Chapter 2 Basic Physics of Semiconductors

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

Semiconductor & PN Junction

- To deal with the *analysis* and *design* of circuits, a good understanding of devices is essential.
- In this chapter, we begin with the concept of semiconductors and study the movement of charge (i.e., the flow of current) in them. 二極體
- Next, we deal with the "***PN junction***," which also serves as ***diode***, and formulate its behavior. PN接面 電路模型
- Our ultimate goal is to represent the device by a *circuit model* (consisting of resistors, voltage or current sources, capacitors, etc.), so that a circuit using such a device can be analyzed easily.
- Semiconductor devices serve as heart of microelectronics.
- PN junction is the most fundamental semiconductor device.

Semiconductors

- Charge Carriers
- Doping
- Transport of Carriers

PN Junction

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

Charge Carriers in Semiconductor

- To understand PN junction's IV characteristics, a logical thought process as follows:
- ① **Charge Carriers in Solids**
  - Crystal Structure
  - Bandgap Energy
  - Holes

  ⇨ ② **Modification of Carrier Densities**
  - Intrinsic Semiconductors
  - Extrinsic Semiconductors
  - Doping

  ⇨ ③ **Transport of Carriers**
  - Diffusion
  - Drift
- First, identify charge carriers in solids and formulate their role in current flow;
- Second, examine means of modifying the density of charge carriers to create desired current flow properties;
- Third, we determine current flow mechanisms.
- These steps naturally lead to the computation of the current/voltage (I/V) characteristics of actual diodes in the next section.

Periodic Table

- This abridged table contains elements with three to five *valence electrons*, with ***Silicon*** (***Si***) being the most important. 價電子
- *Crystalline* semiconductor (IV) and *compound* semiconductor (III-V, II-VI) are commonly used in semiconductor industry. 化合物半導體

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

Table 1.2 A portion of the periodic table

III	IV	V
5 **B** Boron	6 **C** Carbon	
13 **Al** Aluminum	14 **Si** Silicon	15 **P** Phosphorus
31 **Ga** Gallium	32 **Ge** Germanium	33 **As** Arsenic
49 **In** Indium		51 **Sb** Antimony

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.

Table 1.1 A list of some semiconductor materials

Elemental semiconductors		**Compound semiconductors**	
Si	Silicon	GaAs	Gallium arsenide
Ge	Germanium	GaP	Gallium phosphide
		AlP	Aluminum phosphide
		AlAs	Aluminum arsenide
		InP	Indium phosphide

B:硼, Al:鋁, Ga:鎵, In:銦
C:碳, Si:矽, Ge:鍺, Sn:錫
N:氮, P:磷, As:砷, Sb:銻
GaAs:砷化鎵 … … …

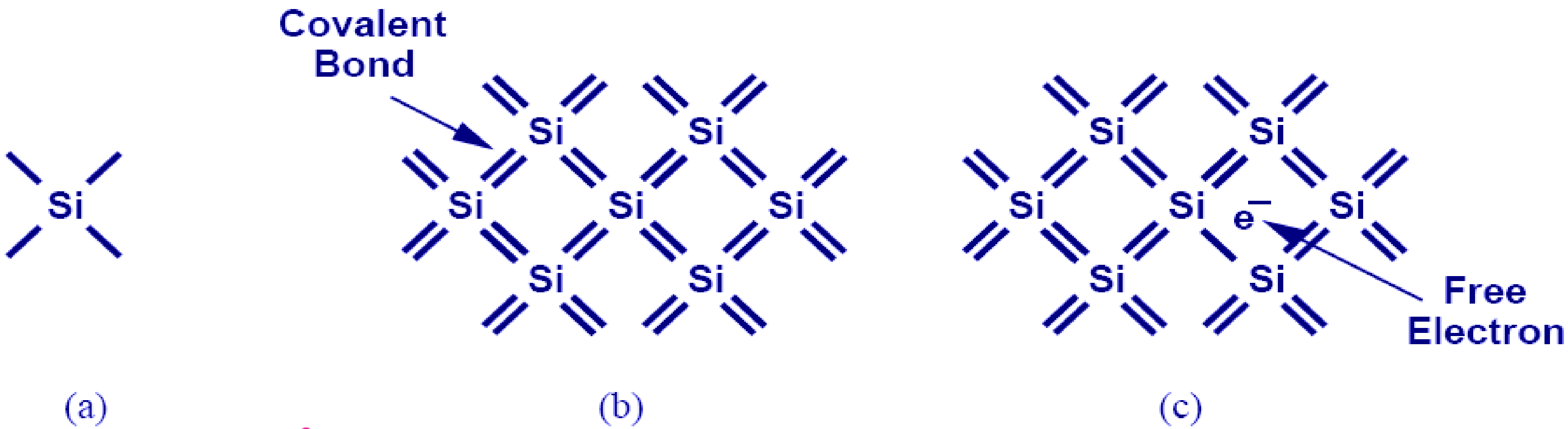
Silicon

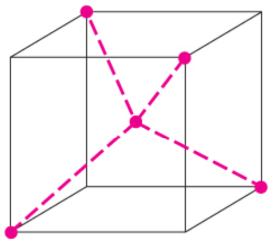
- Si has four valence electrons. Therefore, it can form *covalent bonds* with four of its neighbors. 共價鍵

  Valence electrons: electrons in the outermost shell

  Covalent bond: valence electrons are shared between atoms

- When temperature goes up, ***electrons*** in the covalent bond can become free.

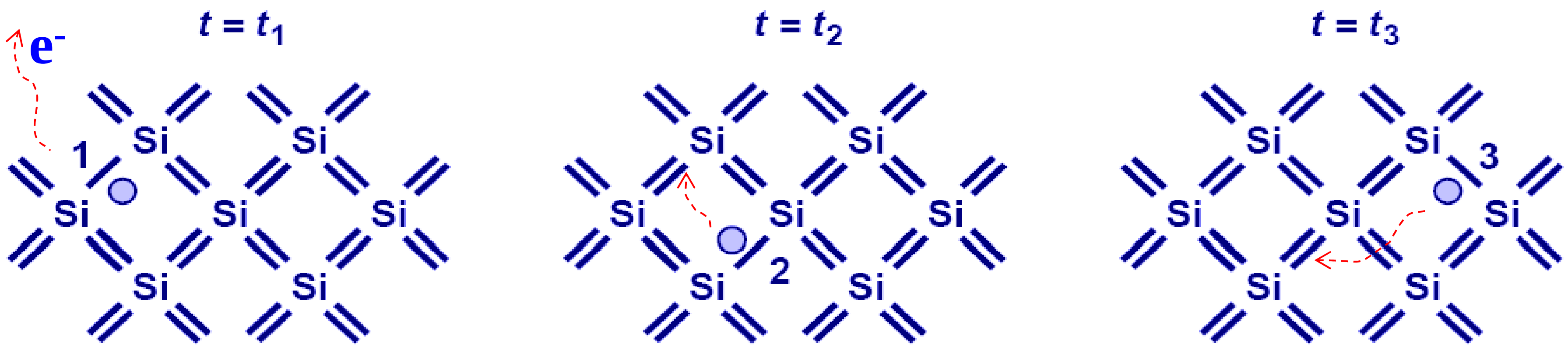




Tetrahedral configuration

Electron-Hole Pair Interaction

- At 0K, no bonds are broken, Si is an insulator.
- As temperature increases, a bond can break, releasing a valence electron and leaving a broken bond (***hole***). Current can flow. 電洞, 帶正電荷
- 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.



Concept of Energy Band

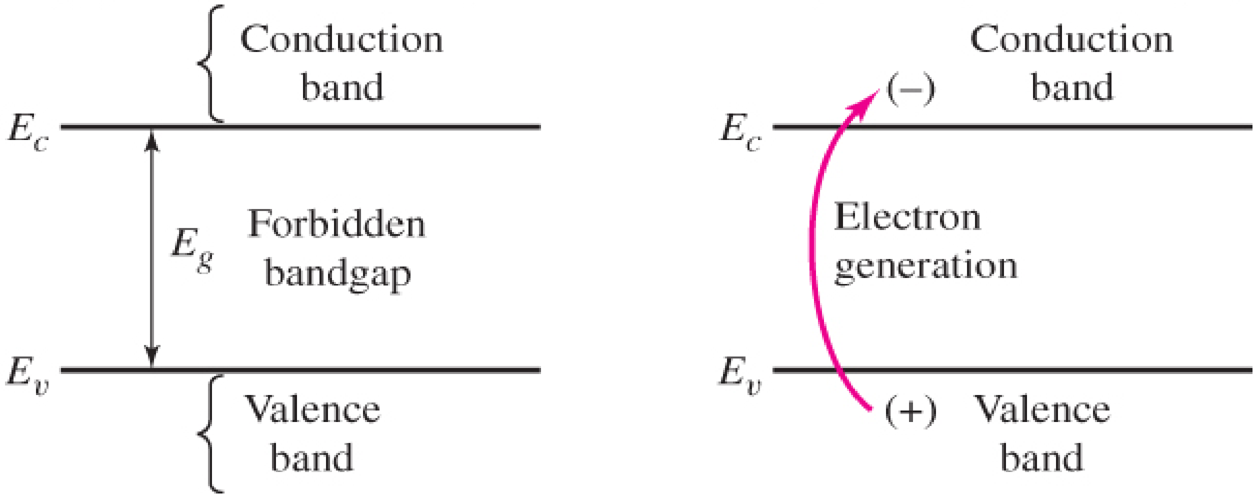
能帶

- E_V : the max energy of valence band
- E_C : the min energy of conduction band
- E_g : the energy required to break the covalent bond
  - ***bandgap*** energy, = $E_V - E_C$
    - E_g of the insulators is in range of 3-6 eV.
    - E_g of the semiconductor is on the order of 1 eV

(1eV=1.6×10-19 J)

- Forbidden bandgap
  - No electron exist within this region
- Electron gaining energy
  - moving into E_C from E_V

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.



Free Electron Density at a Given Temperature

- E_g, or ***bandgap energy*** determines how much effort is needed to break off an electron from its covalent bond. For silicon, E_g = 1.12 eV; 1 eV = 1.6 x 10^{-19}J
- There exists an exponential relationship between the free-electron density, n_i, the number of electronics per unit volume, and bandgap energy.

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

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

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

where k = 1.38 x 10^{-23} J/K, the Boltzmann constant

- Insulators display a high E_g; for example, 2.5 eV for diamond. Conductors, on the other hand, have a small E_g. Finally, *semi*conductors exhibit a moderate E_g, typically ranging from 1 eV to 1.5 eV.
- Silicon has 5 x 10^{22} atoms/cm^3, hence, only one in 5 x 10^{12} atoms benefit from a free electron at room temperature.

