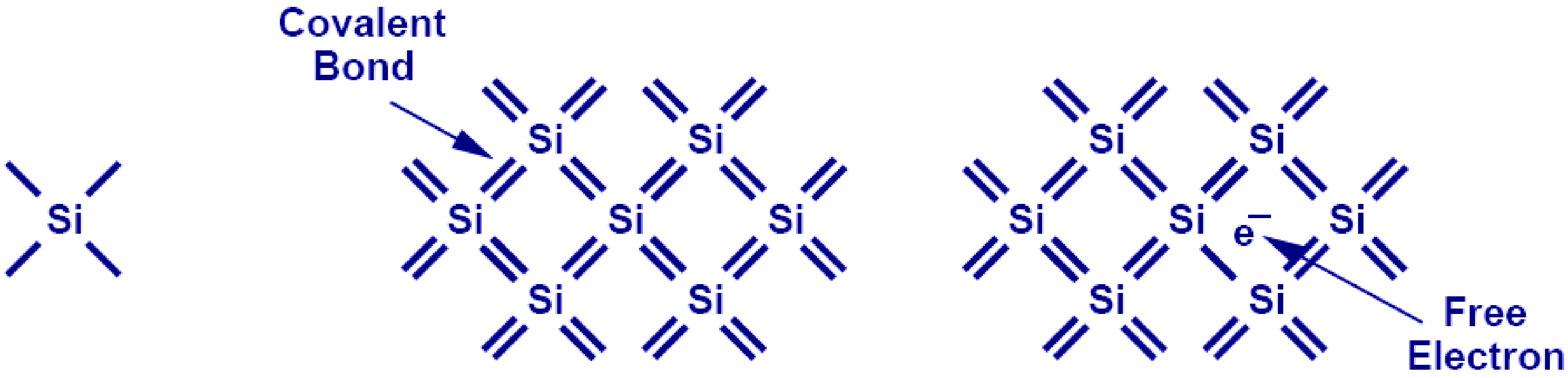
- **To understand PN junction’s IV characteristics, it is important to understand charge carriers’ behavior in solids, how to modify carrier densities, and different mechanisms of charge flow.**

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.

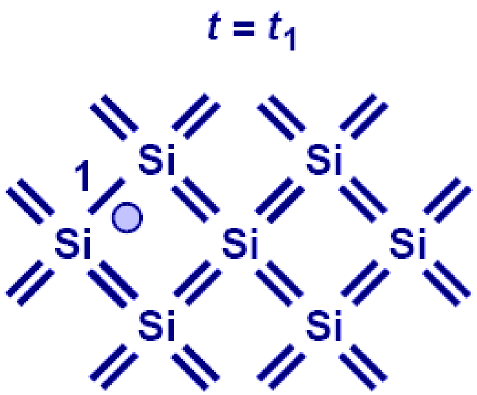
Silicon



(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

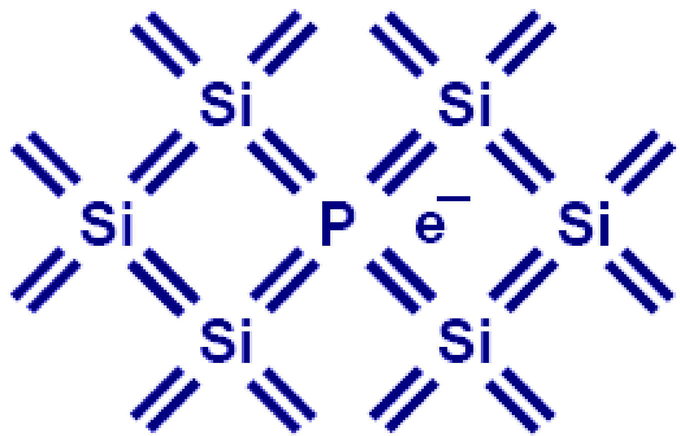
$$n_i = 5.2 \times 10^{15} T^{3/2} \exp \frac{-E_g}{2kT} \, electrons/cm^3$$

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

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

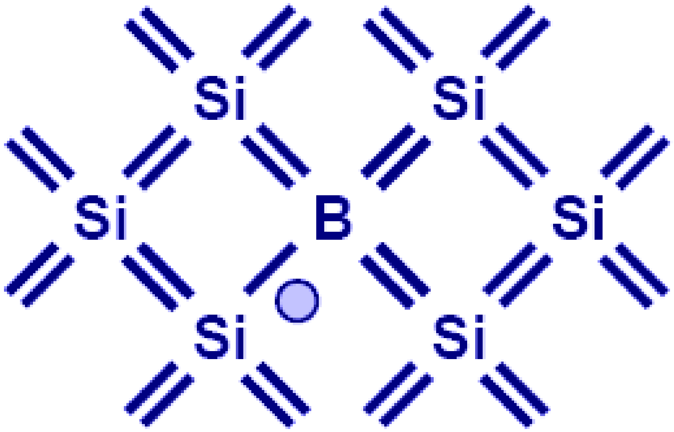
- ***E_g*, or bandgap energy determines how much effort is needed to break off an electron from its covalent bond.**
- **There exists an exponential relationship between the free-electron density and bandgap energy.**

Doping (N type)



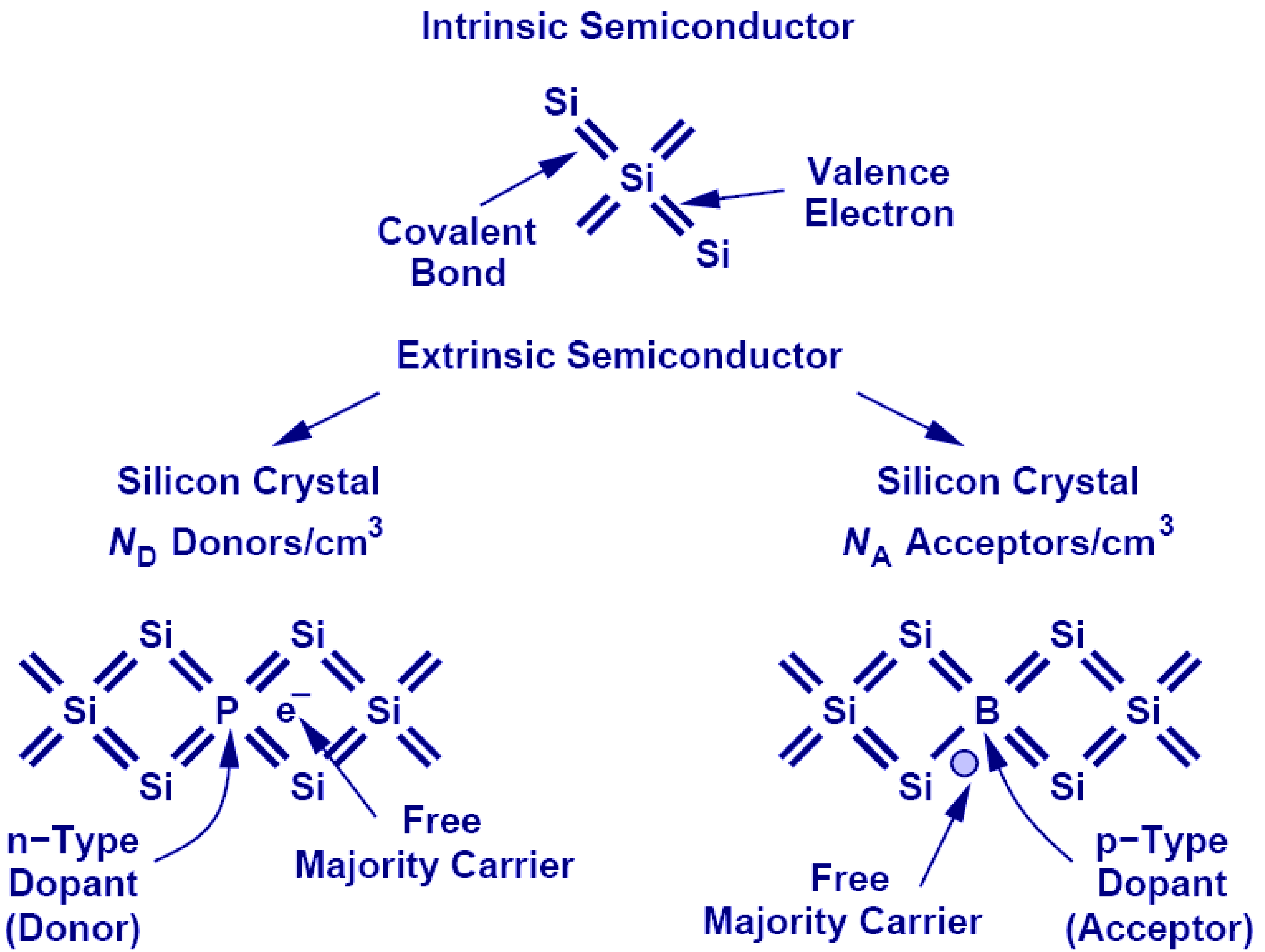
- Pure Si can be doped with other elements to change its electrical properties.
- For example, if Si is doped with P (phosphorous), then it has more electrons, or becomes type N (electron).

