

From "Electronics," 2nd Edition, by Allan R. Hambley, Prentice Hall, 2000.

### EXERCISE

**3.16** At a temperature of 300 K, a certain junction diode has  $i_D = 0.1$  mA for  $v_D = 0.6$  V. Assume that  $n$  is unity and use  $V_T = 0.026$  V. Find the value of the saturation current  $I_s$ . Then compute the diode current at  $v_D = 0.65$  V and at 0.70 V. [Hint: Because  $v_D > 0.1$  V, we have  $i_D \cong I_s \exp(v_D/nV_T)$ .]

**Answer**  $I_s = 9.50 \times 10^{-15}$  A,  $i_D = 0.684$  mA,  $i_D = 4.68$  mA.

### EXERCISE

**3.17** Consider a diode under forward bias, so that  $i_D \cong I_s \exp(v_D/nV_T)$ . Assume that  $V_T = 0.026$  V and  $n = 1$ . (a) By what increment must  $v_D$  increase to double the current? (b) To increase the current by a factor of 10?

**Answer** (a)  $\Delta v_D = 18$  mV; (b)  $\Delta v_D = 59.9$  mV.

## 3.9 BASIC SEMICONDUCTOR CONCEPTS

In this section and the next, we discuss basic semiconductor physics and internal operation of diodes. Our discussion of device physics is brief and mostly of a qualitative nature. It is intended to give you a framework for understanding diode and transistor behavior—particularly high-frequency and switching characteristics.

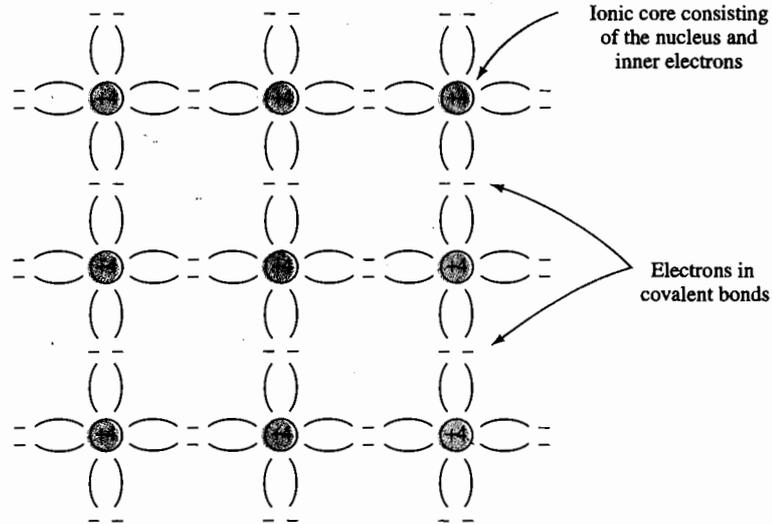
Several materials are useful for the fabrication of solid-state electronic devices—most notably, silicon (Si), germanium (Ge), and gallium arsenide (GaAs). Because of the widespread use of silicon, we reference most of our discussion to it. At least on a qualitative basis, the physics of other semiconductors is similar to that of silicon.

### Intrinsic Silicon

The Bohr model of an isolated silicon atom consists of a nucleus containing 14 protons and most of the mass of the atom. A total of 14 electrons surround the nucleus in specific orbits. The electron orbits occur in groups known as **shells**. The innermost (lowest energy) shell consists of two orbits. The next highest energy shell contains eight orbits. Each orbit can contain at most a single electron. Thus, for a silicon atom in its lowest energy state, the innermost shell contains two electrons, the next higher shell contains eight electrons, and the remaining four electrons occupy orbits in the outermost shell, also called the **valence shell**. It is these outermost valence electrons that provide the moving charge carriers in the solid form of the material.

In an **intrinsic** (i.e., pure) silicon crystal, each atom takes up a lattice position having four nearest neighboring atoms. Each pair of neighboring atoms forms a **covalent bond** consisting of two electrons that orbit around the pair. Each atom contributes one electron to each of the four bonds with its neighbors. This is illustrated by the simple planar

A qualitative knowledge of semiconductor physics helps us to understand diode and transistor behavior, especially in high-speed digital logic circuits.

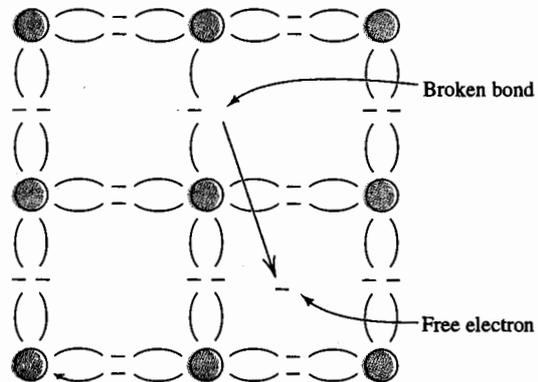


**Figure 3.36** Intrinsic silicon crystal.

diagram shown in Figure 3.36. (In the actual crystal, the arrangement of the atoms is three dimensional—each atom is at the center of a tetrahedron with a neighbor located at each corner.)