Intrinsic Semiconductor

- The "pure" silicon is an "***intrinsic*** semiconductor," suffering from a very high resistance. 本質半導體
- In an intrinsic semiconductor, the electron density, n (= n_i), is equal to the hole density, p. Thus, $\boldsymbol{np = n_i^2}$
- It is possible to modify the ***resistivity*** of silicon by replacing some of the atoms in the crystal with atoms of another material.
- The controlled addition of an "*impurity*" to an intrinsic semiconductor is called "***doping***," and the impurity itself a "***dopant***." 摻雜、摻雜物
- After doped, the equation $np = n_i^2$ still holds, where n and p respectively denote the electron and hole densities in the extrinsic (doped) semiconductor.

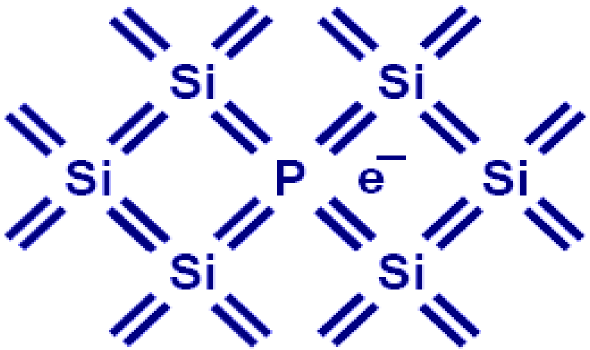
Example 2.2: The above result seems quite strange. How can np remain constant while we add more donor atoms and increase n?

Solution: The equation reveals that p must fall *below* its intrinsic level as more n-type dopants are added to the crystal. This occurs because many of the new electrons donated by the dopant "***recombine***" with the holes that were created in the intrinsic material.

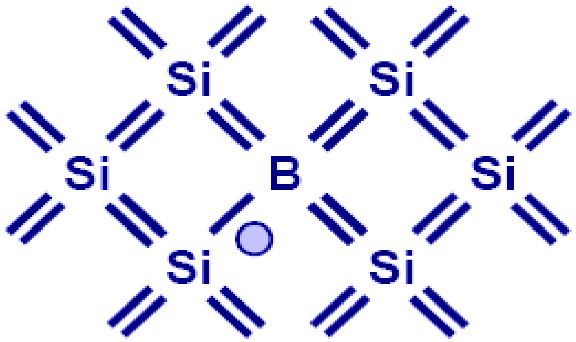
Why can we not say that $n + p$ should remain constant? 再結合

Doping

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



N-type



P-type

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

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

It follows from (2.2) and (2.5) that

$$p = n_i^2/n = 1.17 \times 10^4 \text{ holes/cm}^3$$

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 predominantly consists of electrons.

Exercise At what doping level does the hole density drop by three orders of magnitude?

Electron and Hole Densities

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

$$np = n_i^2$$

多數載子 Majority Carriers : $p \approx N_A$

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

if doped with N_A ($\gg n_i$)

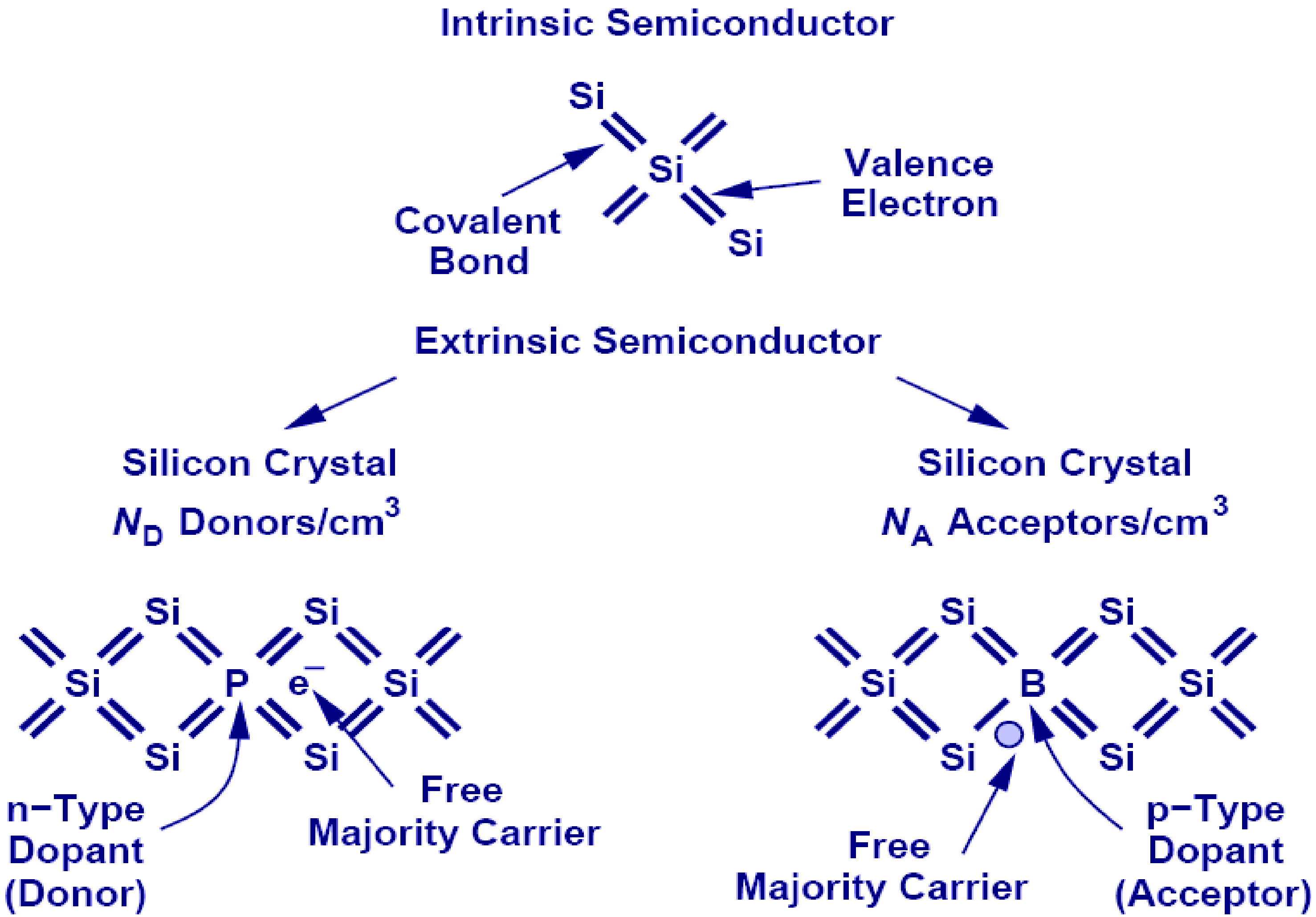
Majority Carriers : $n \approx N_D$

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

if doped with N_D ($\gg n_i$)

Since typical doping densities fall in the range of 10^{15} to 10^{18} atoms/cm^3, the above expressions are quite accurate.

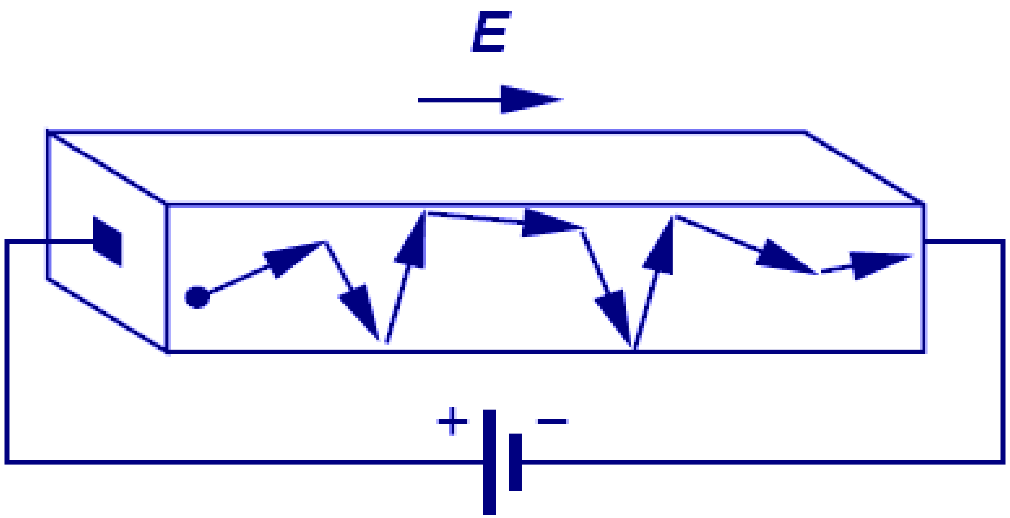
Summary of Charge Carriers



- Charge particles will move in semiconductor, which results electric current.

First Charge Transportation Mechanism: Drift

- Charge particles move due to an electric field is called ***drift***.
- Charge particles will move at a velocity that is proportional to the electric field.



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

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

遷移率

- μ is called the ***mobility***, usually expressed as cm^2/(V·s)
- In silicon, the mobility of electrons is μ_n = 1350 cm^2/(V·s), and hole has μ_p = 480 cm^2/(V·s)

Drift and Diffusion Currents

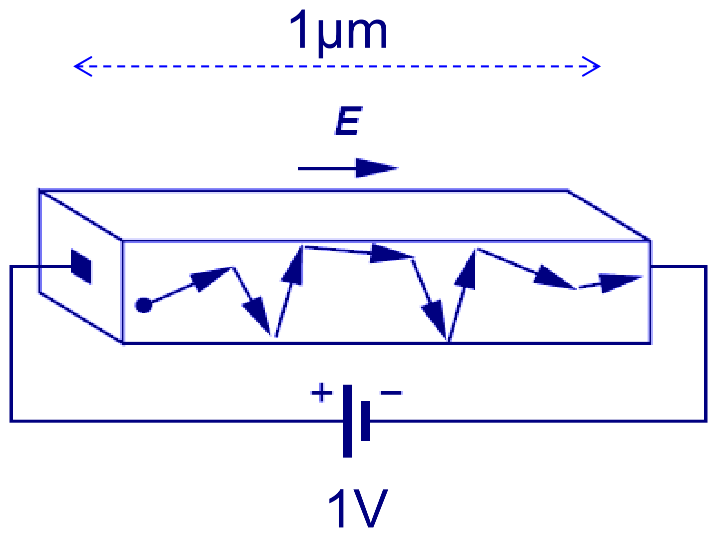
- Two basic processes cause electrons and holes to move in semiconductor.
- Drift: 漂移
  - Cause by electric field (E)
  - E produces a force that acts on free electrons and holes.
- Diffusion: 擴散
  - Cause by variations in the concentration (concentration gradients)
    - Nonhomogeneous doping distribution：Gradients
    - Injection of a quantity of electrons or holes into a region.

