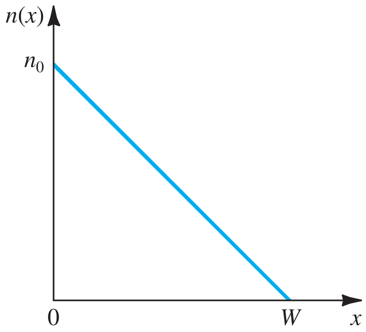

Figure E3.5

Ans. 56 $\mu A/\mu m^2$; 18 μm^2

3.3.3 Relationship between *D* and μ

A simple but powerful relationship ties the diffusion constant with the mobility,

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T \tag{3.21}$$

where $V_T = kT/q$. The parameter V_T is known as the **thermal voltage**. At room temperature, $T \simeq 300$ K and $V_T = 25.9$ mV. We will encounter V_T repeatedly throughout this book. The relationship in Eq. (3.21) is known as the **Einstein relationship**.

EXERCISE

3.6 Use the Einstein relationship to find D_n and D_p for intrinsic silicon using $\mu_n = 1350\ \text{cm}^2/\text{V}\cdot\text{s}$ and $\mu_p = 480\ \text{cm}^2/\text{V}\cdot\text{s}$.

Ans. 35 cm^2/s; 12.4 cm^2/s

3.4 The *pn* Junction

Having learned important semiconductor concepts, we are now ready to consider our first practical semiconductor structure—the *pn* junction. As mentioned previously, the *pn* junction implements the diode (Chapter 4) and plays the dominant role in the structure and operation of the bipolar junction transistor (BJT, Chapter 6). As well, understanding *pn* junctions is very important to the study of the MOSFET operation (Chapter 5).

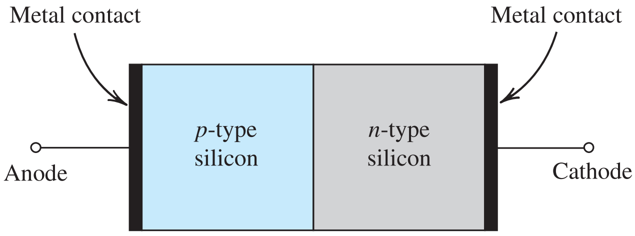

Figure 3.8 Simplified physical structure of the *pn* junction. (Actual geometries are given in Appendix A.) As the *pn* junction implements the junction diode, its terminals are labeled anode and cathode.

3.4.1 Physical Structure

Figure 3.8 shows a simplified physical structure of the *pn* junction. It consists of a *p*-type semiconductor (e.g., silicon) brought into close contact with an *n*-type semiconductor material (also silicon). In actual practice, both the *p* and *n* regions are part of the same silicon crystal; that is, the *pn* junction is formed within a single silicon crystal by creating regions of different dopings (*p* and *n* regions). Appendix A provides a description of the fabrication process of integrated circuits including *pn* junctions. As indicated in Fig. 3.8, external wire connections are made to the *p* and *n* regions through metal (aluminum) contacts. If the *pn* junction is used as a diode, these constitute the diode terminals and are therefore labeled "anode" and "cathode" in keeping with diode terminology.[3]

3.4.2 Operation with Open-Circuit Terminals

Figure 3.9 shows a *pn* junction under open-circuit conditions—that is, the external terminals are left open. The "+" signs in the *p*-type material denote the majority holes. The charge of these holes is neutralized by an equal amount of bound negative charge associated with the acceptor atoms. For simplicity, these bound charges are not shown in the diagram. Also not shown are the minority electrons generated in the *p*-type material by thermal ionization.

In the *n*-type material the majority electrons are indicated by "–" signs. Here also, the bound positive charge, which neutralizes the charge of the majority electrons, is not shown in order to keep the diagram simple. The *n*-type material also contains minority holes generated by thermal ionization but not shown in the diagram.

The Diffusion Current I_D Because the concentration of holes is high in the *p* region and low in the *n* region, holes diffuse across the junction from the *p* side to the *n* side. Similarly, electrons diffuse across the junction from the *n* side to the *p* side. These two current components add together to form the diffusion current I_D, whose direction is from the *p* side to the *n* side, as indicated in Fig. 3.9.