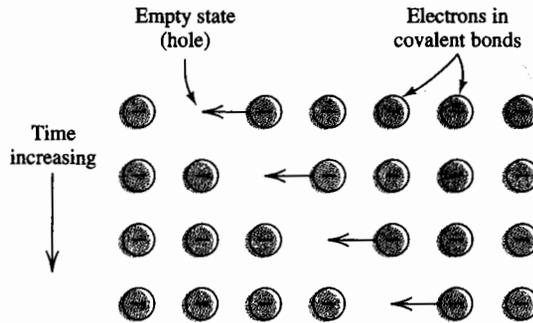
At absolute zero temperature, electrons take the lowest energy states available. Thus, all of the valence electrons are bound in covalent bonds and are not free to move through the crystal. In this condition, silicon is an electrical insulator. However, at “room temperature” (approximately 300 K), a small fraction of the electrons gain sufficient thermal energy to break loose from their bonds. These **free electrons** can easily move through the crystal. This situation is illustrated in Figure 3.37.

If voltage is applied to intrinsic silicon, current flows. However, the number of free electrons is relatively small compared with that found in a good conductor. Thus, intrinsic silicon is classed as a **semiconductor**. Silicon contains about  $5 \times 10^{22}$  atoms/cm<sup>3</sup>. At



**Figure 3.37**  
Thermal energy can break a bond, creating a vacancy and a free electron, both of which can move freely through the crystal.

**Figure 3.38**  
As electrons move to the left to fill a hole, the hole moves to the right.



room temperature, there are  $n_i \cong 1.45 \times 10^{10}$  free electrons per  $\text{cm}^3$ . Thus, only about one valence electron in  $1.4 \times 10^{13}$  has broken loose from its bond at room temperature.

## Conduction by Holes

Free electrons are not the only means by which current flows in intrinsic silicon. A broken bond can be filled by an electron from a nearby bond, as is illustrated in Figure 3.38. Even though it is the bound electrons that actually move, it is helpful to focus on the vacancy, or **hole**. We can think of a hole as a positive charge carrier that is free to move through the crystal, whereas bound electrons can move only if a vacancy exists nearby.

In an intrinsic semiconductor, an equal number of holes and free electrons are available to move easily through the crystal. We denote the free-electron concentration as  $n_i$  and the hole concentration as  $p_i$ . Thus, we can write

$$n_i = p_i \quad (3.24)$$

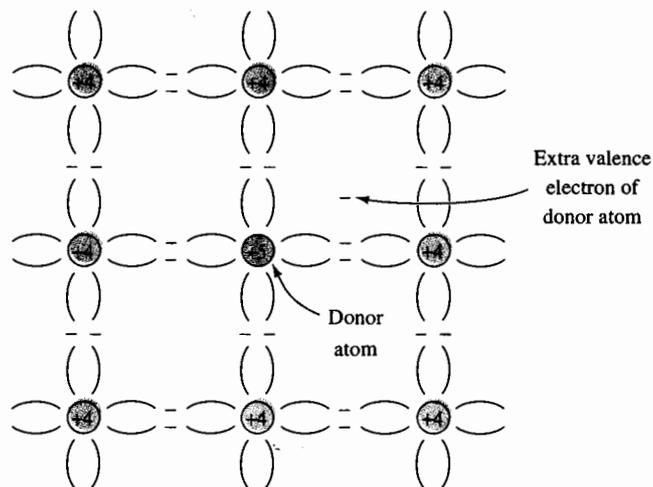
for a pure material. When an electric field is applied to the crystal, both types of carriers contribute to the flow of current.

## Generation and Recombination

Free electrons and holes are generated by thermal energy, which causes covalent bonds to break at a rate depending strongly on temperature. The higher the temperature, the higher the rate of **generation**. On the other hand, when a free electron encounters a hole, **recombination** can occur: The hole and free electron combine to form a filled covalent bond. As the concentration of holes and electrons builds up, recombination occurs more frequently. Thus, at a given temperature, an equilibrium exists at which the rate of recombination equals the rate of generation of charge carriers. As the temperature increases, this equilibrium pertains to ever larger concentrations of charge carriers.

A higher concentration of charge carriers results in an increased capability of the material to conduct electrical current. Thus, the conductivity of an intrinsic semiconductor increases with temperature.

We can think of a hole as a positive charge carrier that is free to move through the crystal...



**Figure 3.39**  
*n*-type silicon is created by adding valence five impurity atoms.

### *n*-Type Semiconductor Material

Adding small amounts of suitable impurities to the crystal dramatically affects the relative concentration of holes and electrons. Then we have an **extrinsic** semiconductor. For example, if we add phosphorus, which has five valence electrons, the phosphorus atoms take positions in the crystal lattice and form covalent bonds with their four neighbors. The fifth valence electron is only weakly bound to the phosphorus atom.

At normal operating temperatures, this extra electron breaks its bond with the impurity atom and becomes a free electron. However, a hole is not created by the impurity atom—the positive charge that balances the free electron is locked in the **ionic core** of the impurity atom. Thus, we can create free electrons by adding pentavalent impurities known as **donors** to silicon. The resulting material is called ***n*-type** material. The crystal lattice of *n*-type silicon is depicted in Figure 3.39.