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.**

Example 2.3

Example 2.3

A piece of crystalline silicon is doped uniformly with phosphorus atoms. The doping density is 10^{16} atoms/cm^3. Determine the electron and hole densities in this material at the room temperature.

Solution The addition of 10^{16} P atoms introduces the same number of free electrons per cubic centimeter. Since this electron density exceeds that calculated in Example 2.1 by six orders of magnitude, we can assume

$$n = 10^{16}\ \text{electrons/cm}^3. \tag{2.6}$$

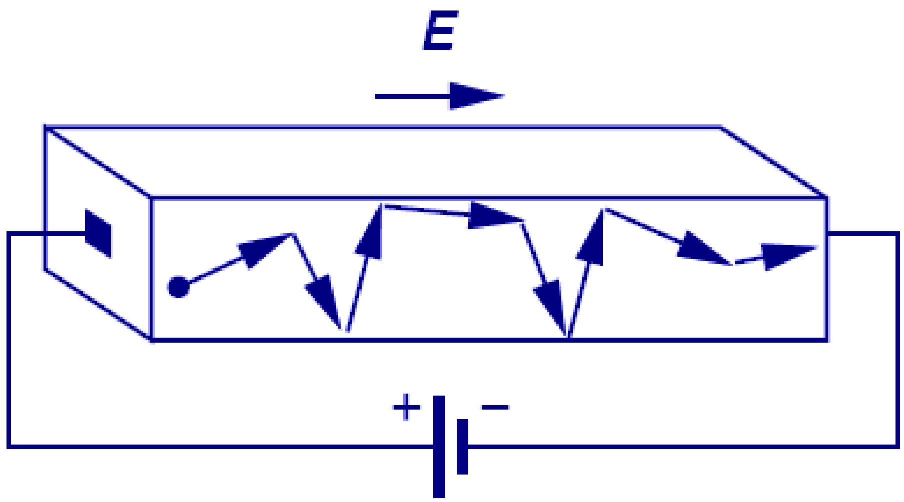
It follows from (2.2) and (2.5) that

$$p = \frac{n_i^2}{n} \tag{2.7}$$

$$= 1.17 \times 10^4\ \text{holes/cm}^3. \tag{2.8}$$

Note that the hole density has dropped below the intrinsic level by six orders of magnitude. Thus, if a voltage is applied across this piece of silicon, the resulting current consists predominantly of electrons.

First Charge Transportation Mechanism: Drift

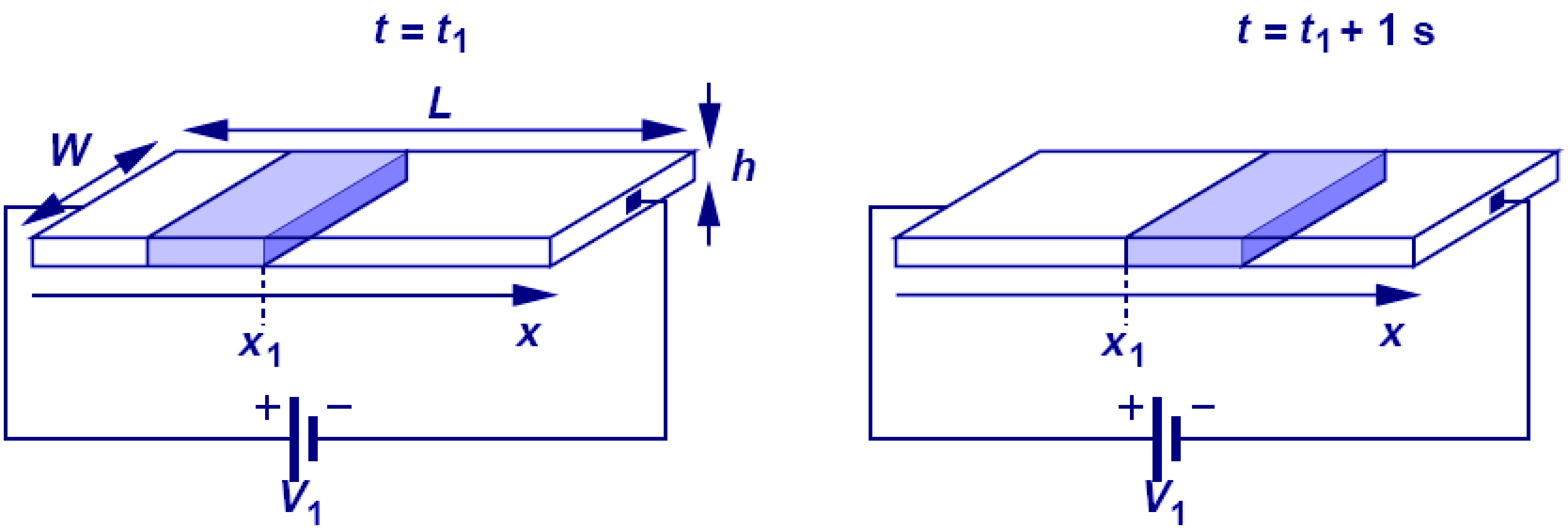


$$\vec{v}_h = \mu_p \vec{E}$$

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

- **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

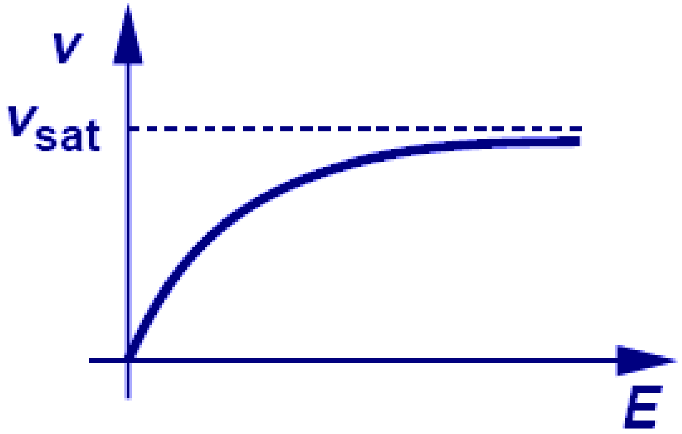
$$J_n = \mu_n E \cdot n \cdot q$$

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

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

- **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.

Example 2.7

Example 2.7 A uniform piece of semiconductor 0.2 μm long sustains a voltage of 1 V. If the low-field mobility is equal to 1350 $\text{cm}^2/(\text{V}\cdot\text{s})$ and the saturation velocity of the carriers 10^7 cm/s, determine the effective mobility. Also, calculate the maximum allowable voltage such that the effective mobility is only 10% lower than μ_0.