Example 2.5

A uniform piece of n-type of silicon that is 1 μm long senses a voltage of 1 V. Determine the velocity of the electrons.

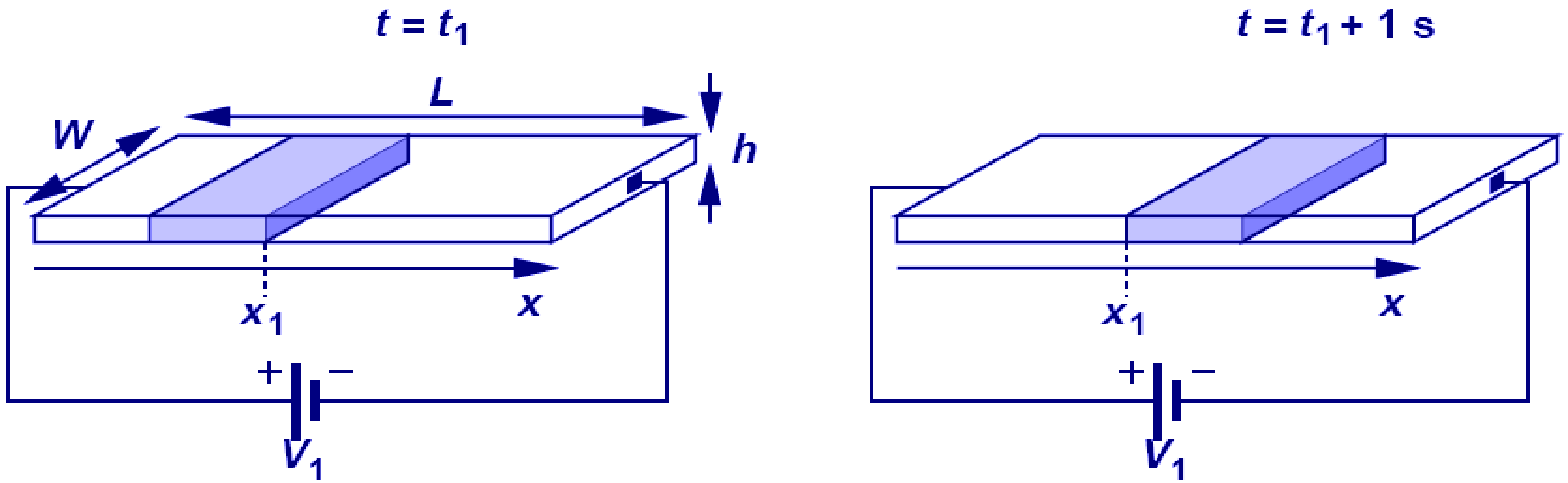
Solution

Since the material is uniform, we have $E = V/L$, where L is the length. Thus, E = 10000 V/cm and hence $v = \mu_n E$ =1.35 x 10^7 cm/s. In other words, electrons take (1 μm)/(1.35 x 10^7 cm/s) = 7.4 ps to cross the 1-μm length.



Current Flow: General Case

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



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

W and *h* are the dimension of the semiconductor bar,

n is the carrier density,

and *q* is the charge of an electron equal to $q = 1.6 \times 10^{-19}$ C

Current Flow: Drift

- Since velocity is equal to μE, drift characteristic is obtained by substituting *v* with μE in the general current equation.
- Since $A = W \cdot h$ is the cross section area of the bar
- And, the current density is $J = I/A$, therefore

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

Also,

$$J_p = \mu_p E \cdot p \cdot q$$

- Thus the total current density consists of both electrons and holes.

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

Example 2.6

In an experiment, it is desired to obtain equal electron and hole drift currents. How should the carrier densities be chosen?

Solution

We must impose $\mu_n n = \mu_p p,$

and hence $\dfrac{n}{p} = \dfrac{\mu_p}{\mu_n}.$

We also recall that $np = n_i^2$. Thus, $p = \sqrt{\dfrac{\mu_n}{\mu_p}} n_i \quad n = \sqrt{\dfrac{\mu_p}{\mu_n}} n_i.$

For example, in silicon, $\mu_n/\mu_p = 1350/480 = 2.81$, yielding

$p = 1.68\ n_i$, and $n = 0.596\ n_i$

Since p and n are of the same order as n_i, equal electron and hole drift currents can occur for only a very *lightly doped* material. This confirms our earlier notion of majority carriers in semiconductors having typical doping levels of 10^{15}- 10^{18} atoms/cm^3.

輕微摻雜

Total drift current density

- The semiconductor contains both electron and hole
  - $J = en\mu_n E + ep\mu_p E = (en\mu_n + ep\mu_p)E = \sigma E = E/\rho$
- σ is the conductivity of semiconductor in $(\Omega\text{-cm})^{-1}$
  - The conductivity is related to the concentration of the electronic and hole.
- ρ is the resistivity of the semiconductor in (Ω-cm)
  - A linear relationship between current and voltage and is one form of ohm's law.
- $$\sigma = \frac{1}{\rho}$$

Example

- Consider silicon at T＝300 K doped with As atoms at a concentration of N_d = $8x10^{15}cm^{-3}$. Assume mobility values are μ_n = $1350cm^2/V$-s and μ_p = $480cm^2/V$-s . Assume the applied electric field is 100 V/cm.
- Solution
  - The electron concentration is

$$n = N_d = 8 \times 10^{15} cm^{-3}$$

  - The hole concentration is

$$p = \frac{n_i^2}{N_d} = \frac{\left(1.08 \times 10^{10}\right)^2}{8 \times 10^{15}} = 1.46 \times 10^4 cm^{-3}$$

Because of the difference in magnitudes between the two concentrations, the conductivity is given by

$$\sigma = e\mu_n n + e\mu_p p \cong e\mu_n n$$

Or

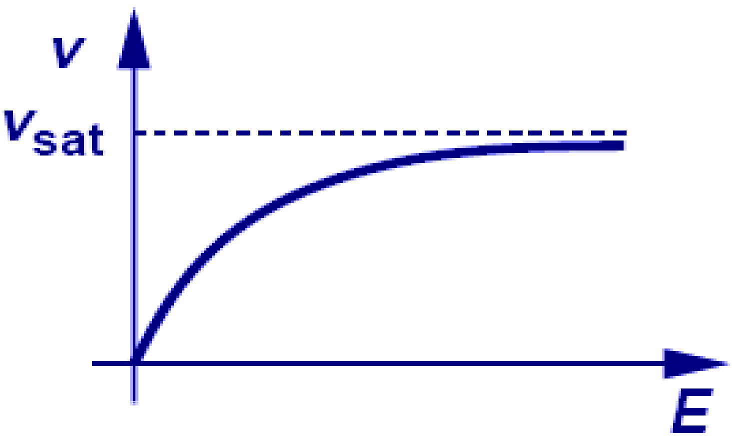
$$\sigma = (1.6 \times 10^{19})(1350)(8 \times 10^{15}) = 1.73(\Omega - cm)^{-1}$$

The drift current density is then

$$J = \sigma E = (1.73)(100) = 173\, A / cm^2$$

Velocity Saturation

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



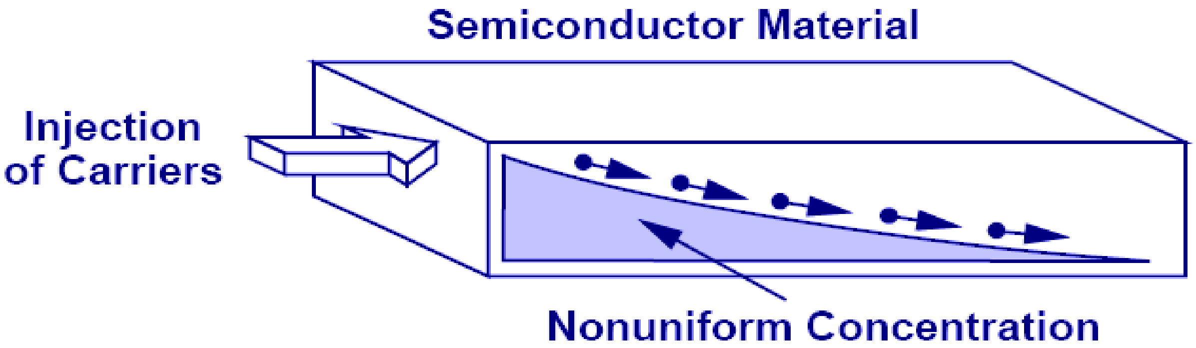
$$\mu = \frac{\mu_0}{1 + bE}$$

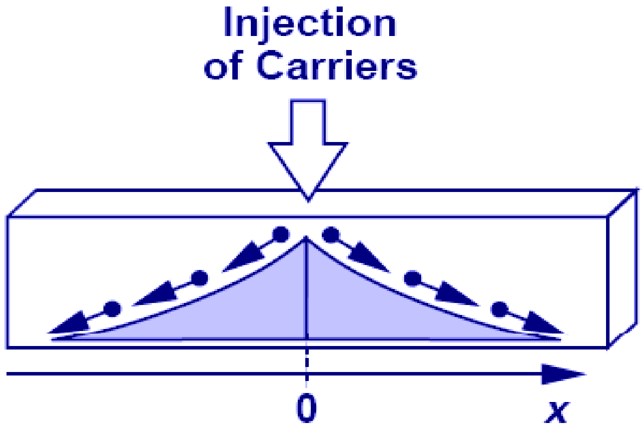
$$v_{sat} = \frac{\mu_0}{b}$$

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

Second Charge Transportation Mechanism: Diffusion

- Charge particles move from a region of high concentration to a region of low concentration, analogous to an every day example of an ink droplet in water.
- This is a statistical phenomenon related to kinetic theory.





Current Flow: Diffusion

- Diffusion current is proportional to the *gradient of charge* (*dn*/*dx*) along the direction of current flow. 電荷梯度

擴散常數

- *D* is a proportionality factor called the "*diffusion constant*" and expressed in cm²/s. For example, in intrinsic silicon, D_n = 34 cm²/s (for electrons), and D_p = 12 cm²/s (for holes).
- Its total current density consists of both electrons and holes.