In *n*-type material, conduction is due mainly to the numerous free electrons. Thus, free electrons are called **majority carriers**, whereas holes are called **minority carriers**.

At normal operating temperatures, nearly all of the donor atoms give up their fifth electron. We say that the donors have become **ionized**. Positive charge is associated with each ionized donor atom. Of course, the net charge concentration in the material is zero. The positive charge of the ionized donors (and holes) is balanced by the negative charge of free electrons. Thus, we can equate the concentration of free electrons to the sum of the hole and donor concentrations; that is,

$$n = p + N_D \quad (3.25)$$

where  $N_D$  represents the concentration of donor atoms.

### The Mass-Action Law

Not only is the free-electron concentration increased by the addition of donor atoms; the hole concentration is reduced, because the increased electron concentration makes hole recombination more likely. It turns out that the product of the hole concentration and

In *n*-type material, free electrons are called **majority carriers**, whereas holes are called **minority carriers**.

the free-electron concentration is constant (for a given temperature). This is known as the **mass-action law**,

$$pn = p_i n_i \quad (3.26)$$

where  $p_i$  is the hole concentration in intrinsic material and  $n_i$  is the electron concentration in intrinsic material. Because Equation (3.24) states that the hole and electron concentrations are equal in intrinsic material, we can write

$$pn = n_i^2 \quad (3.27)$$

Holes are continually generated by thermal energy. Each hole wanders through the material until it finally combines with a free electron. The **average lifetime** of the minority carriers is an important parameter in the switching behavior of diodes and other semiconductor devices. We denote the average lifetime of the holes in  $n$ -type material as  $\tau_p$ .

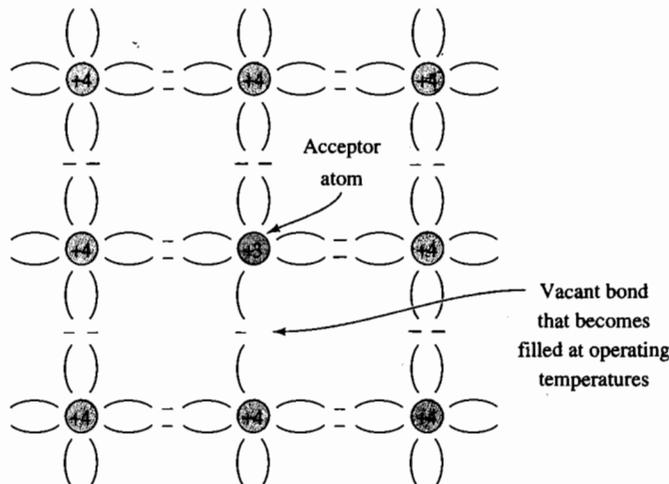
### ***p*-Type Semiconductor Material**

Adding a trivalent impurity such as boron to pure silicon produces ***p*-type material**. Each impurity atom occupies a position in the crystal lattice and forms covalent bonds with three of its nearest neighbors. The impurity atom does not have the fourth electron needed to complete the bond with its fourth neighbor. At usual operating temperatures, an electron from a nearby silicon atom moves in to fill the fourth bond of each impurity atom. This creates a hole moving freely through the crystal. However, the electron is bound to the ionized impurity atom. Thus, conduction in  $p$ -type material is due mainly to holes.

In  $p$ -type material, holes are called majority carriers and electrons are called minority carriers. Of course, this is the reverse of the terminology for  $n$ -type material.

Valence-three impurities are called **acceptors**, because they accept an extra electron. Negative charge is associated with each ionized acceptor atom—four bound electrons are present, but only enough positive charge is present in the ionic core to balance the charge of three electrons. The crystal lattice structure of  $p$ -type silicon is depicted in Figure 3.40.

In  $p$ -type material, holes are called majority carriers and electrons are called minority carriers.



**Figure 3.40**  
 $p$ -type silicon is created by adding valence three impurity atoms.

If we denote the concentration of acceptor atoms as  $N_A$ , we can write

$$N_A + n = p \quad (3.28)$$

because the net charge concentration in the material must be zero. The negative charge of the ionized acceptor atoms plus that of the free electrons equals the positive charge of the holes.

### Cycling the Type of the Material

In fabricating integrated circuits, it is necessary to add impurities in stages, as discussed in Section 1.3. For example, we may start with  $n$ -type material, part of which we wish to change to  $p$ -type. This is accomplished by adding acceptors. When the acceptor concentration exceeds the original donor concentration, the material becomes  $p$ -type. Later, more donors can be added to part of the  $p$  region to change it back to  $n$ -type. For materials with both types of impurities, we have

$$p + N_D = n + N_A \quad (3.29)$$

#### Example 3.6 Calculation of Hole and Free-Electron Concentrations

Often we state units such as atoms/cm<sup>3</sup> (or electrons/cm<sup>3</sup>) simply as cm<sup>-3</sup> because the number of atoms (or electrons) is a pure number without units.