The Depletion Region The holes that diffuse across the junction into the *n* region quickly recombine with some of the majority electrons present there and thus disappear from the scene. This recombination process results also in the disappearance of some free electrons from the

[3]This terminology in fact is a carryover from that used with vacuum-tube technology, which was the technology for making diodes and other electronic devices until the invention of the transistor in 1947. This event ushered in the era of solid-state electronics, which changed not only electronics, communications, and computers but indeed the world!

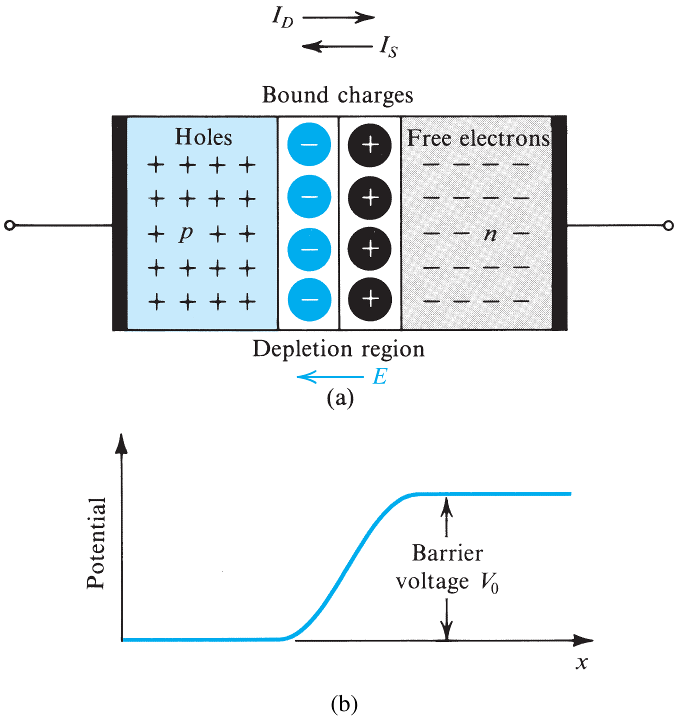

Figure 3.9 **(a)** The *pn* junction with no applied voltage (open-circuited terminals). **(b)** The potential distribution along an axis perpendicular to the junction.

n-type material. Thus some of the bound positive charge will no longer be neutralized by free electrons, and this charge is said to have been **uncovered**. Since recombination takes place close to the junction, there will be a region close to the junction that is *depleted of free electrons* and contains uncovered bound positive charge, as indicated in Fig. 3.9.

The electrons that diffuse across the junction into the *p* region quickly recombine with some of the majority holes there, and thus disappear from the scene. This results also in the disappearance of some majority holes, causing some of the bound negative charge to be uncovered (i.e., no longer neutralized by holes). Thus, in the *p* material close to the junction, there will be a region *depleted of holes* and containing uncovered bound negative charge, as indicated in Fig. 3.9.

From the above it follows that a **carrier-depletion region** will exist on both sides of the junction, with the *n* side of this region positively charged and the *p* side negatively charged. This carrier-depletion region—or, simply, **depletion region—**is also called the **space-charge region**. The charges on both sides of the depletion region cause an electric field E to be established across the region in the direction indicated in Fig. 3.9. Hence a potential difference results across the depletion region, with the *n* side at a positive voltage relative to the *p* side, as shown in Fig. 3.9(b). Thus the resulting electric field opposes the diffusion of holes into the *n* region and electrons into the *p* region. In fact, the voltage drop across the depletion region acts as a **barrier** that has to be overcome for holes to diffuse into the *n* region and electrons to diffuse into the *p* region. The larger the barrier voltage, the smaller the number of carriers that will be able to overcome the barrier, and hence the lower the magnitude of diffusion current. Thus it is the appearance of the barrier voltage V_0 that limits the carrier diffusion process. It follows that the diffusion current I_D depends strongly on the voltage drop V_0 across the depletion region.