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

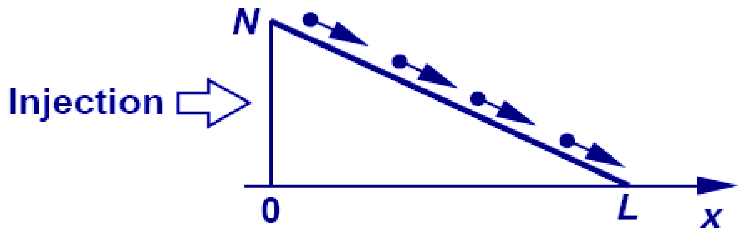
$$J_n = qD_n \frac{dn}{dx}$$

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

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

Example 2.9 & 2.10

Consider the scenario depicted in Fig. 2.11 again. Suppose the electron concentration is equal to N at $x = 0$ and falls linearly to zero at $x = L$ (Fig. 2.13). Determine the diffusion current.



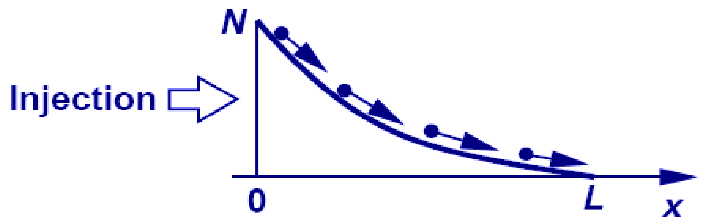
Solution

We have $J_n = qD_n \frac{dn}{dx} \quad = -qD_n \cdot \frac{N}{L}.$

The current is constant along the x-axis; i.e., all of the electrons entering the material at successfully reach the point at $x = L$. While obvious, this observation prepares us for the next example.

Repeat the above example but assume an exponential gradient (Fig. 2.14):

$n(x) = N \exp \frac{-x}{L_d}$, where L_d is a constant.



Solution

We have $J_n = qD_n \frac{dn}{dx} \quad = \frac{-qD_n N}{L_d} \exp \frac{-x}{L_d}.$

Interestingly, the current is not constant along the x-axis. That is, some electrons vanish while traveling from $x = 0$ to the right. What happens to these electrons? Does this example violate the law of conservation of charge?

Einstein's Relation

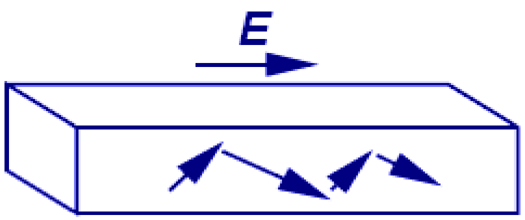
- While the underlying physics behind drift and diffusion currents are totally different, Einstein's relation provides a mysterious link between the two.

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

Note that $kT/q \approx 26$ mV at $T = 300$ K.

- The charge transport mechanisms

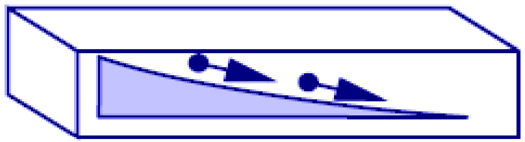
Drift Current



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

$$J_p = q\,\mu_p$$

Diffusion Current

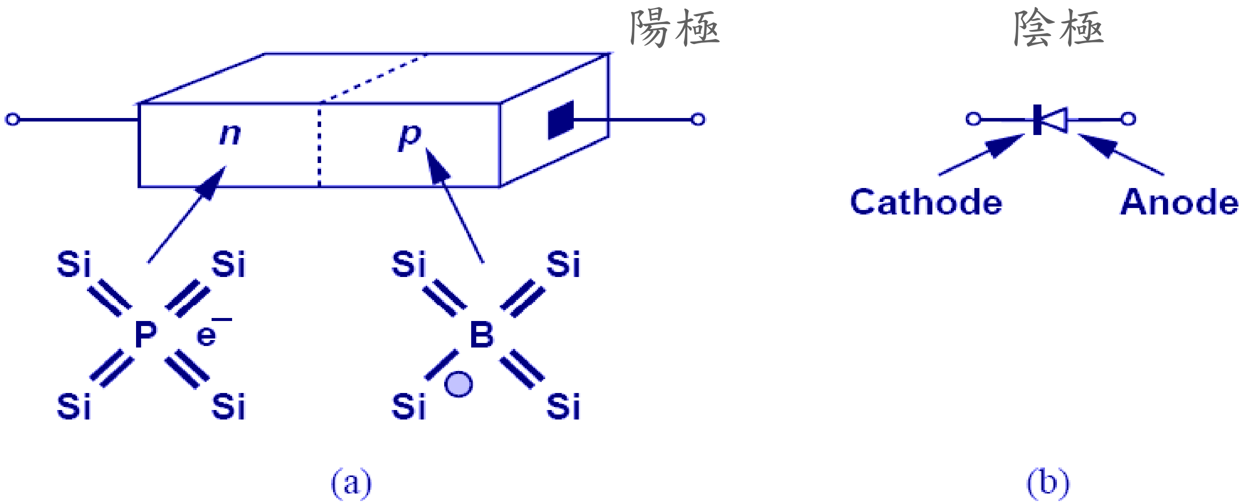


$$J_n = q\,D_n \frac{dn}{dx}$$

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

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.
- The *p* and *n* sides are called the "***anode***" and the "***cathode***," respectively.



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

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

⇨

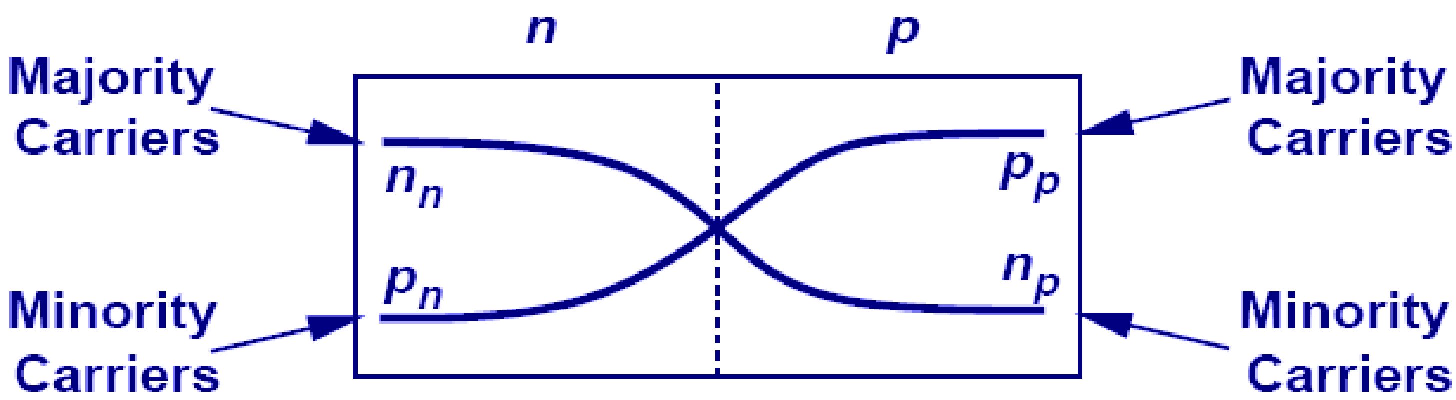
PN Junction Under Reverse Bias
- Junction Capacitance

⇨

PN Junction Under Forward Bias
- I/V Characteristics

Current Flow Across Junction: Diffusion

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



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

Example 2.11

A junction employs the following doping levels: $N_A = 10^{16}$ cm^{-3} and $N_D = 5 \times 10^{15}$ cm^{-3}. Determine the hole and electron concentrations on the two sides.

Solution:

From Eqs. (2.11) and (2.12), we express the concentrations of holes and electrons on the *p* side respectively as:

$$p_p \approx N_A = 10^{16}\ \text{cm}^{-3},$$

$$n_p \approx n_i^2/N_A = (1.08 \times 10^{10}\ \text{cm}^{-3})^2/10^{16}\ \text{cm}^{-3} \approx 1.17 \times 10^4\ \text{cm}^{-3}.$$

Similarly, the concentrations on the *n* side are given by

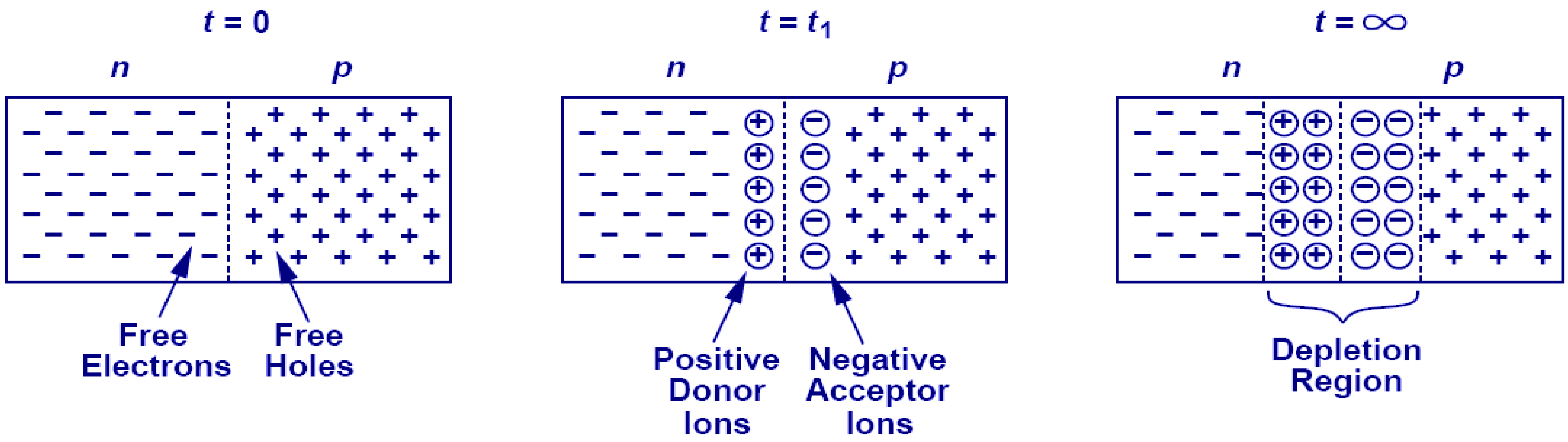
$$n_n \approx N_D = 5 \times 10^{15}\ \text{cm}^{-3},$$

$$p_n \approx n_i^2/N_D = (1.08 \times 10^{10}\ \text{cm}^{-3})^2/5 \times 10^{15}\ \text{cm}^{-3} \approx 2.3 \times 10^4\ \text{cm}^{-3}.$$

Note that the majority carrier concentration on each side is many orders of magnitude higher than the minority carrier concentration on either side.