Suppose that we have silicon with  $N_A = 10^{13}$  atoms/cm<sup>3</sup> and  $N_D = 2 \times 10^{13}$  atoms/cm<sup>3</sup>. The intrinsic electron concentration of silicon at room temperature (300 K) is  $1.45 \times 10^{10}$  cm<sup>-3</sup>. Find the approximate hole and electron concentration for this doped material.

**SOLUTION** Because the donor concentration is greater than the acceptor concentration, we have  $n$ -type material. Thus, we anticipate that  $n$  is greater than  $n_i$ , and that  $p$  is less than  $n_i$ . Rearranging Equation (3.29), we obtain

$$n = p + N_D - N_A$$

Substituting values into this equation, we have

$$n = p + 10^{13}$$

Since  $p < n_i = 1.45 \times 10^{10}$  cm<sup>-3</sup>, we conclude that

$$n \cong N_D - N_A = 10^{13} \text{ cm}^{-3}$$

Now we use the mass-action law given in Equation (3.27), to get

$$np = n_i^2$$

Solving for  $p$  and substituting, we find that

$$p = 2.1 \times 10^7 \text{ cm}^{-3}$$

Notice that the free-electron concentration is about six orders of magnitude greater than the hole concentration in this material.

□

## Drift

Charge carriers move about randomly in the crystal due to thermal agitation. Collisions with the lattice cause the charge carriers to change direction frequently. The direction of travel after a collision is random. Consequently, with no applied electric field, the average velocity of the charge carriers in any particular direction is zero.

If an electric field is applied, force is exerted on the free charge carriers. (For holes, the force is in the same direction as the electric field, whereas for electrons, the force is opposite to the field.) Between collisions, the charge carriers are accelerated in the direction of the force. When the carriers collide with the lattice, their direction of travel becomes random again. Thus, the charge carriers do not keep accelerating. The net result is a constant average velocity in the direction of the force.

The average motion of the charge carriers due to an applied electric field is called **drift**. The average drift velocity is proportional to the electric field vector  $\mathcal{E}$ . We denote the drift velocity vector of electrons as  $\mathbf{V}_n$  and the hole velocity vector as  $\mathbf{V}_p$ . Thus, we can write

$$\mathbf{V}_n = -\mu_n \mathcal{E} \quad (3.30)$$

in which the constant of proportionality  $\mu_n$  is called the **mobility** of the free electrons. Because of the minus sign, the direction of the drift velocity is opposite that of the electric field.

Similarly, for holes, we have

$$\mathbf{V}_p = \mu_p \mathcal{E} \quad (3.31)$$

For silicon at 300 K, the approximate electron mobility is  $\mu_n = 1500 \text{ cm}^2/(\text{Vs})$ , whereas for holes it is  $\mu_p = 475 \text{ cm}^2/(\text{Vs})$ . (These values are approximate—the exact values depend on the concentrations of impurities and defects in the crystal.)

For a given applied field, electrons move about three times faster than holes in silicon. Later, we will see that transistors can be fabricated such that the current is mainly carried either by holes or by electrons. For fast digital circuits and high-frequency analog circuits, devices in which conduction is due to electrons are preferable to devices in which conduction is due to holes.

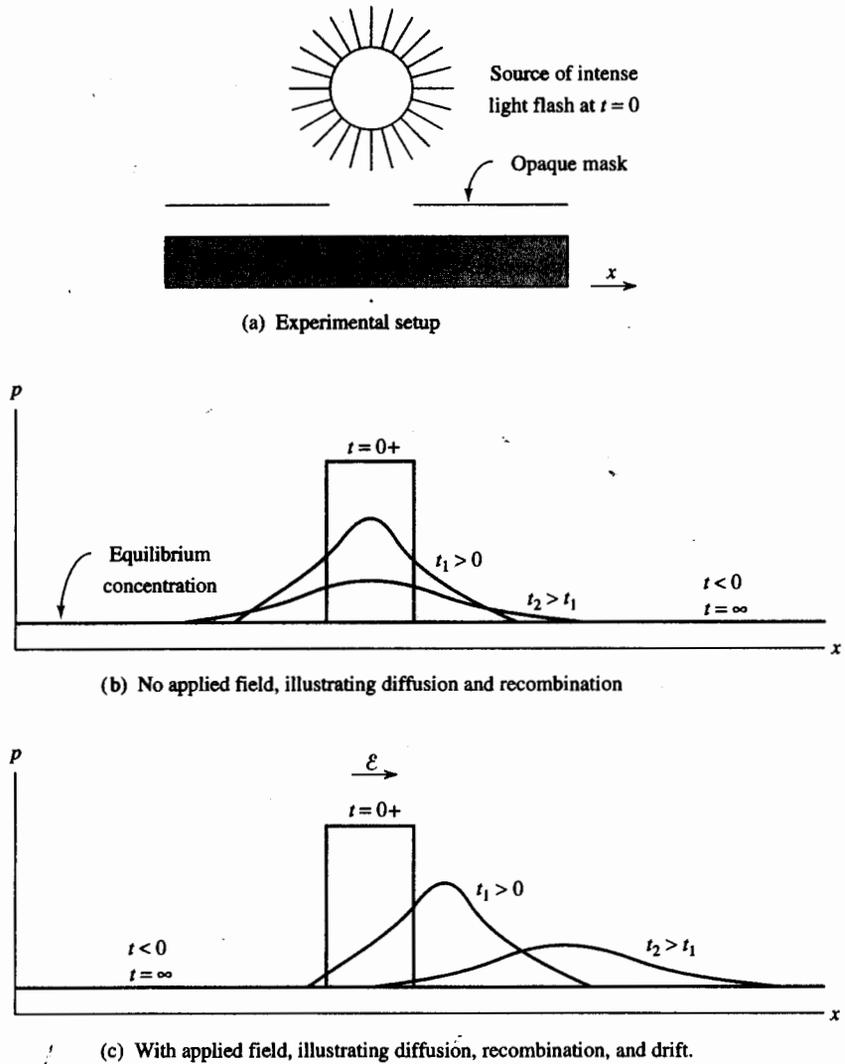
For fast digital circuits and high-frequency analog circuits, devices in which conduction is due to electrons are preferable to devices in which conduction is due to holes.