Solution We have

$$E = \frac{V}{L} \tag{2.31}$$

$$= 50\ \text{kV/cm}. \tag{2.32}$$

It follows that

$$\mu = \frac{\mu_0}{1 + \dfrac{\mu_0 E}{v_{sat}}} \tag{2.33}$$

$$= \frac{\mu_0}{7.75} \tag{2.34}$$

$$= 174\ \text{cm}^2/(\text{V}\cdot\text{s}). \tag{2.35}$$

Example 2.7

If the mobility must remain within 10% of its low-field value, then

$$0.9\mu_0 = \frac{\mu_0}{1 + \frac{\mu_0 E}{v_{sat}}}, \tag{2.36}$$

and hence

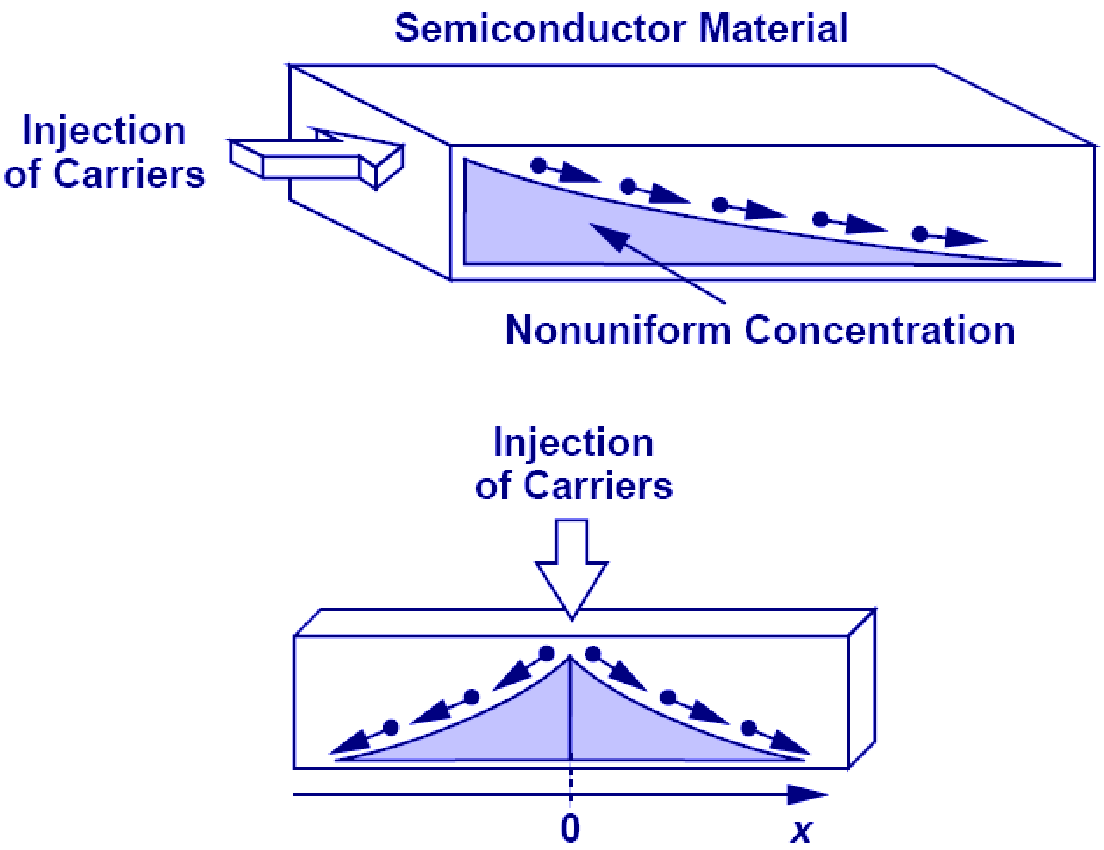
$$E = \frac{1}{9}\frac{v_{sat}}{\mu_0} \tag{2.37}$$

$$= 823\ \text{V/cm}. \tag{2.38}$$

A device of length 0.2 μm experiences such a field if it sustains a voltage of $(823\ \text{V/cm}) \times (0.2 \times 10^{-4}\ \text{cm}) = 16.5\ \text{mV}$.

This example suggests that modern (submicron) devices incur substantial velocity saturation because they operate with voltages much greater than 16.5 mV.

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.**

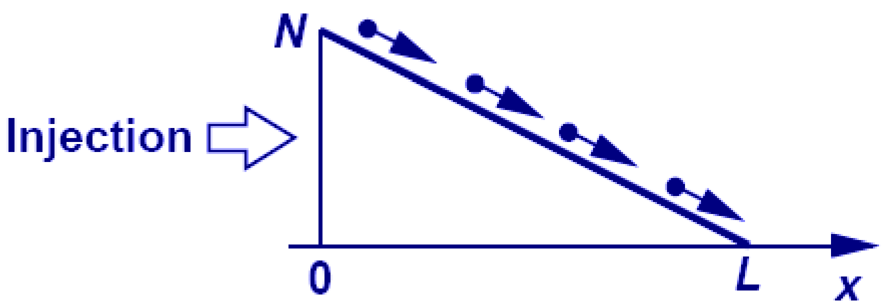
Current Flow: Diffusion

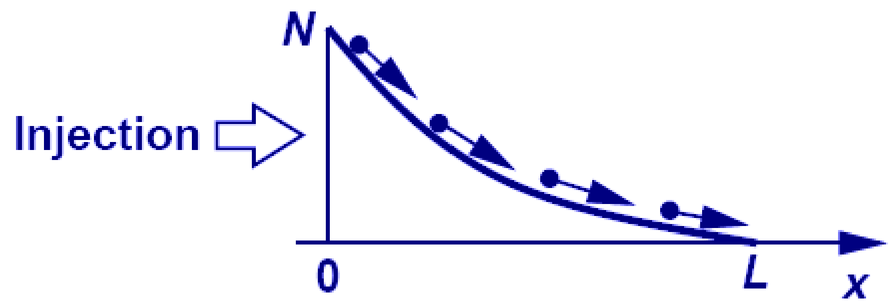
$$I = AqD_n \frac{dn}{dx} \qquad J_p = -qD_p \frac{dp}{dx}$$

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

- **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





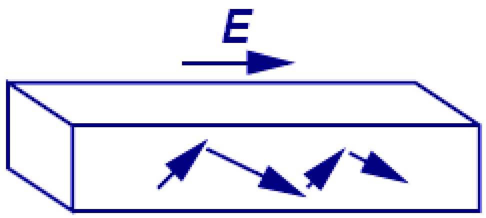
$$J_n = qD_n \frac{dn}{dx} = -qD_n \cdot \frac{N}{L}$$

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

- **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

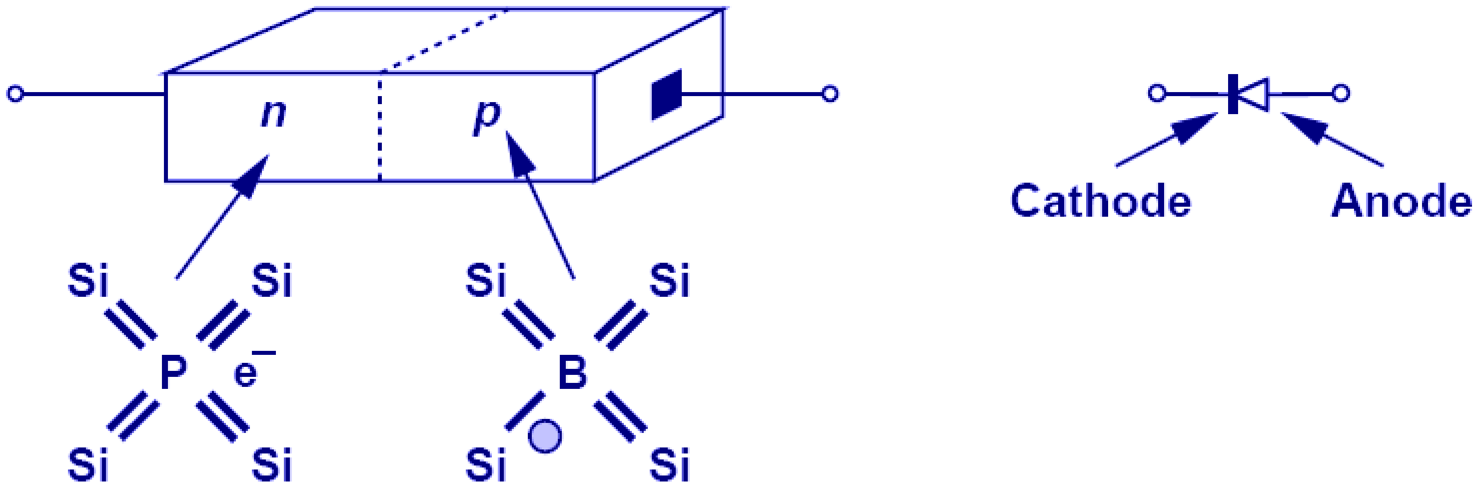
$$J_n = q D_n \frac{dn}{dx}$$

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

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

- **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

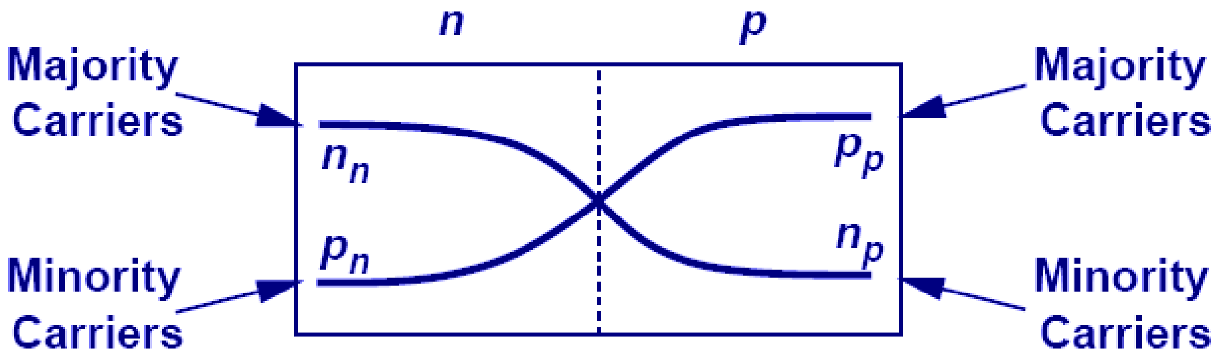
PN Junction in Equilibrium
- Depletion Region
- Built-in Potential