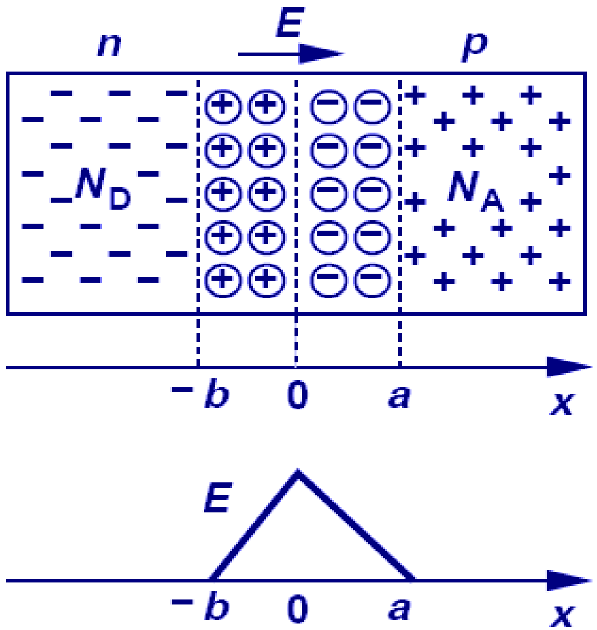
Depletion Region

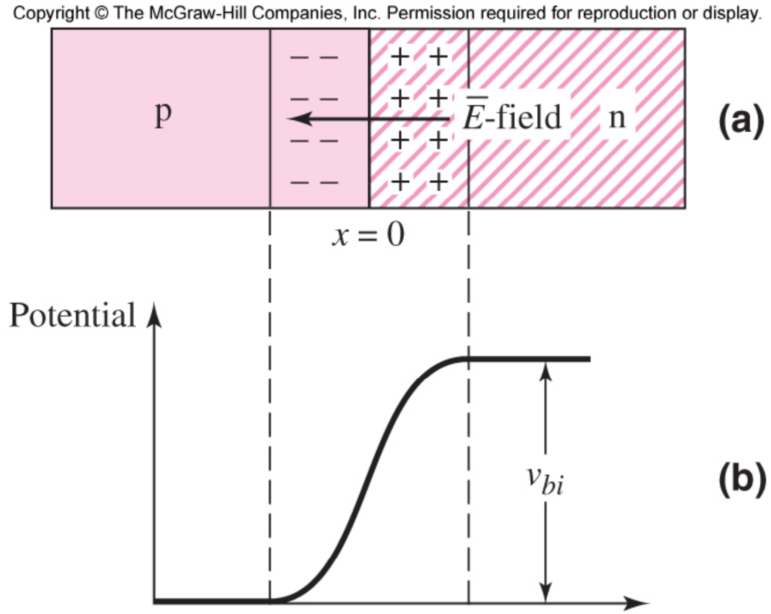
- As free electrons and holes diffuse across the junction, a region of fixed ions is left behind. This region is known as the "***depletion*** region." 空乏區
- The junction is suddenly formed at $t = 0$, and the diffusion currents continue to expose more ions as time progresses. Consequently, the immediate vicinity of the junction is depleted of free carriers and hence called the "depletion region."
- What stops the diffusion currents?



Current Flow Across Junction: Drift

- The fixed ions in depletion region create an electric field that results in a drift current.
- The field tends to force positive charge flow from left to right whereas the concentration gradients necessitate the flow of holes from right to left.
- The junction reaches ***equilibrium*** once the electric field is strong enough to completely stop the diffusion currents.



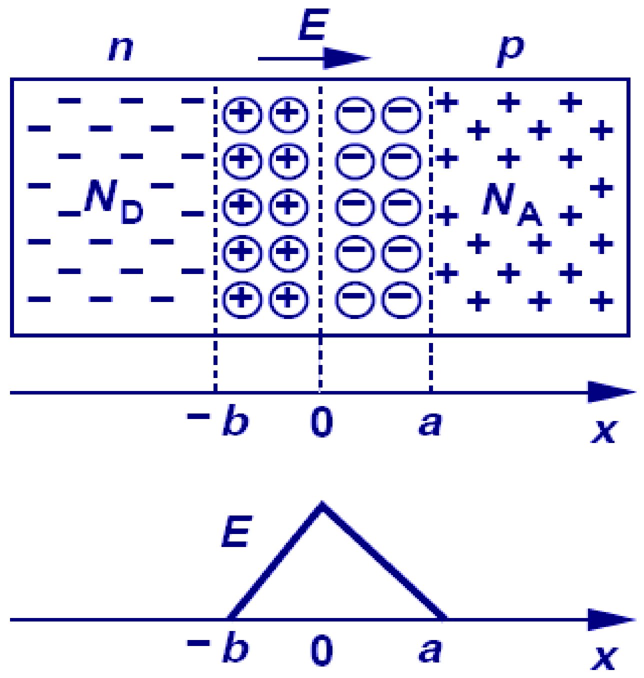


Example 2.12

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.

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 $E = 0$.



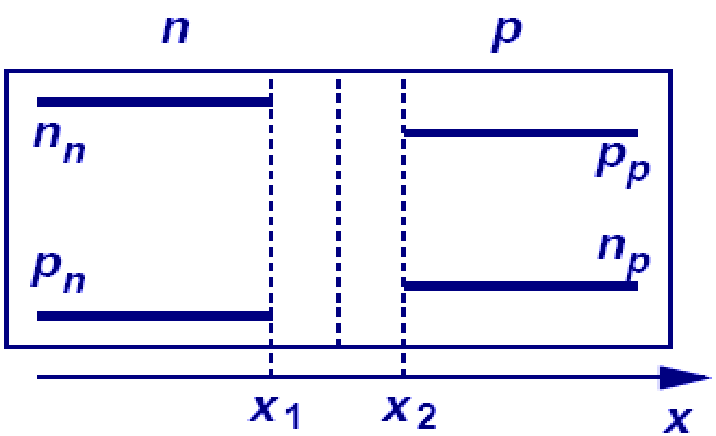
Current Flow Across Junction: Equilibrium

- 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.

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

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

- The figure shows the charge profile of the PN junction.



$$n_n = N_D \text{ and } p_p = N_A$$

where p_n and p_p are the hole concentrations at x_1 and x_2, respectively.

Built-in Potential

- Because of the electric field across the junction, $E = -dV/dx$, there exists a ***built-in potential***, V_0. Its derivation is shown above. 內建障壁電壓

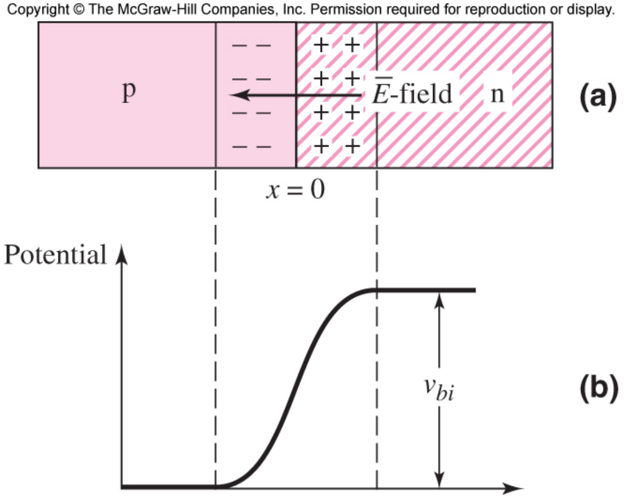
$$q\mu_p pE = -qD_p \frac{dp}{dx} \quad \Rightarrow \quad -\mu_p p \frac{dV}{dx} = -D_p \frac{dp}{dx}$$

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

- Replace D_p/μ_p with kT/q. And $p_p = N_A$, $p_n = n_i^2/N_D$

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

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.



Example 2.13 & 2.14

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

Solution

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

$$V_0 \approx (26\text{mV}) \ln \frac{(2\times10^{16})\times(4\times10^{16})}{(1.08\times10^{10})^2} \approx 768\text{mV}.$$

The built-in potential equation reveals that V_0 is a weak function of the doping levels. How much does V_0 change if N_A or N_D is increased by one order of magnitude?

Solution

We can write

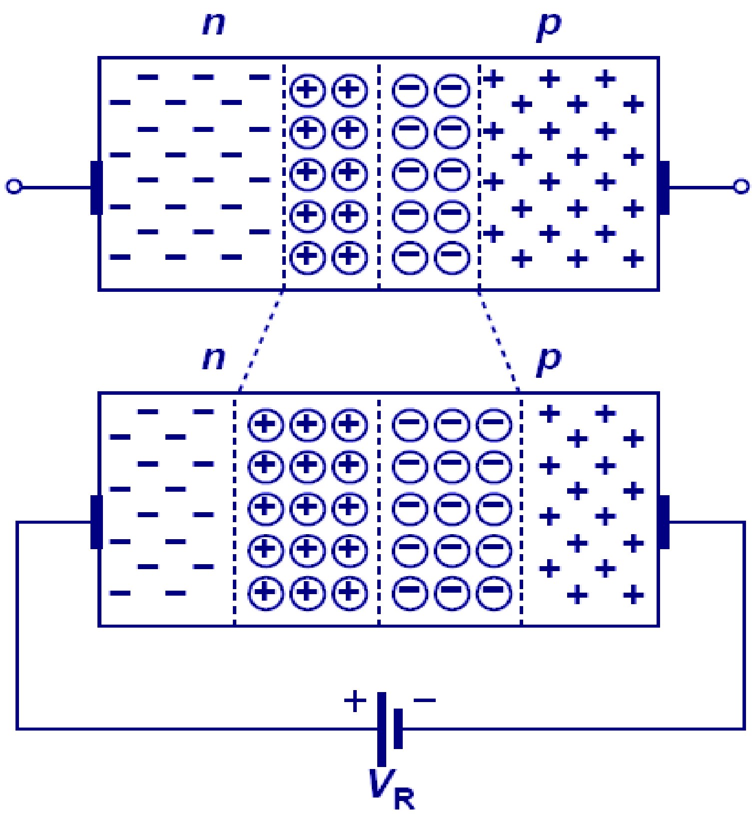
$$\Delta V_0 = V_T \ln \frac{10 N_A \cdot N_D}{n_i^2} - V_T \ln \frac{N_A \cdot N_D}{n_i^2} = V_T \ln 10 \approx 60\text{mV} (\text{at } T = 300\text{K}).$$