## Diffusion

We will see that several mechanisms can create a higher-than-normal concentration of holes or electrons in a particular region of a semiconductor crystal. Because of their random thermal velocity, a concentration of charge carriers tends to spread out with time. This causes a flow of current known as **diffusion current**. Unless some action keeps producing excess charge carriers in a particular region of the crystal, the carrier concentration tends to become uniform and diffusion current ceases.

## The Shockley–Haynes Experiment

Diffusion, recombination, and drift can be demonstrated by the Shockley–Haynes experiment. In this experiment, an excess of minority charge carriers is observed in an extrinsic semiconductor. For example, consider the bar of  $n$ -type material shown in Figure 3.41a. At  $t = 0$ , an intense flash of light illuminates a narrow region of the bar. The light causes



**Figure 3.41** Shockley-Haynes experiment.

covalent bonds to be broken and increases the hole concentration in the illuminated portion of the bar. Figure 3.41b shows the plot of hole concentration versus  $x$  for  $t = 0+$  (i.e., immediately after the flash at  $t = 0$ ). With time, the concentration of holes spreads out due to diffusion.

Of course, the excess holes tend to recombine in addition to spreading by diffusion. Thus, the hole concentration eventually returns to its equilibrium value. The interval required for this to take place depends on the hole lifetime,  $\tau_p$ .

If an external electric field is applied to the crystal, the carriers also move due to drift. (See Figure 3.41c.)

In this section, we have discussed conduction in semiconductors. Recombination, drift, and diffusion of charge carriers are important concepts in understanding device behavior. In the next section, we apply these concepts to the  $pn$  junction.

### EXERCISE

**3.18** Doped silicon contains  $10^{16}$  donor atoms/cm<sup>3</sup>. Find the free-electron concentration and the hole concentration.

**Answer**  $n \cong 10^{16}$  electrons/cm<sup>3</sup>,  $p \cong 2.1 \times 10^4$  holes/cm<sup>3</sup>.

## 3.10 PHYSICS OF THE JUNCTION DIODE

### The Unbiased $pn$ Junction

A  $pn$  junction consists of a single crystal of semiconductor material that is doped to produce  $n$ -type material on one side and  $p$ -type on the other side. The impurities can be added to the crystal as it is grown or added later, either by diffusion of impurity atoms into the crystal or by ion implantation. It is important for the crystal lattice to join the  $n$ -side to the  $p$ -side without disruption. This is possible only if the junction is grown as a single crystal. However, it is instructive to imagine the formation of a  $pn$  junction by joining a  $p$ -type crystal to an  $n$ -type crystal.

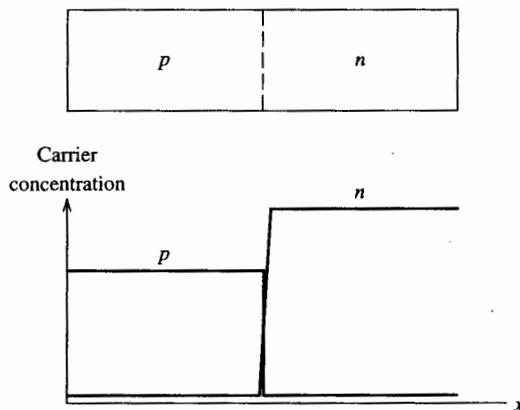
Before the two halves of the junction are joined together, the  $n$  side contains a high concentration of free electrons and a low concentration of holes. The reverse condition exists in the  $p$ -type material. Immediately after the two types of material are joined, a concentration gradient exists across the junction for both types of carriers. (See Figure 3.42.)

Charge carriers diffuse whenever a concentration gradient exists (unless some force opposes the diffusion). Consequently, after the junction is formed, holes diffuse from the  $p$ -side to the  $n$ -side, and electrons diffuse in the opposite direction. This mutual diffusion

... it is instructive to imagine the formation of a  $pn$  junction by joining a  $p$ -type crystal to an  $n$ -type crystal.