EXERCISES

3.7 Show that

$$V_0 = \frac{1}{2}\left(\frac{q}{\epsilon_s}\right)\left(\frac{N_A N_D}{N_A + N_D}\right)W^2$$

3.8 Show that for a *pn* junction in which the *p* side is much more heavily doped than the *n* side (i.e., $N_A \gg N_D$), referred to as a p^+n diode, Eqs. (3.26), (3.27), (3.28), (3.29), and (3.30) can be simplified as follows:

$$W \simeq \sqrt{\frac{2\epsilon_s}{qN_D}V_0} \quad (3.26')$$

$$x_n \simeq W \quad (3.27')$$

$$x_p \simeq W/(N_A/N_D) \quad (3.28')$$

$$Q_J \simeq AqN_D W \quad (3.29')$$

$$Q_J \simeq A\sqrt{2\epsilon_s qN_D V_0} \quad (3.30')$$

3.9 If in the fabrication of the *pn* junction in Example 3.5, it is required to increase the minority-carrier concentration in the *n* region by a factor of 2, what must be done?
Ans. Lower N_D by a factor of 2.

3.5 The *pn* Junction with an Applied Voltage

Having studied the open-circuited *pn* junction in detail, we are now ready to apply a dc voltage between its two terminals to find its electrical conduction properties. If the voltage is applied so that the *p* side is made more positive than the *n* side, it is referred to as a forward-bias[6] voltage. Conversely, if our applied dc voltage is such that it makes the *n* side more positive than the *p* side, it is said to be a reverse-bias voltage. As will be seen, the *pn* junction exhibits vastly different conduction properties in its forward and reverse directions.

Our plan is as follows. We begin by a simple qualitative description in Section 3.5.1 and then consider an analytical description of the *i–v* characteristic of the junction in Section 3.5.2.

3.5.1 Qualitative Description of Junction Operation

Figure 3.11 shows the *pn* junction under three different conditions: (a) the open-circuit or equilibrium condition studied in the previous section; (b) the reverse-bias condition, where a dc voltage V_R is applied; and (c) the forward-bias condition, where a dc voltage V_F is applied.

[6]For the time being, we take the term *bias* to refer simply to the application of a dc voltage. We will see in later chapters that it has a deeper meaning in the design of electronic circuits.