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

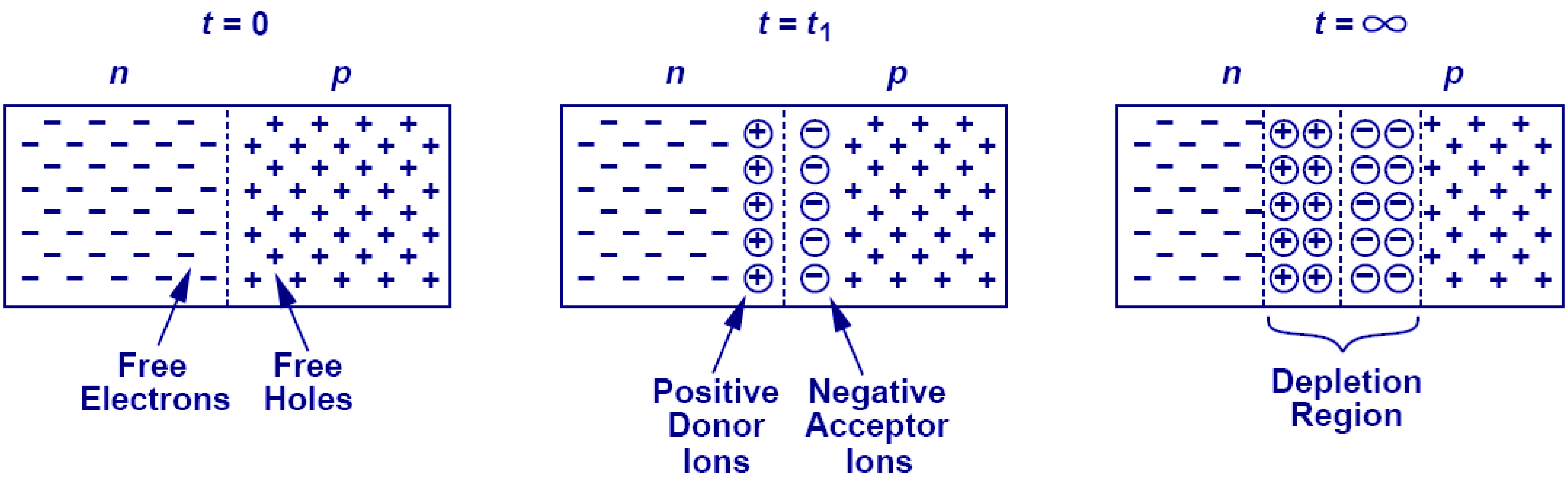
p_n : Concentration of holes on n side

p_p : Concentration of holes on p side

n_p : Concentration of electrons on p side

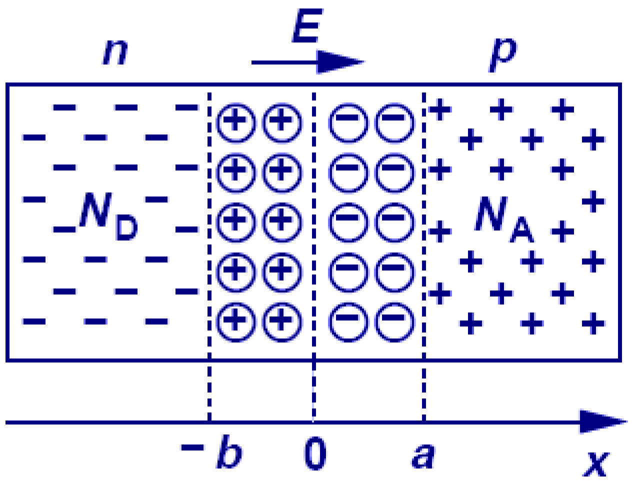
- **Because each side of the junction contains an excess of holes or electrons compared to the other side, there exists a large concentration gradient. Therefore, a diffusion current flows across the junction from each side.**

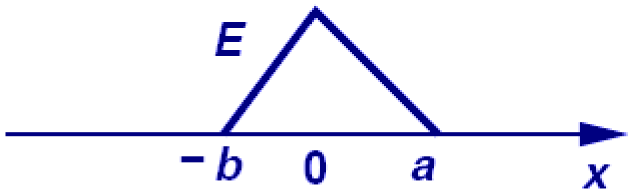
Depletion Region



- 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.**

Example 2.12

Example 2.12

In the junction shown in Fig. 2.21, the depletion region has a width of b on the n side and a on the p side. Sketch the electric field as a function of x.

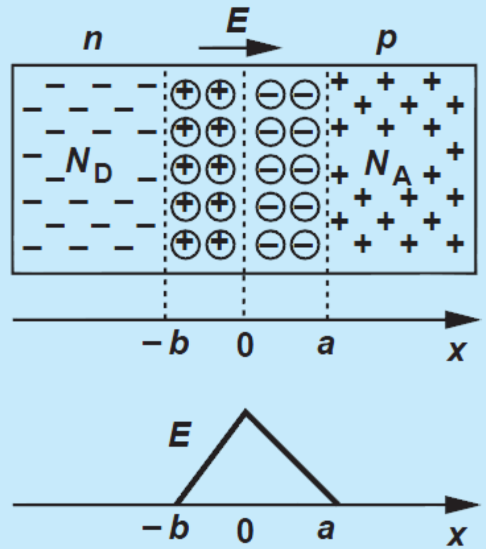
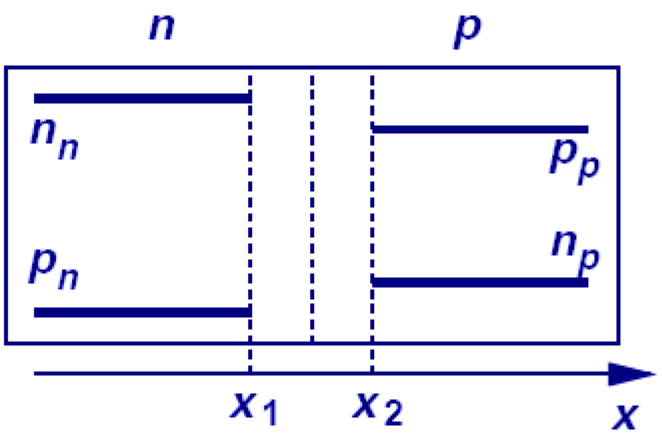


Figure 2.21 Electric field profile in a pn junction.

Solution Beginning at $x < -b$, we note that the absence of net charge yields $E = 0$. At $x > -b$, each positive donor ion contributes to the electric field, i.e., the magnitude of E rises as x approaches zero. As we pass $x = 0$, the negative acceptor atoms begin to contribute negatively to the field, i.e., E falls. At $x = a$, the negative and positive charge exactly cancel each other and $E = 0$.

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.**

Example 2.13

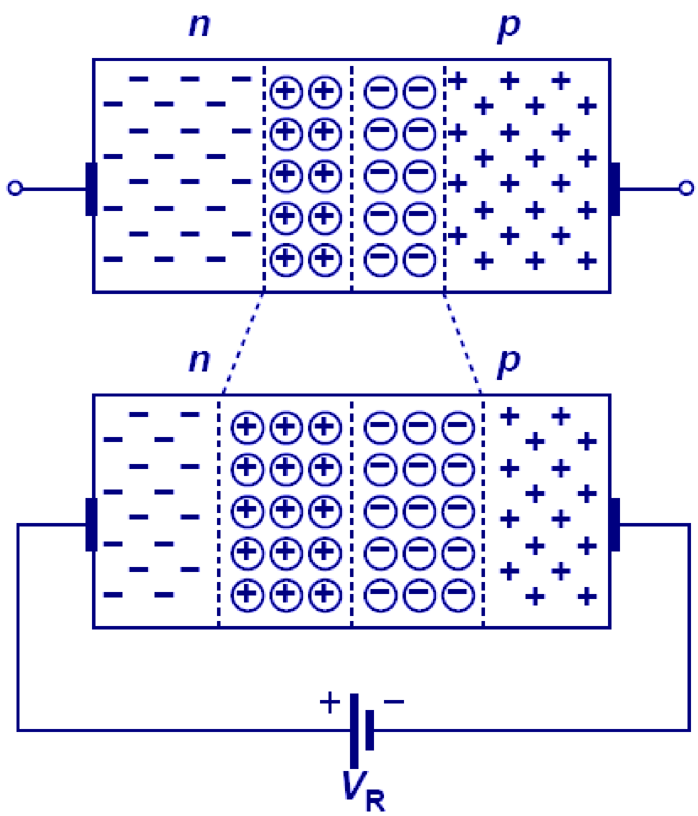
Example 2.13 A silicon *pn* junction employs $N_A = 2 \times 10^{16}\ \text{cm}^{-3}$ and $N_D = 4 \times 10^{16}\ \text{cm}^{-3}$. Determine the built-in potential at room temperature ($T = 300$ K).