**Figure 3.42**

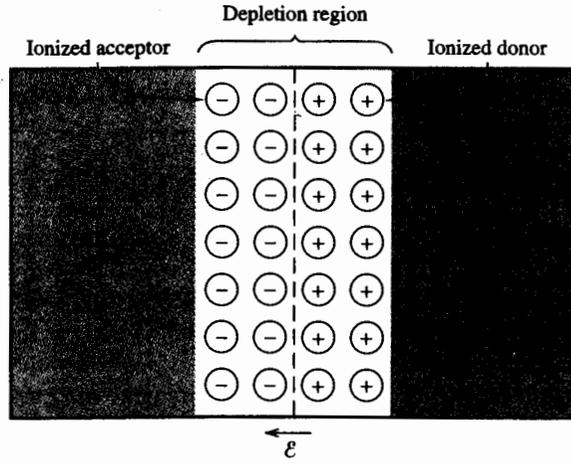
If a  $pn$  junction could be formed by joining a  $p$ -type crystal to an  $n$ -type crystal, a sharp gradient of hole concentration and electron concentration would exist at the junction immediately after joining the crystals.



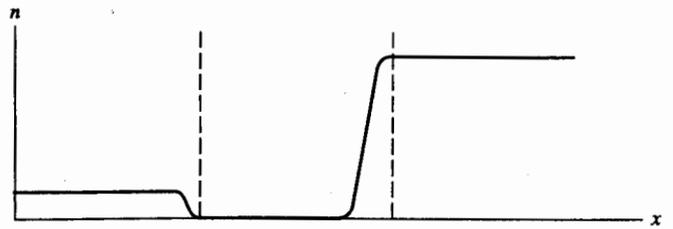
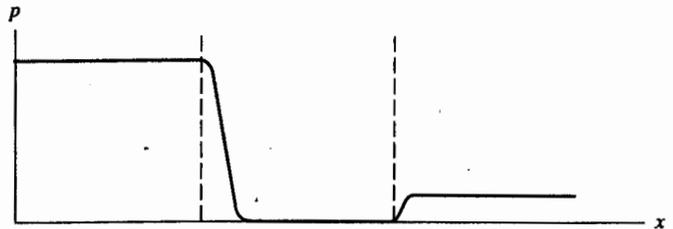
causes net negative charge to build up on the  $p$ -side of the junction (because positively charged holes are leaving and electrons are entering). Similarly, positive charge builds up on the  $n$ -side. Thus, an electric field is created in the crystal pointing from the  $n$ -side to the  $p$ -side. This field opposes further diffusion, which soon comes to a halt. After diffusing across the junction, the charge carriers become minority carriers that quickly recombine.

The result is that a **depletion region** is formed at the junction, extending a short distance into both sides. This is illustrated in Figure 3.43a. Virtually no free charge carriers exist in the depletion region. On the  $p$ -side of the depletion region, a layer of

On the  $p$ -side of the depletion region, a layer of bound negative charge is present.



(a)  $pn$  junction



**Figure 3.43**  
Diffusion of majority carriers into the opposite sides causes a depletion region to appear at the junction.

bound negative charge is present—the charge associated with the ionized acceptor atoms. Some of the holes that originally balanced this negative charge have crossed to the  $n$ -side, and some have combined with electrons that crossed from the  $n$ -side.

Similarly, on the  $n$ -side of the depletion region, we have a layer of bound positive charge. This is the positive charge associated with the ionized donor atoms.

In Figure 3.43a, we have shown the layer of negatively charged acceptor atoms just inside the  $p$ -side and the layer of positively charged donor atoms just inside the  $n$ -side. Of course, acceptor atoms extend throughout the  $p$ -material, but outside the depletion region their negative charge is balanced by the positive charge on the holes. Similarly, donor atoms extend throughout the  $n$ -material, and outside the depletion region their positive charge is balanced by the negative charge of the free electrons. The concentrations of holes and free electrons versus distance are illustrated in Figures 3.43b and 3.43c.

Notice that the net charge concentration and the resulting electric field are confined to the depletion region. Of course, the entire crystal is electrically neutral—the positive charge on the  $n$ -side of the depletion layer is balanced by the negative charge on the  $p$ -side.

The primary effect of the electric field in the depletion region is to repel the further diffusion of majority carriers across the junction. For example, a hole on the  $p$ -side that tries to cross the junction experiences a force pushing it back to the  $p$ -side. We say that a **built-in barrier potential** exists for the majority carriers.

An electron crossing from the  $n$ -side to the  $p$ -side loses energy to the electric field in the depletion region. Thus, the electron sees a potential-energy barrier at the junction. The height of this barrier, denoted by  $\phi_0$ , is typically about one electron volt. Similarly, holes on the  $p$ -side have less potential energy than holes on the  $n$ -side.

With no external voltage applied to the junction, two equal, but opposite, currents cross the junction, so that zero net current flows. One component of current is due to minority carriers on both sides of the junction that enter the depletion region. For example, holes on the  $n$ -side that enter the depletion region are pulled across to the  $p$ -side by the field. Similarly, electrons on the  $p$ -side that enter the depletion region are pulled to the  $n$ -side. This minority current is directed from the  $n$ -side to the  $p$ -side. On the other hand, particularly energetic majority carriers can cross the depletion region in opposition to the field, resulting in a current directed from the  $p$ -side to the  $n$ -side.