摻雜濃度增加10倍，V_0只增加60mV，不到1/10

Diode in Reverse Bias

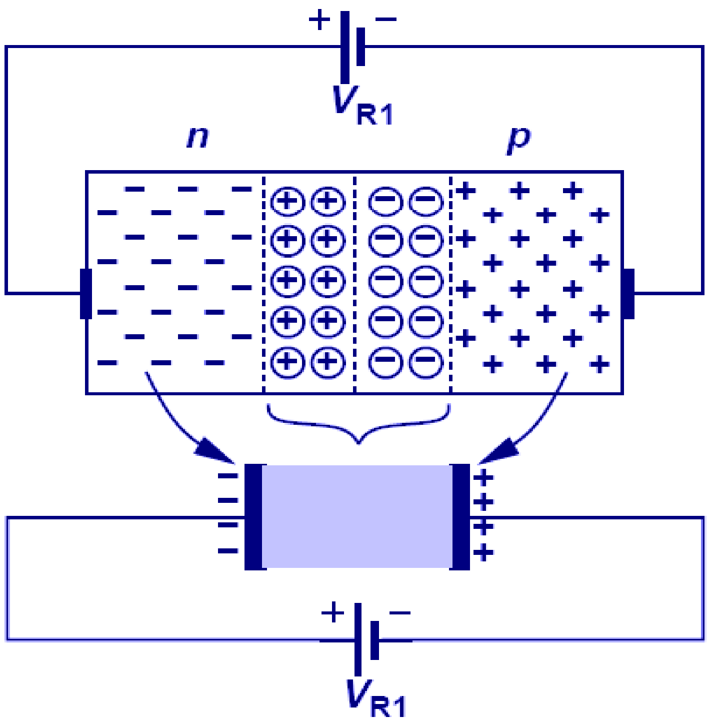
- When the N-type region of a diode is connected to a higher potential than the P-type region, the diode is under ***reverse bias***, which results in wider depletion region and larger built-in electric field across the junction.

反向偏壓



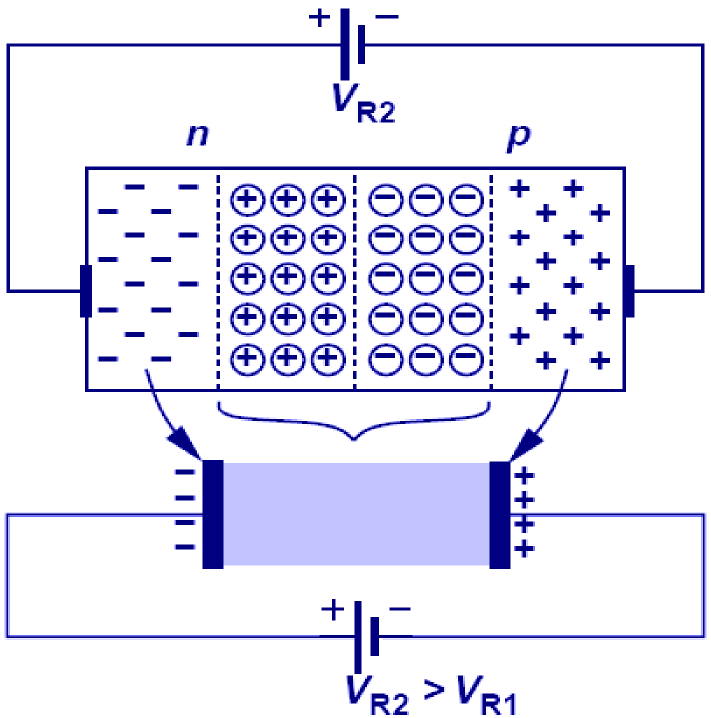
Reverse Biased Diode's Application: Voltage-Dependent Capacitor

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



(a)

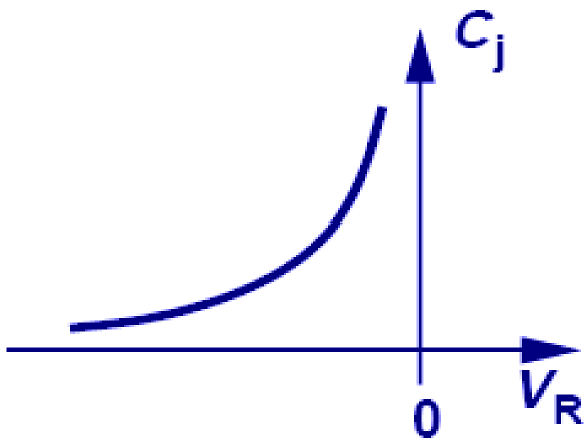
$$C = \frac{A \cdot \varepsilon}{d}$$



(b)

Voltage-Dependent Capacitance

- The equations that describe the voltage-dependent capacitance are shown.
- It is also called ***varactor diodes***. 變容器
- C_j decreases as $|V_R|$ increases.



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

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

where ϵ_{si} represents the *dielectric constant* of silicon and is equal to $\epsilon_r \epsilon_0 = 11.7 \times 8.85 \times 10^{-14}$ F/cm

Example 2.15

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

Solution

We first obtain the built-in potential: $V_0 = V_T \ln \frac{N_A N_D}{n_i^2} = 0.73\text{V}.$

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

$$C_{j0} = \sqrt{\frac{\varepsilon_{si} q}{2} \frac{N_A N_D}{N_A + N_D} \cdot \frac{1}{V_0}} = 2.65 \times 10^{-8}\,\text{F/cm}^2.$$

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

$$C_{j0} = 0.265\text{fF}/\mu\text{m}^2,$$

where 1 fF (femtofarad) = 10^{-15} F.

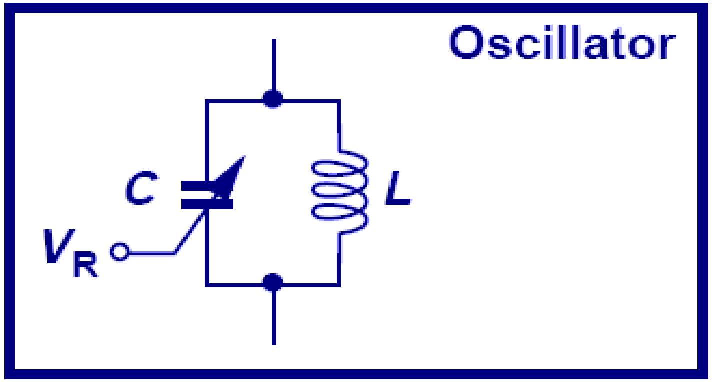
For $V_R = 1$V,

$$C_j = \frac{C_{j0}}{\sqrt{1 + \frac{V_R}{V_0}}} = 0.172\text{fF}/\mu\text{m}^2.$$

Voltage-Controlled Oscillator (VCO)

電壓控制振盪器

- 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.



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

Example 2.16

A cellphone incorporates a 2-GHz oscillator whose frequency is defined by the resonance frequency of an LC tank. 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.

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 $f_{res} = 1/(2\pi\sqrt{LC})$. At $V_R = 0$, $C_j = 0.265$ fF/μm^2, yielding a total device capacitance of $C_{j,tot}(V_R=0) = (0.265 \text{ fF}/\mu m^2) \times (2000\ \mu m^2) = 530$ fF.

Setting f_{res} to 2 GHz, we obtain $L = 11.9$ nH.

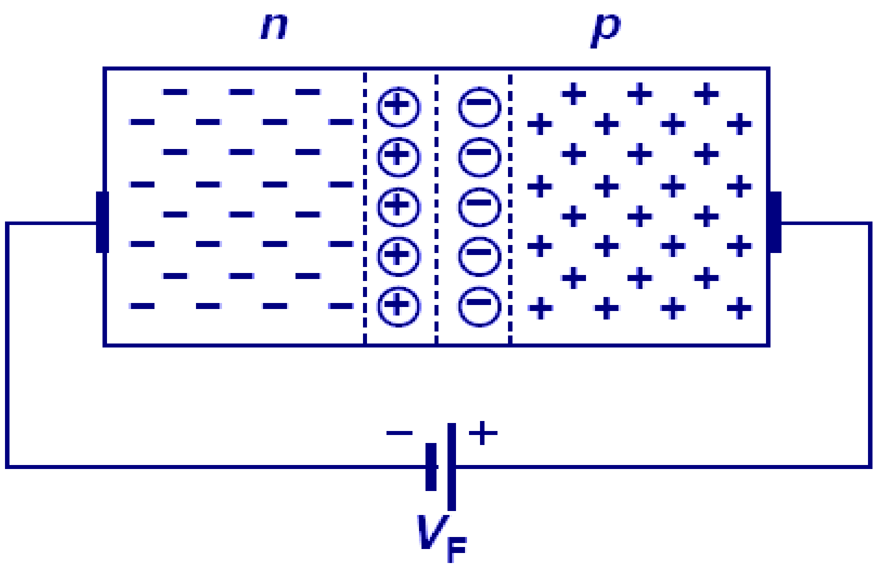
If V_R goes to 2V, $C_{j,tot}(V_R = 2\text{V}) = \dfrac{C_{j0}}{\sqrt{1+\dfrac{2}{0.73}}} \times 2000\mu\text{m}^2 = 274$ fF

Using this value along with $L = 11.9$ nH, we have $f_{res}(V_R=2) = 2.79$ GHz.

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

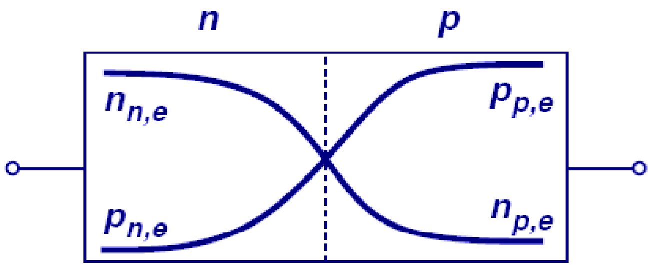
- When the N-type region of a diode is at a lower potential than the P-type region, the diode is in ***forward bias***. 順向偏壓
- The external voltage, V_F, tends to create a field directed from the *p* side toward the *n* side—opposite to the built-in field that was developed to stop the diffusion currents.
- The depletion width is shortened and the built-in electric field decreased.