Solution Recall from Example 2.1 that $n_i(T = 300\ \text{K}) = 1.08 \times 10^{10}\ \text{cm}^{-3}$. Thus,

$$V_0 \approx (26\ \text{mV}) \ln \frac{(2 \times 10^{16}) \times (4 \times 10^{16})}{(1.08 \times 10^{10})^2} \tag{2.70}$$

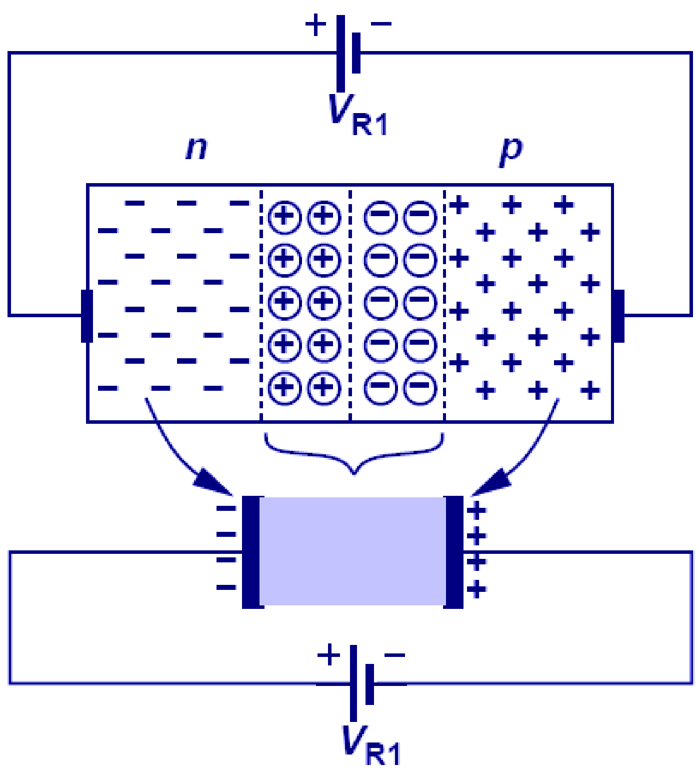
$$\approx 768\ \text{mV}. \tag{2.71}$$

Diode in Reverse Bias

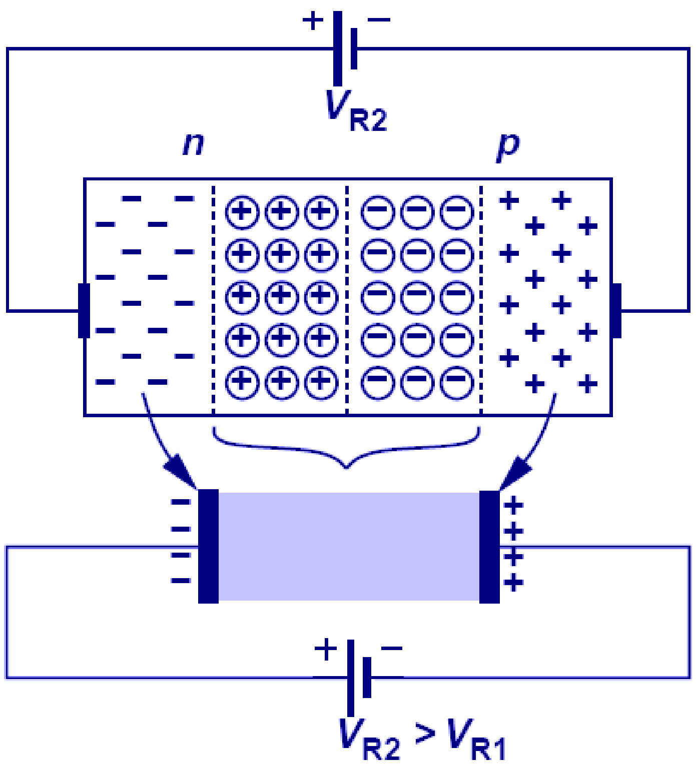


- When the N-type region of a diode is connected to a higher potential than the P-type region, the diode is under reverse bias, which results in wider depletion region and larger built-in electric field across the junction.

Reverse Biased Diode's Application: Voltage-Dependent Capacitor



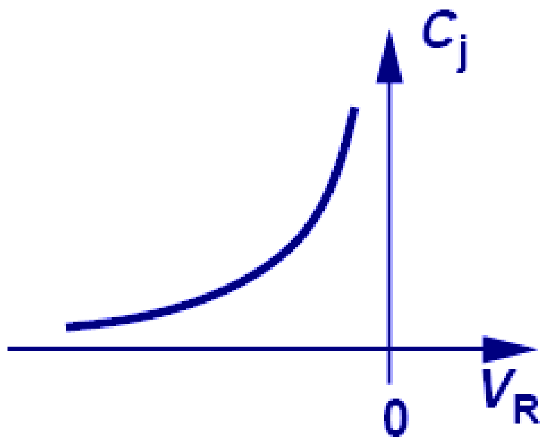
(a)



(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.**

Example 2.15

Example 2.15

A *pn* junction is doped with $N_A = 2 \times 10^{16}\ \mathrm{cm}^{-3}$ and $N_D = 9 \times 10^{15}\ \mathrm{cm}^{-3}$. Determine the capacitance of the device with (a) $V_R = 0$ and $V_R = 1$ V.

Solution We first obtain the built-in potential:

$$V_0 = V_T \ln \frac{N_A N_D}{n_i^2} \tag{2.77}$$

$$= 0.73\ \mathrm{V}. \tag{2.78}$$

Thus, for $V_R = 0$ and $q = 1.6 \times 10^{-19}$ C, we have

$$C_{j0} = \sqrt{\frac{\epsilon_{si} q}{2} \frac{N_A N_D}{N_A + N_D} \cdot \frac{1}{V_0}} \tag{2.79}$$

$$= 2.65 \times 10^{-8}\ \mathrm{F/cm^2}. \tag{2.80}$$

In microelectronics, we deal with very small devices and may rewrite this result as

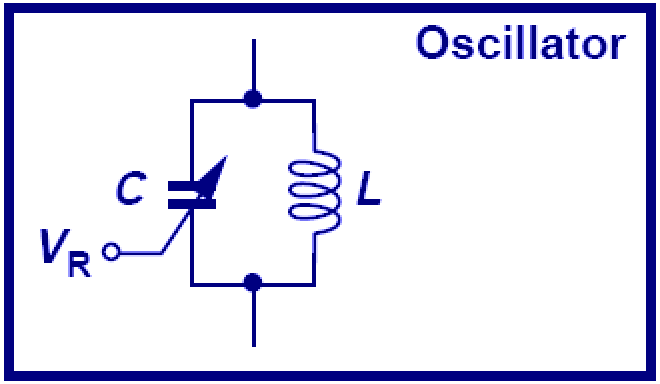
$$C_{j0} = 0.265\ \mathrm{fF}/\mu\mathrm{m}^2, \tag{2.81}$$

where 1 fF (femtofarad) $= 10^{-15}$ F. For $V_R = 1$ V,

$$C_j = \frac{C_{j0}}{\sqrt{1 + \frac{V_R}{V_0}}} \tag{2.82}$$

$$= 0.172\ \mathrm{fF}/\mu\mathrm{m}^2. \tag{2.83}$$

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.**

Example 2.16

Example 2.16

A cellphone incorporates a 2-GHz oscillator whose frequency is defined by the resonance frequency of an LC tank (Fig. 2.26). If the tank capacitance is realized as the pn junction of Example 2.15, calculate the change in the oscillation frequency while the reverse voltage goes from 0 to 2 V. Assume the circuit operates at 2 GHz at a reverse voltage of 0 V, and the junction area is 2000 μm^2.

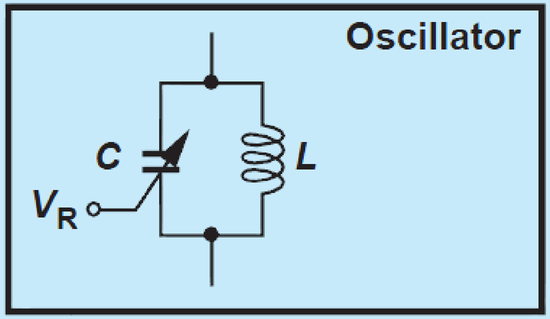


Figure 2.26 Variable capacitor used to tune an oscillator.