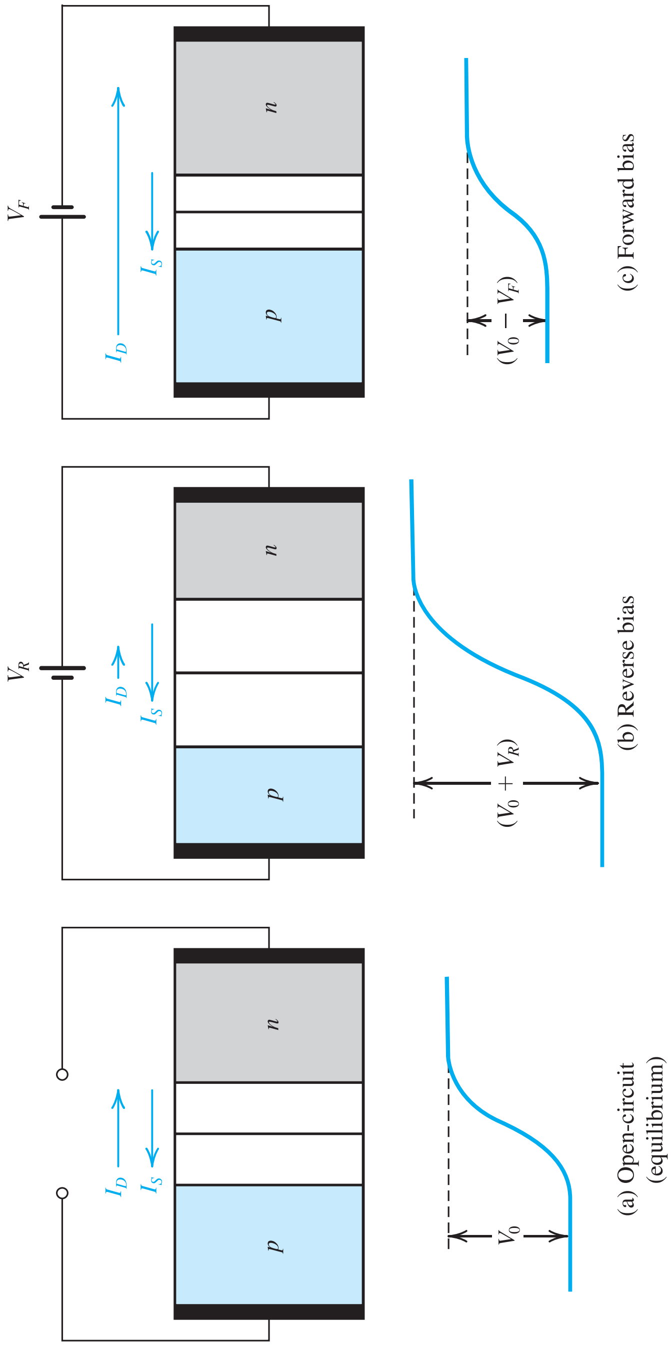

Figure 3.11 The *pn* junction in: **(a)** equilibrium; **(b)** reverse bias; **(c)** forward bias.

Observe that in the open-circuit case, a barrier voltage V_0 develops, making n more positive than p, and limiting the diffusion current I_D to a value exactly equal to the drift current I_S, thus resulting in a zero current at the junction terminals, as should be the case, since the terminals are open-circuited. Also, as mentioned previously, the barrier voltage V_0, though it establishes the current equilibrium across the junction, does *not* in fact appear between the junction terminals.

Consider now the reverse-bias case in (b). The externally applied reverse-bias voltage V_R is in the direction to add to the barrier voltage, and it does, thus increasing the effective barrier voltage to $(V_0 + V_R)$ as shown. This reduces the number of holes that diffuse into the n region and the number of electrons that diffuse into the p region. The end result is that the diffusion current I_D is dramatically reduced. As will be seen shortly, a reverse-bias voltage of a volt or so is sufficient to cause $I_D \simeq 0$, and the current across the junction and through the external circuit will be equal to I_S. Recalling that I_S is the current due to the drift across the depletion region of the thermally generated minority carriers, we expect I_S to be very small and to be strongly dependent on temperature. We will show this to be the case very shortly. We thus conclude that in the reverse direction, the *pn* junction conducts a very small and almost-constant current equal to I_S.

Before leaving the reverse-bias case, observe that the increase in barrier voltage will be accompanied by a corresponding increase in the stored uncovered charge on both sides of the depletion region. This in turn means a wider depletion region, needed to uncover the additional charge required to support the larger barrier voltage $(V_0 + V_R)$. Analytically, these results can be obtained easily by a simple extension of the results of the equilibrium case. Thus the width of the depletion region can be obtained by replacing V_0 in Eq. (3.26) by $(V_0 + V_R)$,

$$W = x_n + x_p = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 + V_R)} \tag{3.31}$$

and the magnitude of the charge stored on either side of the depletion region can be determined by replacing V_0 in Eq. (3.30) by $(V_0 + V_R)$,

$$Q_J = A\sqrt{2\epsilon_s q\left(\frac{N_A N_D}{N_A + N_D}\right)(V_0 + V_R)} \tag{3.32}$$

We next consider the forward-bias case shown in Fig. 3.11(c). Here the applied voltage V_F is in the direction that subtracts from the built-in voltage V_0, resulting in a reduced barrier voltage $(V_0 - V_F)$ across the depletion region. This reduced barrier voltage will be accompanied by reduced depletion-region charge and correspondingly narrower depletion-region width W. Most importantly, the lowering of the barrier voltage will enable more holes to diffuse from p to n and more electrons to diffuse from n to p. Thus the diffusion current I_D increases substantially and, as will be seen shortly, can become many orders of magnitude larger than the drift current I_S. The current I in the external circuit is of course the difference between I_D and I_S,

$$I = I_D - I_S$$

and it flows in the forward direction of the junction, from p to n. We thus conclude that the *pn* junction can conduct a substantial current in the forward-bias region and that current is mostly a diffusion current whose value is determined by the forward-bias voltage V_F.