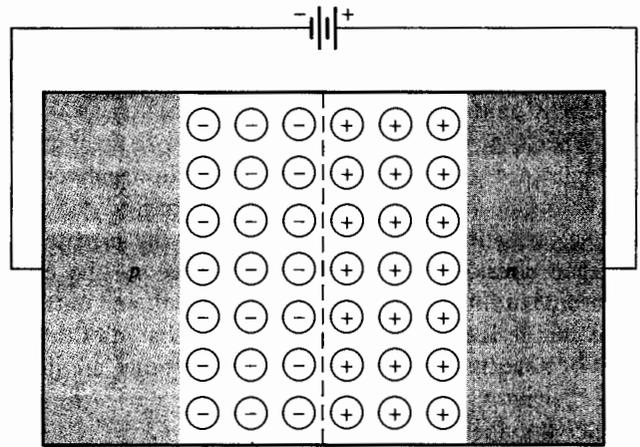
... on the  $n$ -side of the depletion region, we have a layer of bound positive charge.

The primary effect of the electric field in the depletion region is to repel the diffusion of majority carriers across the junction.

## The $pn$ Junction with Reverse Bias

A  $pn$  junction is reverse biased if an external voltage source is applied with the positive polarity on the  $n$ -side with respect to the  $p$ -side, as illustrated in Figure 3.44. The applied voltage aids the built-in barrier field in the depletion region. Thus, the majority carriers are held even more firmly on their respective sides of the junction. Because the majority carriers are pulled back from the junction, the depletion region becomes wider.

With an applied voltage greater than a few tenths of a volt, the current due to majority carriers is reduced to virtually zero. Thus, it is only the minority carriers that contribute to current under reverse bias. The reverse current is small, since few minority carriers are available. Furthermore, because the current is limited by the number of minority charge carriers, the current is almost independent of the magnitude of the reverse voltage.



**Figure 3.44**  
Under reverse bias,  
the depletion re-  
gion becomes wider.

Minority carrier concentration is maintained on both sides of the junction by thermal generation. As the temperature increases, the minority carrier concentration and reverse current increase.

The current through a  $pn$  junction is related to the applied voltage by the Shockley equation,

$$i_D = I_s \left[ \exp \left( \frac{v_D}{nV_T} \right) - 1 \right]$$

Under reverse bias,  $v_D$  is negative, and if  $v_D$  is sufficiently large in magnitude, the equation yields  $i_D = -I_s$ . Thus, we can identify the saturation current  $I_s$  as the current carried by minority carriers crossing the junction.

The device designer can control the magnitude of  $I_s$  by selecting the degree of doping. For example, if both sides of the junction are doped very heavily, the minority carrier concentrations are very small and  $I_s$  is small. On the other hand, light doping (either on one side or on both sides) leads to higher values for  $I_s$ . Typical small-signal silicon diodes have  $I_s$  on the order of  $10^{-14}$  A.

Besides depending on the doping levels, the value of  $I_s$  depends on the area of the junction. The value of  $I_s$  is approximately proportional to the junction area. A diode intended for high-power rectifier applications must have a large junction area to allow the dissipated power to flow away without an excessive rise in temperature. Thus,  $I_s$  is much larger for high-power devices than for small-signal devices. Furthermore,  $I_s$  increases with temperature—doubling for approximately each  $5^\circ\text{C}$ , due to increased thermal generation of minority carriers.

The actual reverse-bias current observed for real silicon diodes is much larger than  $I_s$  because of secondary effects for which the Shockley equation does not account—particularly the generation of carriers in the depletion region. Thus, we cannot find a value for  $I_s$  that is valid in the forward-bias region by measuring the actual reverse current. (Even though the actual reverse current is much larger than  $I_s$ , the reverse current is usually small enough to be neglected in circuit applications.)

At high currents, the ohmic voltage drop caused by current flowing through the doped semiconductor becomes significant. This drop can be taken into account by placing a

The actual reverse-bias current observed for real silicon diodes is much larger than  $I_s$  because of secondary effects for which the Shockley equation does not account.

resistance  $R_s$  in series with the junction modeled by the Shockley equation. In that case, the terminal voltage and current of the device are related by

$$v_D = nV_T \ln[(i_D/I_s) + 1] + R_s i_D \quad (3.32)$$

Typically,  $R_s$  ranges from  $10 \Omega$  to  $100 \Omega$  for small-signal devices.

This equation accounts for the series resistance of the  $pn$  junction.