Example 2.16

Solution Recall from basic circuit theory that the tank "resonates" if the impedances of the inductor and the capacitor are equal and opposite: $jL\omega_{res} = -(jC\omega_{res})^{-1}$. Thus, the resonance frequency is equal to

$$f_{res} = \frac{1}{2\pi}\frac{1}{\sqrt{LC}}. \tag{2.84}$$

At $V_R = 0, C_j = 0.265\ \mathrm{fF}/\mu\mathrm{m}^2$, yielding a total device capacitance of

$$C_{j,tot}(V_R = 0) = (0.265\ \mathrm{fF}/\mu\mathrm{m}^2) \times (2000\ \mu\mathrm{m}^2) \tag{2.85}$$

$$= 530\ \mathrm{fF}. \tag{2.86}$$

Setting f_{res} to 2 GHz, we obtain

$$L = 11.9\ \mathrm{nH}. \tag{2.87}$$

If V_R goes to 2 V,

$$C_{j,tot}(V_R = 2\ \mathrm{V}) = \frac{C_{j0}}{\sqrt{1 + \frac{2}{0.73}}} \times 2000\ \mu\mathrm{m}^2 \tag{2.88}$$

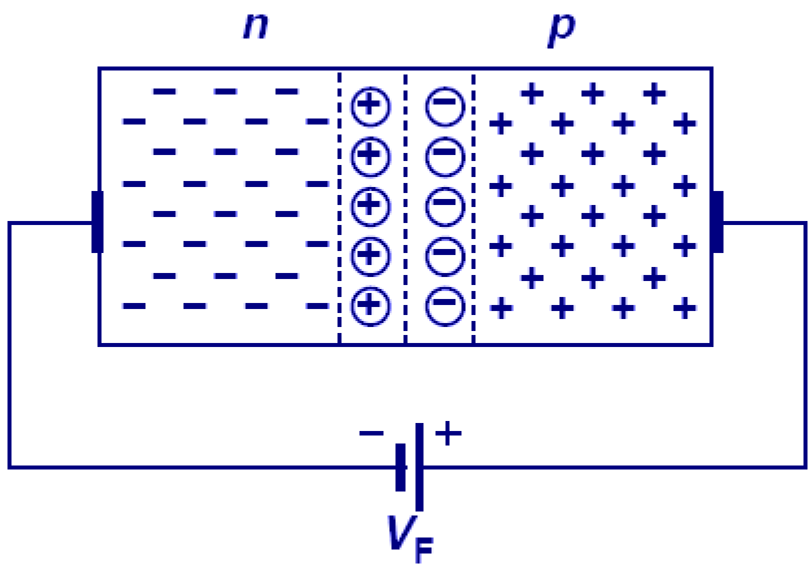
$$= 274\ \mathrm{fF}. \tag{2.89}$$

Using this value along with $L = 11.9$ nH in Eq. (2.84), we have

$$f_{res}(V_R = 2\ \mathrm{V}) = 2.79\ \mathrm{GHz}. \tag{2.90}$$

An oscillator whose frequency can be varied by an external voltage (V_R in this case) is called a "voltage-controlled oscillator" and used extensively in cellphones, microprocessors, personal computers, etc.

Diode in Forward Bias

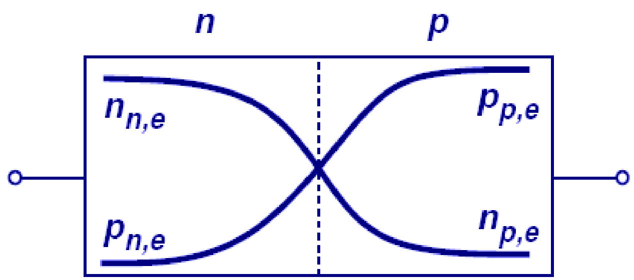


- When the N-type region of a diode is at a lower potential than the P-type region, the diode is in forward bias.
- The depletion width is shortened and the built-in electric field decreased.

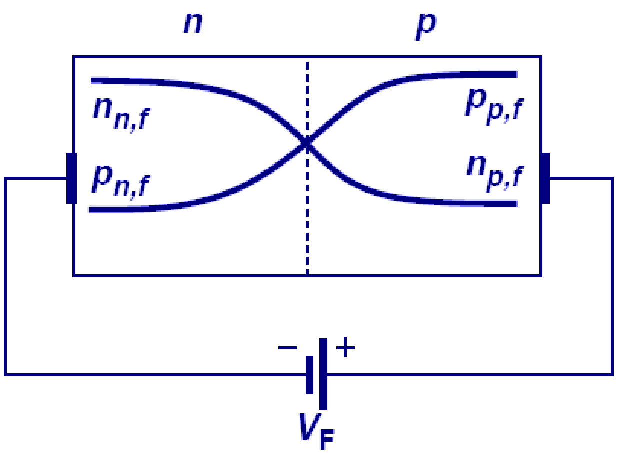
Minority Carrier Profile in Forward Bias

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

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



(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.**

Example 2.17

Example 2.17

Determine I_S for the junction of Example 2.13 at $T = 300\text{K}$ if $A = 100\ \mu\text{m}^2$, $L_n = 20\ \mu\text{m}$, and $L_p = 30\ \mu\text{m}$.

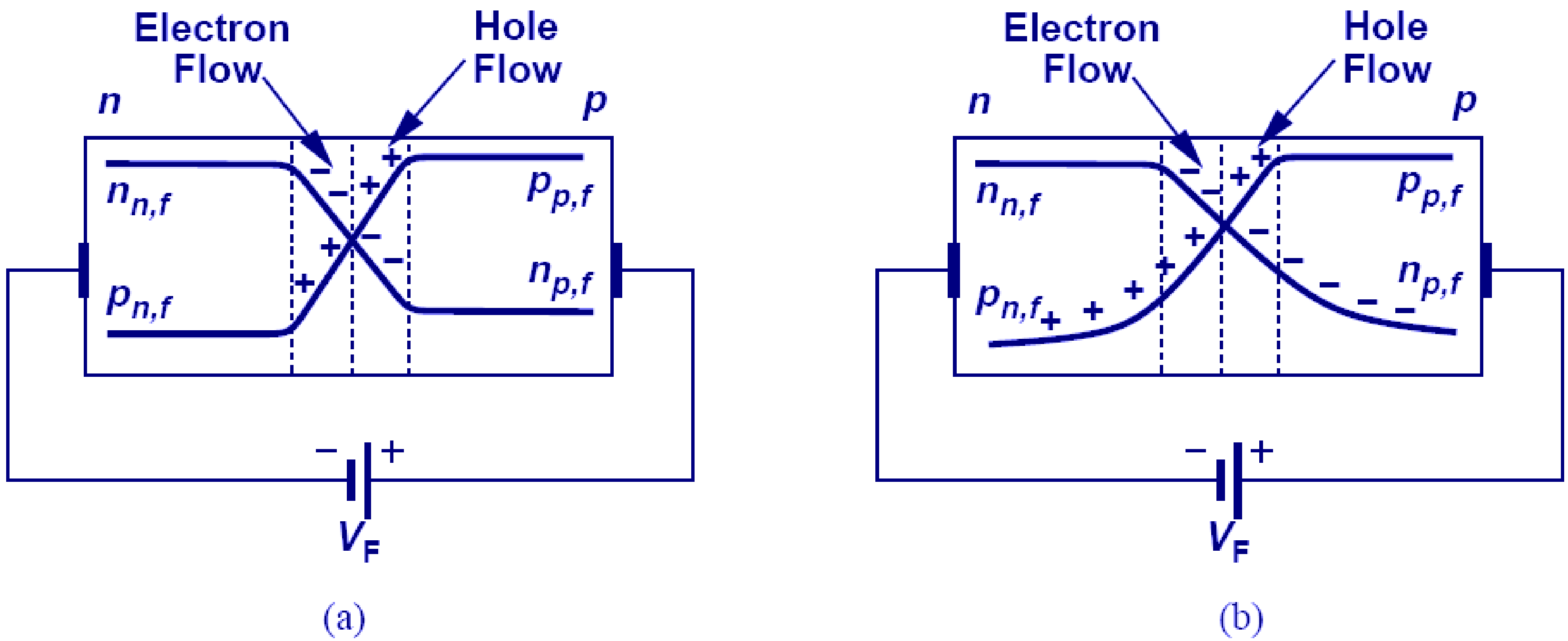
$N_A = 2 \times 10^{16}\ \text{cm}^{-3}$ and $N_D = 4 \times 10^{16}\ \text{cm}^{-3}$

Solution Using $q = 1.6 \times 10^{-19}$ C, $n_i = 1.08 \times 10^{10}$ electrons/cm^3 [Eq. (2.2)], $D_n = 34\ \text{cm}^2/\text{s}$, and $D_p = 12\ \text{cm}^2/\text{s}$, we have

$$I_S = Aqn_i^2 \left(\frac{D_n}{N_A L_n} + \frac{D_p}{N_D L_p} \right) = 1.77 \times 10^{-17}\ \text{A}. \quad (2.100)$$

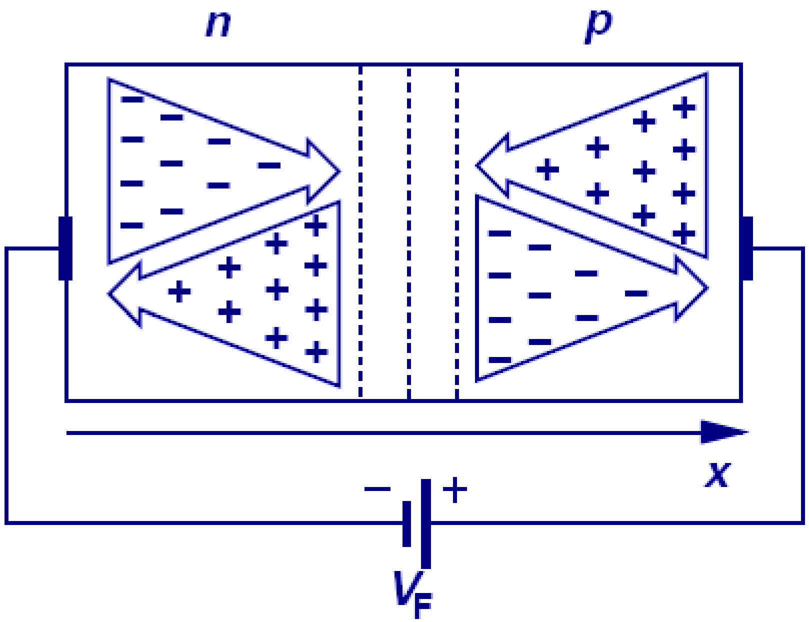
Since I_S is extremely small, the exponential term in Eq. (2.98) must assume very large values so as to yield a useful amount (e.g., 1 mA) for I_{tot}.