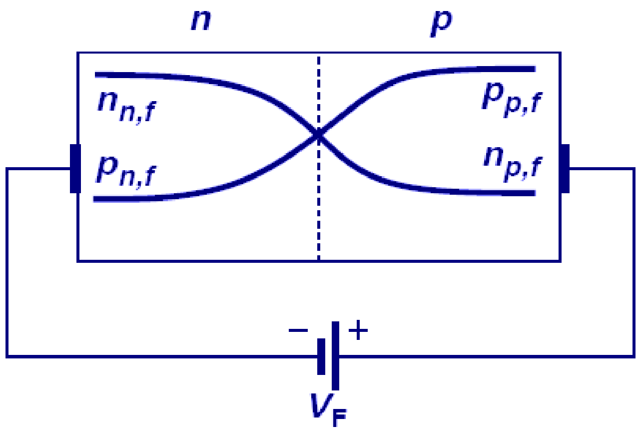


Minority Carrier Profile in Forward Bias

- 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.
- In equilibrium, $p_{n,e} = \dfrac{p_{p,e}}{\exp \dfrac{V_0}{V_T}}$ and in forward bias $p_{n,f} = \dfrac{p_{p,f}}{\exp \dfrac{V_0 - V_F}{V_T}}$

$$V_0 = \frac{kT}{q} \ln \frac{p_p}{p_n}$$





- We expect $p_{n,f}$ to be much higher than $p_{n,e}$ (it can be proved that $p_{p,f} \approx p_{p,e} \approx N_A$).
- In other words, the minority carrier concentration on the *p* side rises rapidly with the forward bias voltage while the majority carrier concentration remains relatively constant. This statement applies to the *n* side as well.

Diffusion Current in Forward Bias

- As the junction goes from equilibrium to forward bias, n_p and p_n increase dramatically, leading to a proportional change in the diffusion currents.
- We can express the change in the hole concentration on the n side as:

$$\Delta p_n = p_{n,f} - p_{n,e} = \frac{p_{p,f}}{\exp\frac{V_0 - V_F}{V_T}} - \frac{p_{p,e}}{\exp\frac{V_0}{V_T}} \approx \frac{N_A}{\exp\frac{V_0}{V_T}}(\exp\frac{V_F}{V_T} - 1).$$

- Similarly, for the electron concentration on the p side:

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

- The total increased diffusion current is proportional to:

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

IV Characteristic of Diode

- The current characteristic of diode can be proved that

$$I_{tot} = I_s(\exp\frac{V_F}{V_T} - 1) = I_s(e^{\frac{V_F}{V_T}} - 1)$$

反向飽和電流

where $$I_s = Aqn_i^2(\frac{D_n}{N_A L_n} + \frac{D_p}{N_D L_p})$$ is called the "***reverse saturation current***"

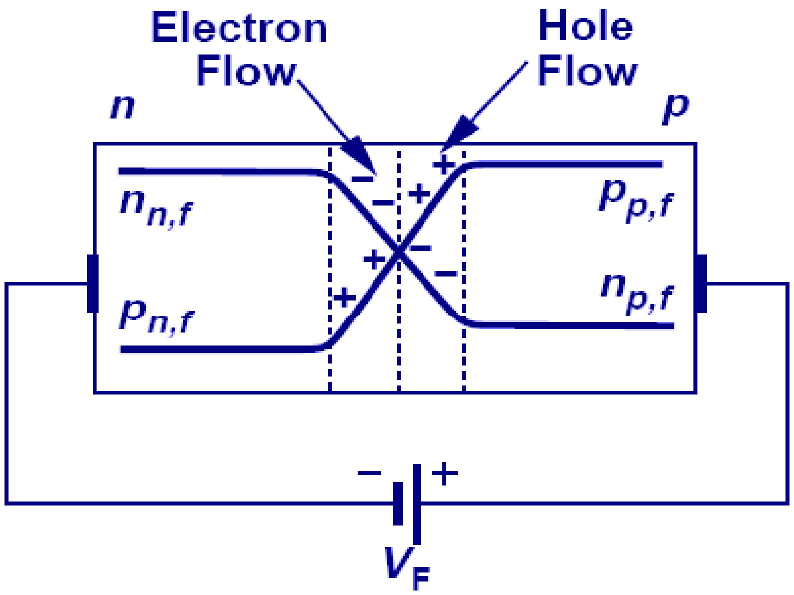
and *A* is the cross section area of the device; L_n and L_p are electron and hole "diffusion lengths," respectively, typically in the range of tens of micrometers.

Example 2.17: Determine I_S for the junction of Example 2.13 at T = 300K if A = 100μm², L_n = 20 μ m, and L_p = 30 μ m.

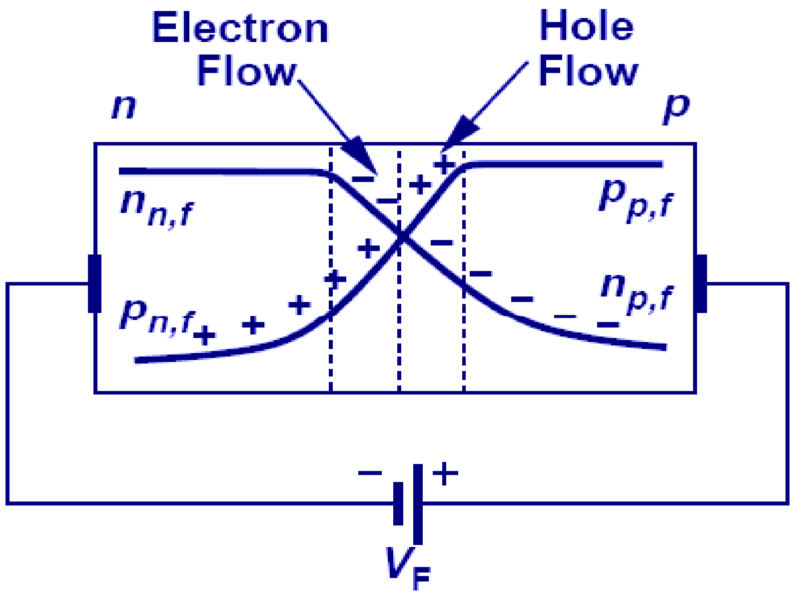
Solution: Using $q = 1.6 \times 10^{-19}$ C, $n_i = 1.08 \times 10^{10}$ electrons/cm³, D_n = 34 cm²/s, and D_p = 12 cm²/s, we have $I_S = 1.77 \times 10^{-17}$ A.

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



(a)

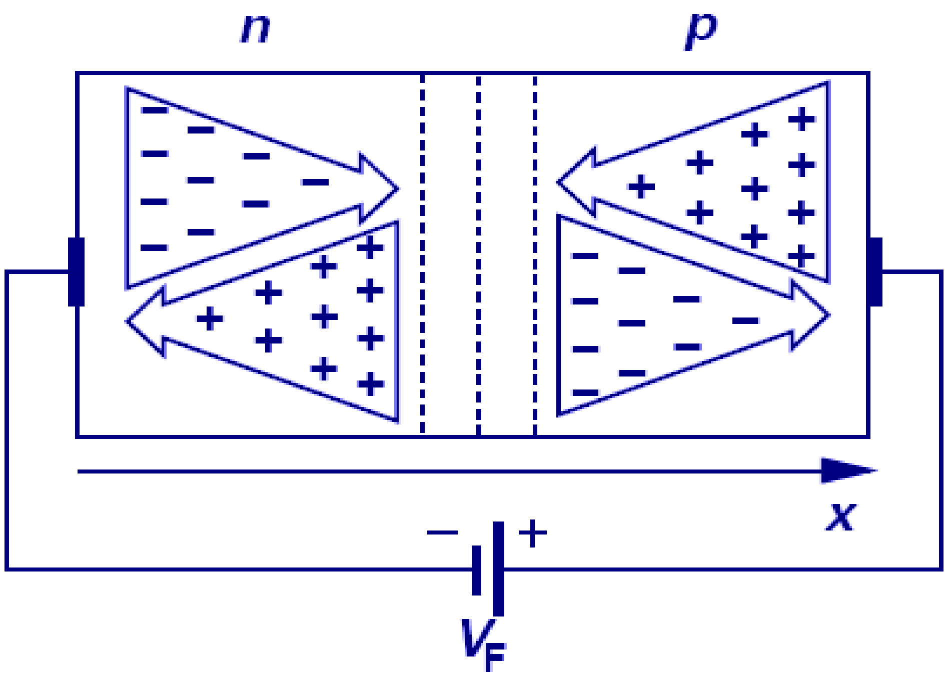


(b)

- Minority charge profile should not be constant along the *x*-axis, as Fig. (a) shows; 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, as shown in Fig. (b).

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

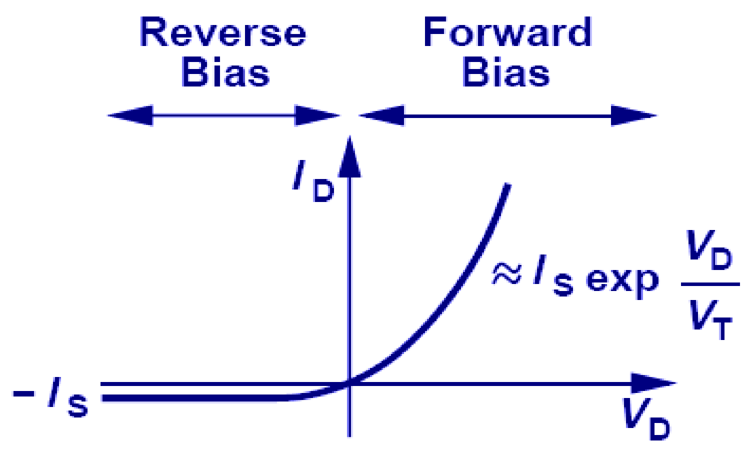
- The current and voltage relationship of a PN junction is exponential in forward bias region, and relatively constant in reverse bias region.

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

where I_D and V_D denote the diode current and voltage, respectively.