## The $pn$ Junction with Forward Bias

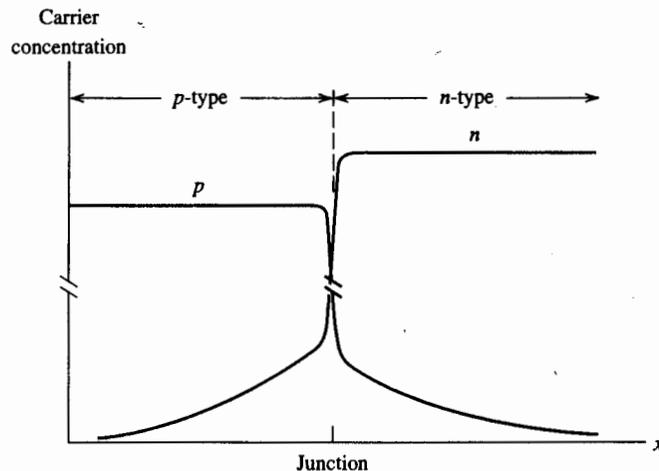
If a positive voltage is applied to the  $p$ -side with respect to the  $n$ -side, the  $pn$  junction is forward biased. Forward bias acts in opposition to the built-in field in the depletion region. The depletion region becomes narrower, and the electric field is reduced. Thus, the built-in barrier for the majority carriers is reduced, and a large current flows across the junction.

In practice, a barrier exists even with forward bias. If sufficient forward bias were applied to reduce the barrier to zero, an excessively large current would flow, and the junction would be destroyed by overheating.

After crossing the junction, the carriers diffuse away from the junction until they combine with the majority carriers. For example, electrons on the  $n$ -side overcome the barrier and cross to the  $p$ -side, where they are minority carriers. These electrons diffuse into the  $p$ -side and eventually combine with holes.

The hole and electron concentrations versus distance for a junction under forward bias are illustrated in Figure 3.45. Notice that the hole concentration  $p$  is high in the  $p$ -type material and drops rapidly across the depletion region because the field pushes the holes back toward the  $p$ -side. On the  $n$ -side, we see a declining hole density with distance because the holes combine with electrons as they diffuse. Far from the junction on the  $n$ -side, the hole concentration is determined by the donor doping level. Similar statements apply to the electron concentration.

Part of the current carried across the junction is due to holes, and part is due to electrons. Thus, we can divide the current into hole current and electron current. The total current is the sum of the two constituents. As the distance from the junction in



**Figure 3.45**  
Carrier concentrations versus distance for a forward-biased  $pn$  junction.

The device designer can control the fraction of the current crossing the junction due to electrons by appropriately selecting the doping levels on the two sides of the junction.

In many applications, ... diodes that can rapidly switch between the conducting and the nonconducting states are extremely desirable.

the  $n$ -side increases, the hole concentration declines and the current is predominantly electron current. Similarly, far from the junction on the  $p$ -side, the current becomes predominantly hole current.

The device designer can control the fraction of the current crossing the junction due to electrons by appropriately selecting the doping levels on the two sides of the junction. For example, if the  $n$ -side is doped very heavily compared with the  $p$ -side, the current crossing the junction is due mostly to electrons. On the other hand, if the  $p$ -side is doped more heavily, the current at the junction is mostly hole current. This point will be important in Chapter 4, when we consider bipolar transistors.

### 3.11 SWITCHING AND HIGH-FREQUENCY BEHAVIOR

We have seen that the  $pn$  junction conducts little current when it is reverse biased and easily conducts large current when it is forward biased. In many applications, such as high-speed logic circuits and high-frequency rectifiers, diodes that can rapidly switch between the conducting and the nonconducting states are extremely desirable.

Unfortunately, the  $pn$  junction displays two charge-storage mechanisms that slow switching. Both of these mechanisms can be modeled as nonlinear capacitances. Before we consider charge storage in  $pn$  junctions, we briefly review conventional linear capacitors.

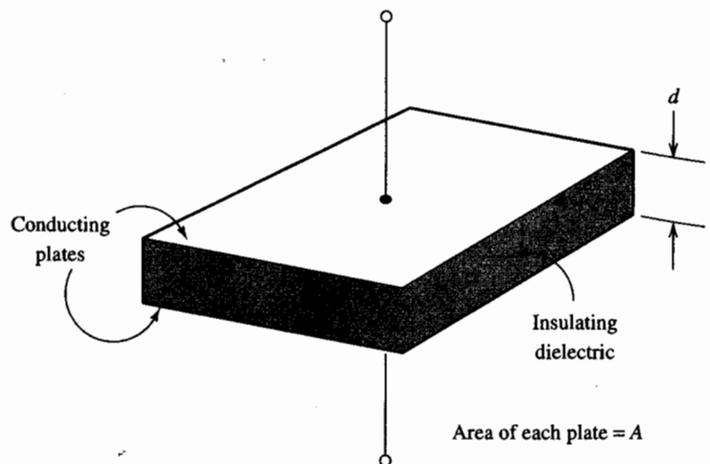
#### Review of Capacitance

A capacitor is constructed by separating two conducting plates by an insulator. (See Figure 3.46.) If voltage is applied to the capacitor terminals, charge flows in and collects on one plate. Meanwhile, current flows out of the other terminal, and a charge of opposite polarity collects on the other plate.

The magnitude of the net charge  $Q$  on one plate is proportional to the applied voltage  $V$ . Thus, we have

$$Q = CV \quad (3.33)$$

in which  $C$  is the capacitance.



**Figure 3.46**  
Parallel-plate capacitor.