Minority Charge Gradient



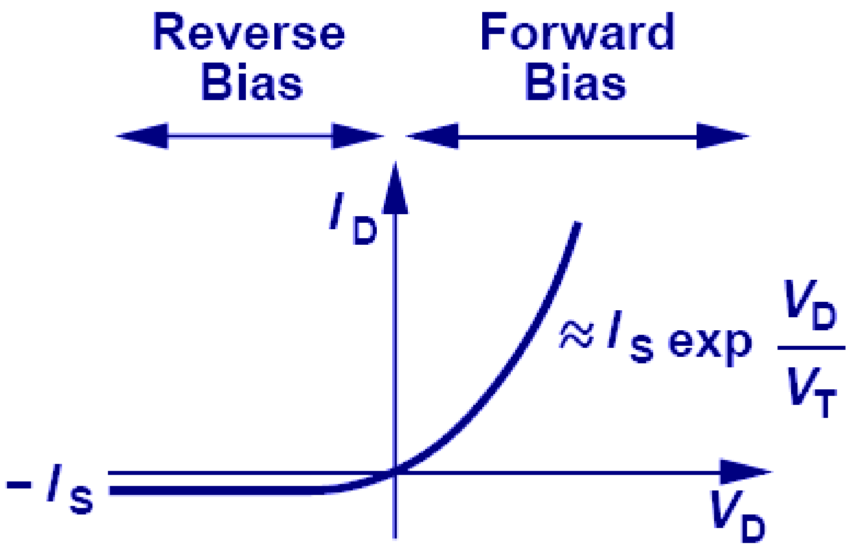
- **Minority charge profile should not be constant along the x-axis; otherwise, there is no concentration gradient and no diffusion current.**
- **Recombination of the minority carriers with the majority carriers accounts for the dropping of minority carriers as they go deep into the P or N region.**

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.

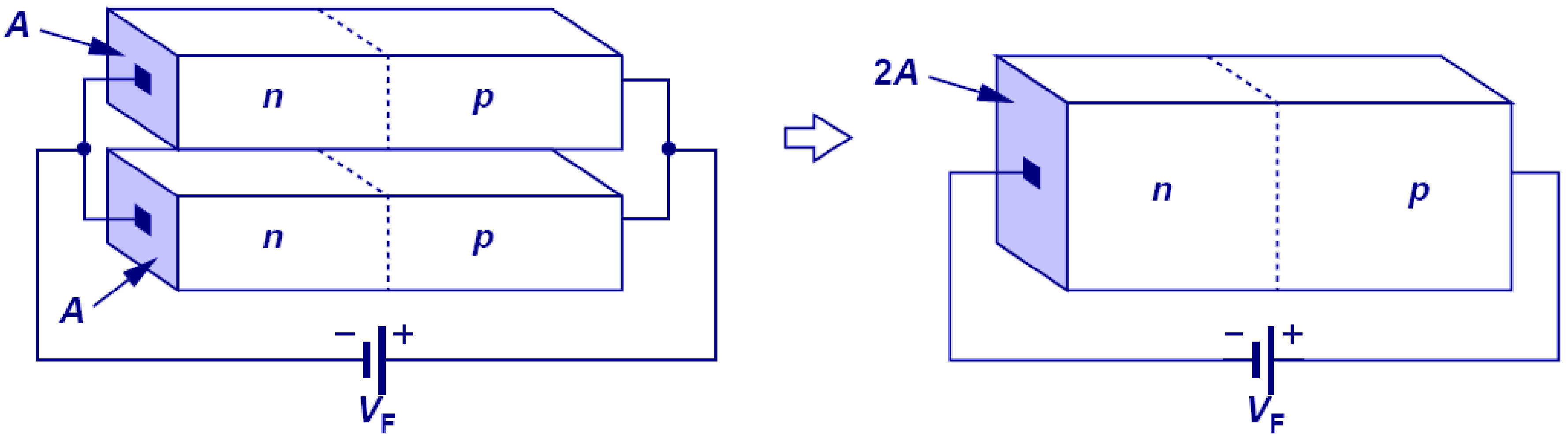
IV Characteristic of PN Junction



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

- **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.

Example 2.18

Example 2.18 Each junction in Fig. 2.32 employs the doping levels described in Example 2.13. Determine the forward bias current of the composite device for $V_D = 300$ mV and 800 mV at $T = 300$ K.

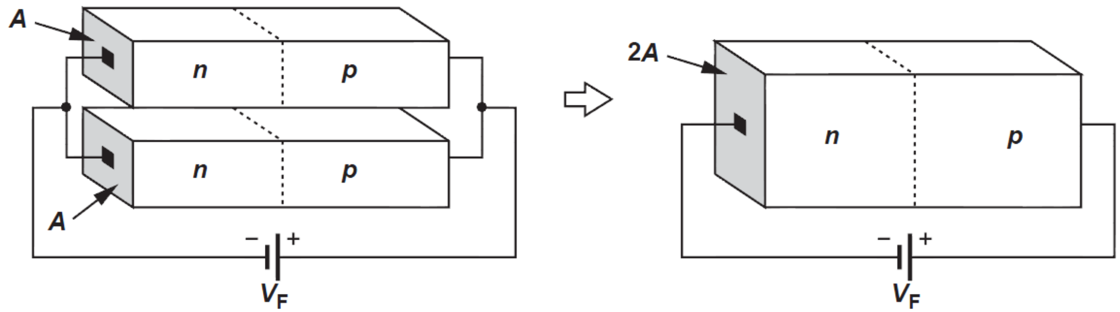


Figure 2.32 Equivalence of parallel devices to a larger device.

Solution From Example 2.17, $I_S = 1.77 \times 10^{-17}$ A for each junction. Thus, the total current is equal to

$$I_{D,tot}\,(V_D = 300\,\text{mV}) = 2I_S\left(\exp\frac{V_D}{V_T} - 1\right) \tag{2.103}$$

$$= 3.63\,\text{pA}. \tag{2.104}$$

Similarly, for $V_D = 800$ mV:

$$I_{D,tot}(V_D = 800\,\text{mV}) = 82\,\mu\text{A}. \tag{2.105}$$

Example 2.20

Example 2.20

The cross section area of a diode operating in the forward bias region is increased by a factor of 10. (a) Determine the change in I_D if V_D is maintained constant. (b) Determine the change in V_D if I_D is maintained constant. Assume $I_D \approx I_S \exp(V_D/V_T)$.

Solution (a) Since $I_S \propto A$, the new current is given by

$$I_{D1} = 10 I_S \exp\frac{V_D}{V_T} \tag{2.110}$$

$$= 10 I_D. \tag{2.111}$$

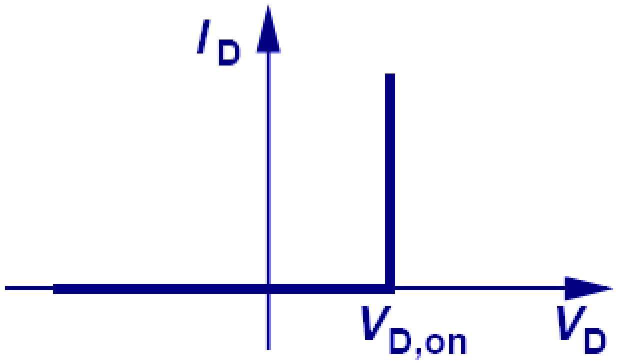
(b) From the above example,

$$V_{D1} = V_T \ln \frac{I_D}{10 I_S} \tag{2.112}$$

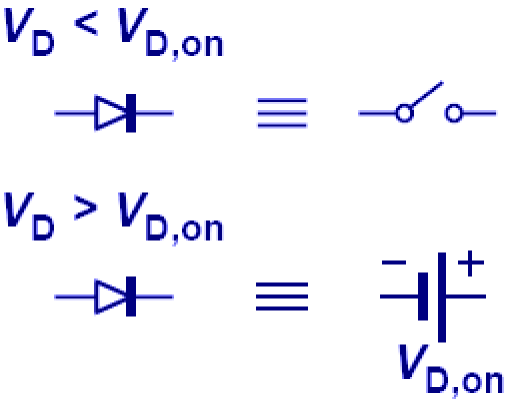
$$= V_T \ln \frac{I_D}{I_S} - V_T \ln 10. \tag{2.113}$$

Thus, a tenfold increase in the device area lowers the voltage by 60 mV if I_D remains constant.