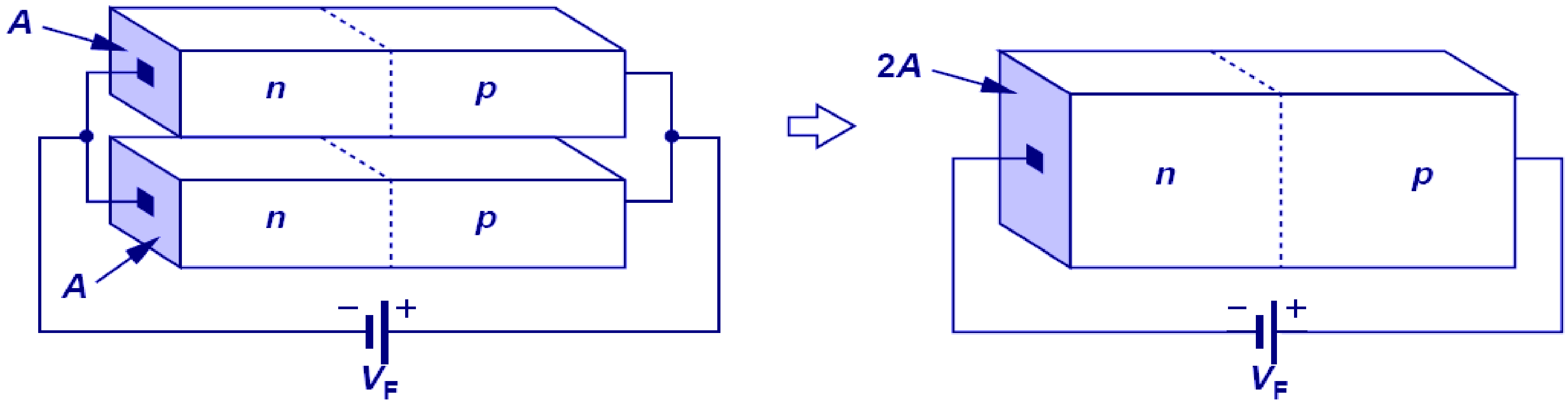
- As expected, $V_D = 0$ yields $I_D = 0$.
- As V_D becomes positive and exceeds several V_T, the exponential term grows rapidly and $I_D = I_S \exp(V_D/V_T)$. We hereafter assume in the forward bias region.
- If $V_D < 0$ and $|V_D|$ reaches several V_T, then $I_D \approx I_S$
- I_S is called the “reverse saturation current,” typically small, and can be regarded as “***leakage***” current

漏電流



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: 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.

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

$$I_{D,tot}(V_D = 300\text{mV}) = 2I_S(\exp\frac{V_D}{V_T} - 1) = 3.63\text{pA}.$$

Similarly, for V_D = 800 mV: $I_{D,tot}(V_D = 800\text{mV}) = 816\ \mu\text{A}$

Example 2.19

A diode operates in the forward bias region with a typical current level [i.e., $I_D \approx I_S \exp(V_D/V_T)$]. Suppose we wish to increase the current by a factor of 10. How much change in V_D is required?

Solution:

Let us first express the diode voltage as a function of its current:

$$V_D = V_T \ln \frac{I_D}{I_S}.$$

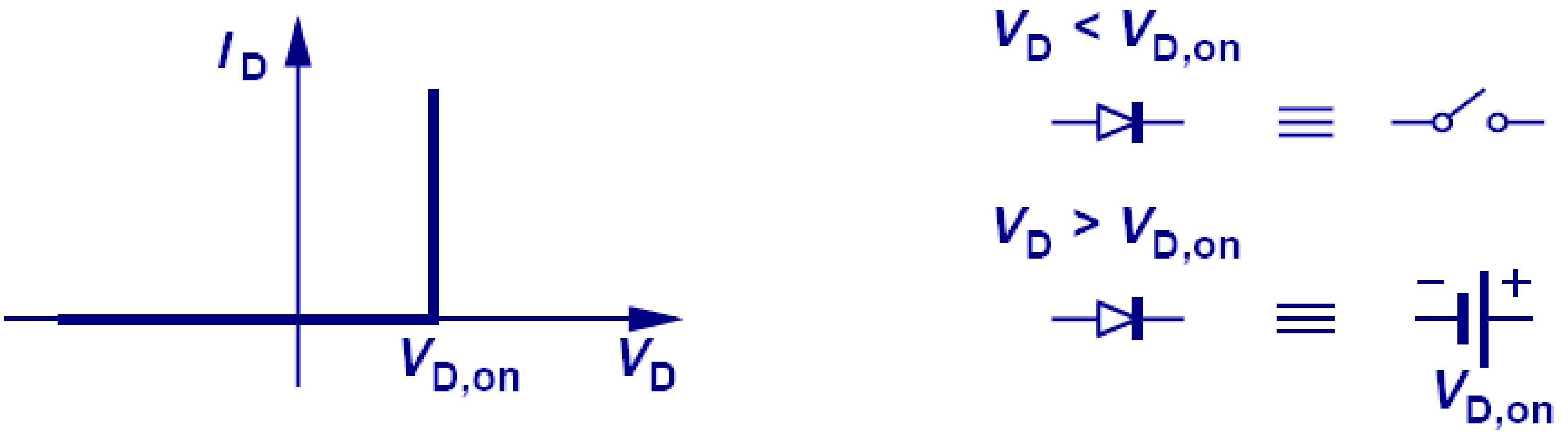
We define $I_1 = 10I_D$ and seek the corresponding voltage, V_{D1}:

$$V_{D1} = V_T \ln \frac{10 I_D}{I_S} = V_T \ln \frac{I_D}{I_S} + V_T \ln 10 = V_D + V_T \ln 10.$$

Thus, the diode voltage must rise by $V_T \ln 10 \approx 60$ mV (at 300 K) to accommodate a tenfold increase in the current. We say the device exhibits a 60-mV/decade characteristic, meaning V_D changes by 60 mV for a decade (tenfold) change in I_D. More generally, an n-fold change in I_D translates to a change of $V_T \ln n$ in V_D.

Constant-Voltage Diode Model

- With typical current levels and areas, V_D falls in the range of 700 - 800 mV.
- We often approximate the forward bias voltage by a *constant* value of 800 mV, $V_{D,on}$, (like an ideal battery), considering the device fully off if V_D < 800 mV.
- 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 $V_{D,on}$.



(a) (b)

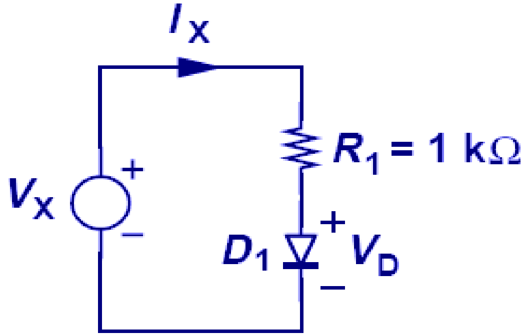
Example 2.21

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

Solution:

(a) Noting that $I_D = I_X$, we have $V_X = I_X R_1 + V_D$, and $V_D = V_T \ln(I_X/I_S)$

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 $V_D = 750$ mV and hence



$$I_X = \frac{V_X - V_D}{R_1} = \frac{3\text{V} - 0.75\text{V}}{1\text{k}\Omega} = 2.25\text{mA}.$$

Thus,

$$V_D = V_T \ln \frac{I_X}{I_S} = 799\text{mV}.$$

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

$$I_X = \frac{3\text{V} - 0.799\text{V}}{1\text{k}\Omega} = 2.201\text{mA}.$$

Example 2.21 (cnt'd)

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

$$I_X = \frac{1\text{V} - 0.75\text{V}}{1\text{k}\Omega} = 0.25\text{mA},$$

which yields $V_D = 0.742$ V and hence $I_X = 0.258$ mA.

(b) A constant-voltage model readily gives

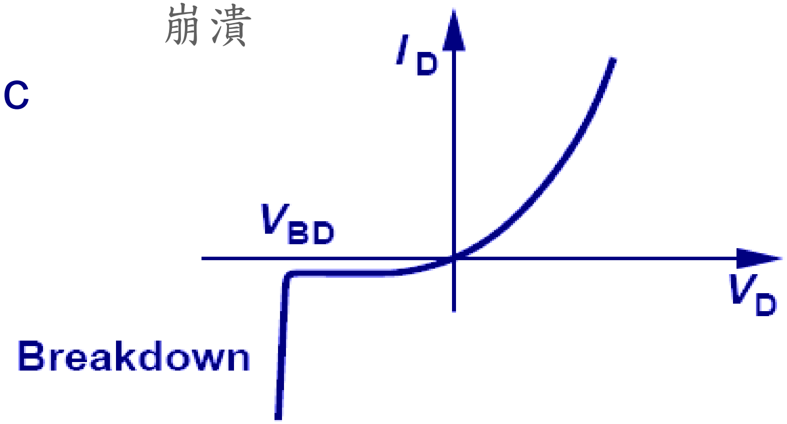
$I_X = 2.2$ mA for $V_X = 3$V

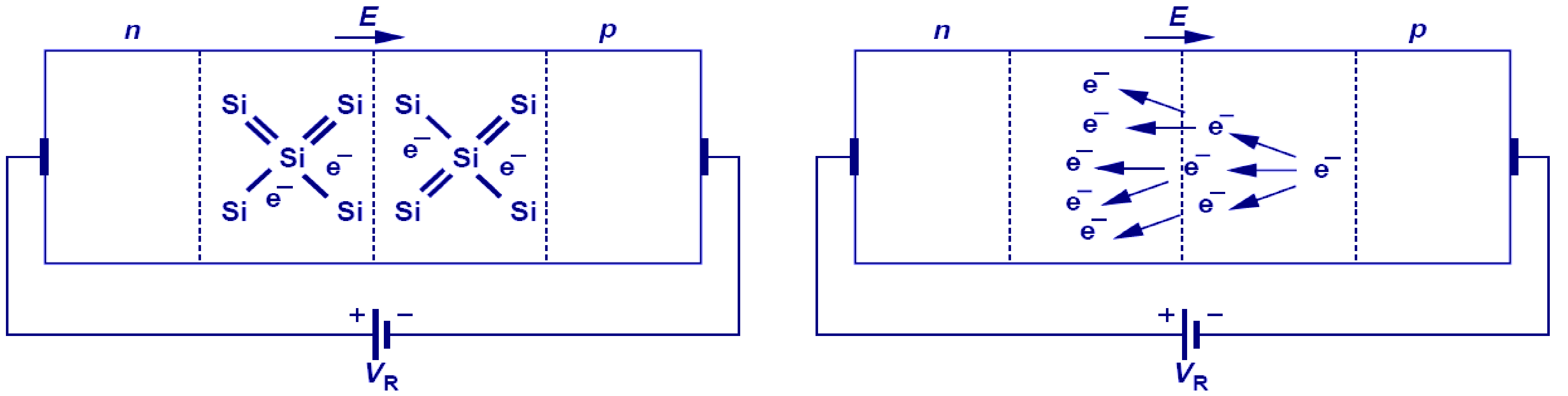
$I_X = 0.2$ mA for $V_X = 1$V

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*** 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.





(a) (b)

Temperature Effect

- For a given current, V_D decreases as T increases.
  - I_S and V_T are function of temperature
  - For *Si* diodes, V_D increases approximately 2 mV/^{o}C.
  - I_S is a function of n_i, which in turn is dependent on T.
  - Theoretically, I_S doubles for every 5 ^{o}C increase in temperature.
  - Realistically, doubles for 10 ^{o}C rise, including the V_T influence

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display.