Constant-Voltage Diode Model



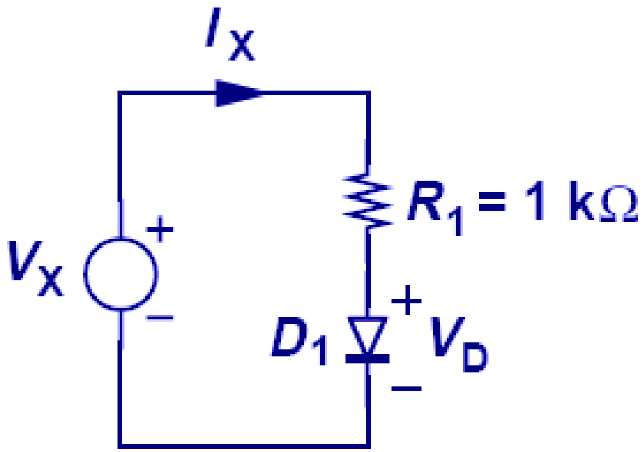
(a)



(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.

Example 2.21

Example 2.21

Consider the circuit of Fig. 2.34. Calculate I_X for $V_X = 3\,\text{V}$ and $V_X = 1\,\text{V}$ using (a) an exponential model with $I_S = 10^{-16}\,\text{A}$ and (b) a constant-voltage model with $V_{D,on} = 800\,\text{mV}$.

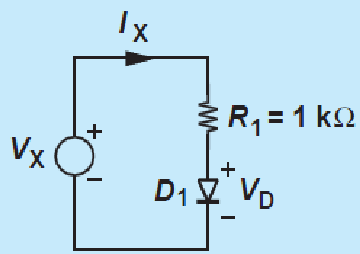


Figure 2.34 Simple circuit using a diode.

Solution (a) Noting that $I_D = I_X$, we have

$$V_X = I_X R_1 + V_D \tag{2.114}$$

$$V_D = V_T \ln \frac{I_X}{I_S}. \tag{2.115}$$

This equation must be solved by iteration: we guess a value for V_D, compute the corresponding I_X from $I_X R_1 = V_X - V_D$, determine the new value of V_D from $V_D = V_T \ln (I_X/I_S)$ and iterate. Let us guess $V_D = 750\,\text{mV}$ and hence

$$I_X = \frac{V_X - V_D}{R_1} \tag{2.116}$$

$$= \frac{3\,\text{V} - 0.75\,\text{V}}{1\,\text{k}\Omega} \tag{2.117}$$

$$= 2.25\,\text{mA}. \tag{2.118}$$

Example 2.21

Thus,

$$V_D = V_T \ln \frac{I_X}{I_S} \tag{2.119}$$

$$= 799\,\text{mV}. \tag{2.120}$$

With this new value of V_D, we can obtain a more accurate value for I_X:

$$I_X = \frac{3\,\text{V} - 0.799\,\text{V}}{1\,\text{k}\Omega} \tag{2.121}$$

$$= 2.201\,\text{mA}. \tag{2.122}$$

We note that the value of I_X rapidly converges. Following the same procedure for $V_X = 1$ V, we have

$$I_X = \frac{1\,\text{V} - 0.75\,\text{V}}{1\,\text{k}\Omega} \tag{2.123}$$

$$= 0.25\,\text{mA}, \tag{2.124}$$

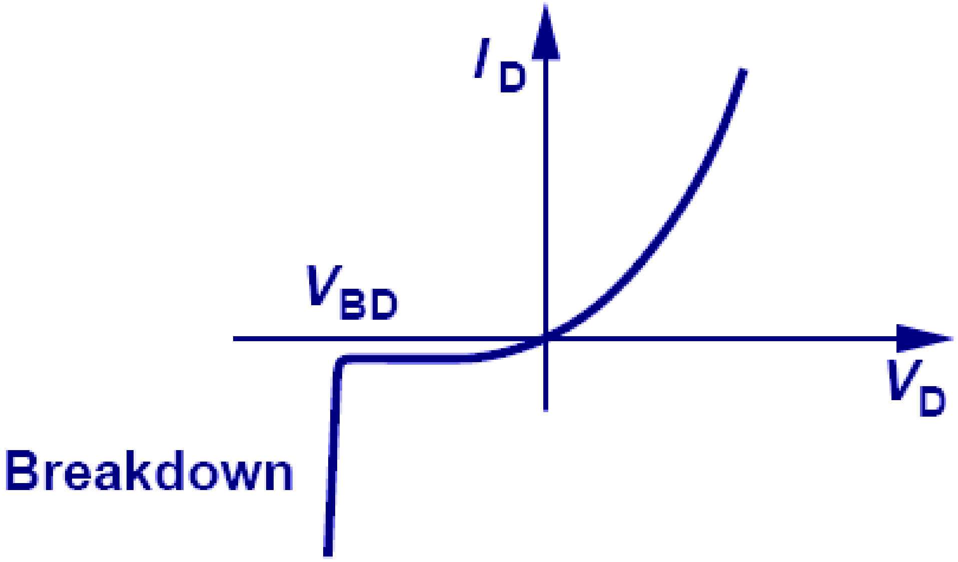
which yields $V_D = 0.742$ V and hence $I_X = 0.258$ mA. (b) A constant-voltage model readily gives

$$I_X = 2.2\,\text{mA for } V_X = 3\,\text{V} \tag{2.125}$$

$$I_X = 0.2\,\text{mA for } V_X = 1\,\text{V}. \tag{2.126}$$

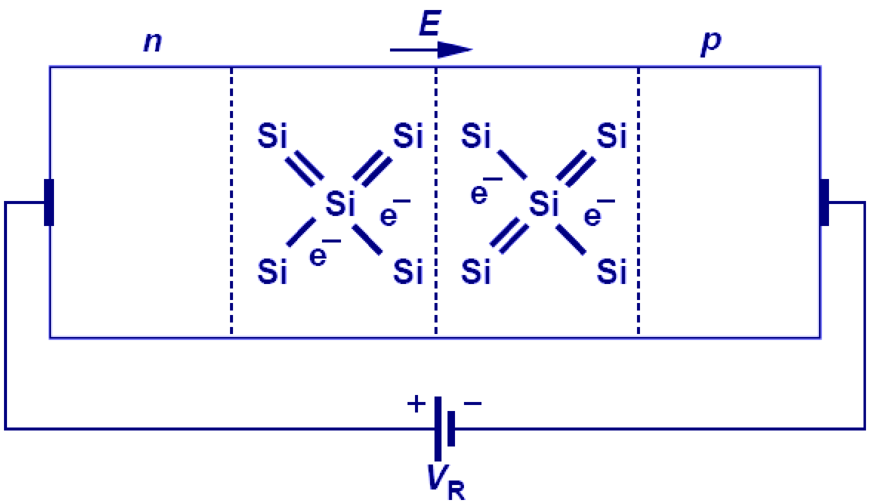
The value of I_X incurs some error, but it is obtained with much less computational effort than that in part (a).

Reverse Breakdown

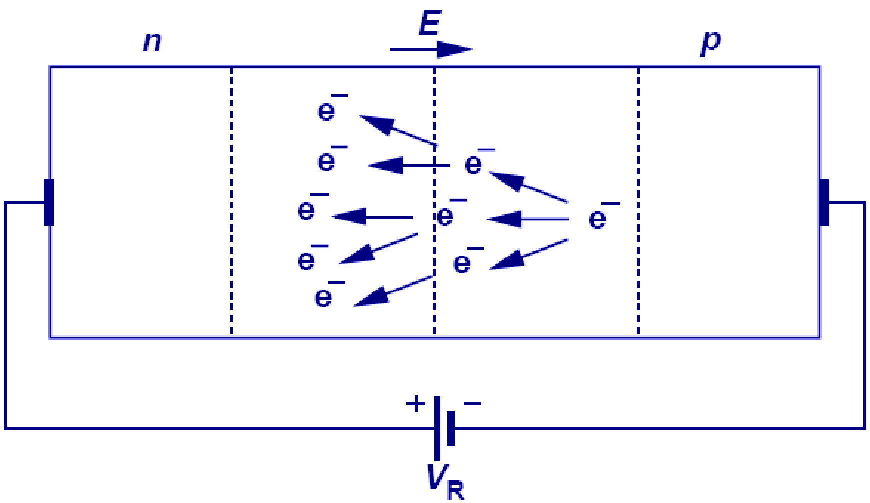


- **When a large reverse bias voltage is applied, breakdown occurs and an enormous current flows through the diode.**

Zener vs. Avalanche Breakdown



(a)



(b)

- **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.**