### SECTION 1–5 REVIEW

1. Define *doping*.
2. What is the difference between a pentavalent atom and a trivalent atom? What are other names for these atoms?
3. How is an *n*-type semiconductor formed?
4. How is a *p*-type semiconductor formed?
5. What is the majority carrier in an *n*-type semiconductor?
6. What is the majority carrier in a *p*-type semiconductor?
7. By what process are the majority carriers produced?
8. By what process are the minority carriers produced?
9. What is the difference between intrinsic and extrinsic semiconductors?

## 1–6 THE DIODE

If you take a block of silicon and dope part of it with a trivalent impurity and the other part with a pentavalent impurity, a boundary called the *pn* junction is formed between the resulting *p*-type and *n*-type portions and a basic diode is created. A **diode** is a device that conducts current in only one direction. The *pn* junction is the feature that allows diodes, certain transistors, and other devices to work.

After completing this section, you should be able to

- **Describe a diode and how a *pn* junction is formed**
- Discuss diffusion across a *pn* junction
- Explain the formation of the depletion region
- Define *barrier potential* and discuss its significance
- State the values of barrier potential in silicon and germanium

A *p*-type material consists of silicon atoms and trivalent impurity atoms such as boron. The boron atom adds a hole when it bonds with the silicon atoms. However, since the number of protons and the number of electrons are equal throughout the material, there is no net charge in the material and so it is neutral.

An *n*-type silicon material consists of silicon atoms and pentavalent impurity atoms such as antimony. As you have seen, an impurity atom releases an electron when it bonds with four silicon atoms. Since there is still an equal number of protons and electrons (including the free electrons) throughout the material, there is no net charge in the material and so it is neutral.

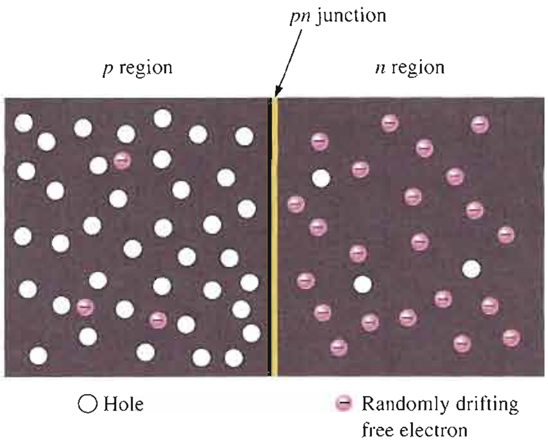
If a piece of intrinsic silicon is doped so that part is *n*-type and the other part is *p*-type, a ***pn* junction** forms at the boundary between the two regions and a diode is created, as indicated in Figure 1–17. The *p* region has many holes (majority carriers) from the impurity atoms and only a few thermally generated free electrons (minority carriers). The *n* region has many free electrons (majority carriers) from the impurity atoms and only a few thermally generated holes (minority carriers).

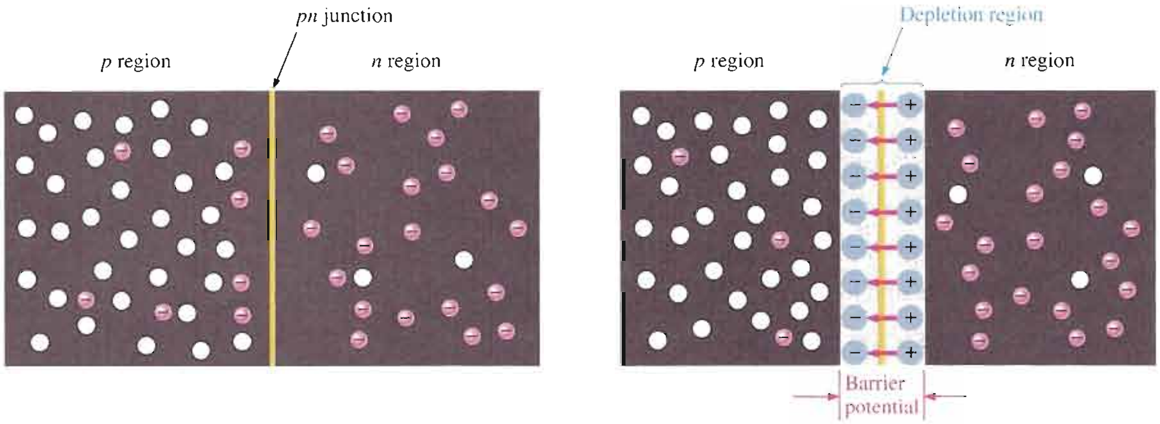
### Formation of the Depletion Region

As you have seen, the free electrons in the *n* region are randomly drifting in all directions. At the instant of the *pn* junction formation, the free electrons near the junction in the *n* region begin to diffuse across the junction into the *p* region where they combine with holes near the junction, as shown in Figure 1–18(a).

**FIGURE 1–17**

The basic diode structure at the instant of junction formation showing only the majority and minority carriers.





(a) At the instant of junction formation, free electrons in the *n* region near the *pn* junction begin to diffuse across the junction and fall into holes near the junction in the *p* region.

(b) For every electron that diffuses across the junction and combines with a hole, a positive charge is left in the *n* region and a negative charge is created in the *p* region, forming a barrier potential. This action continues until the voltage of the barrier repels further diffusion.

**FIGURE 1–18**

Formation of the depletion region. The width of the depletion region is exaggerated for illustration purposes.

Before the *pn* junction is formed, recall that there are as many electrons as protons in the *n*-type material, making the material neutral in terms of net charge. The same is true for the *p*-type material.

When the *pn* junction is formed, the *n* region loses free electrons as they diffuse across the junction. This creates a layer of positive charges (pentavalent ions) near the junction. As the electrons move across the junction, the *p* region loses holes as the electrons and holes combine. This creates a layer of negative charges (trivalent ions) near the junction. These two layers of positive and negative charges form the **depletion region**, as shown in Figure 1–18(b). The term *depletion* refers to the fact that the region near the *pn* junction is depleted of charge carriers (electrons and holes) due to diffusion across the junction. Keep in mind that the depletion region is formed very quickly and is very thin compared to the *n* region and *p* region.

After the initial surge of free electrons across the *pn* junction, the depletion region has expanded to a point where equilibrium is established and there is no further diffusion of electrons across the junction. This occurs as follows. As electrons continue to diffuse across the junction, more and more positive and negative charges are created near the junction as the depletion region is formed. A point is reached where the total negative charge in the depletion region repels any further diffusion of electrons (negatively charged particles) into the *p* region (like charges repel) and the diffusion stops. In other words, the depletion region acts as a barrier to the further movement of electrons across the junction.

**Barrier Potential** Any time there is a positive charge and a negative charge near each other, there is a force acting on the charges as described by Coulomb's law. In the depletion region there are many positive charges and many negative charges on opposite sides of the *pn* junction. The forces between the opposite charges form a "field of forces" called an *electric field*, as illustrated in Figure 1–18(b) by the red arrows between the positive charges and the negative charges. This electric field is a barrier to the free electrons in the *n* region, and energy must be expended to move an electron through the electric field. That is, external energy must be applied to get the electrons to move across the barrier of the electric field in the depletion region.

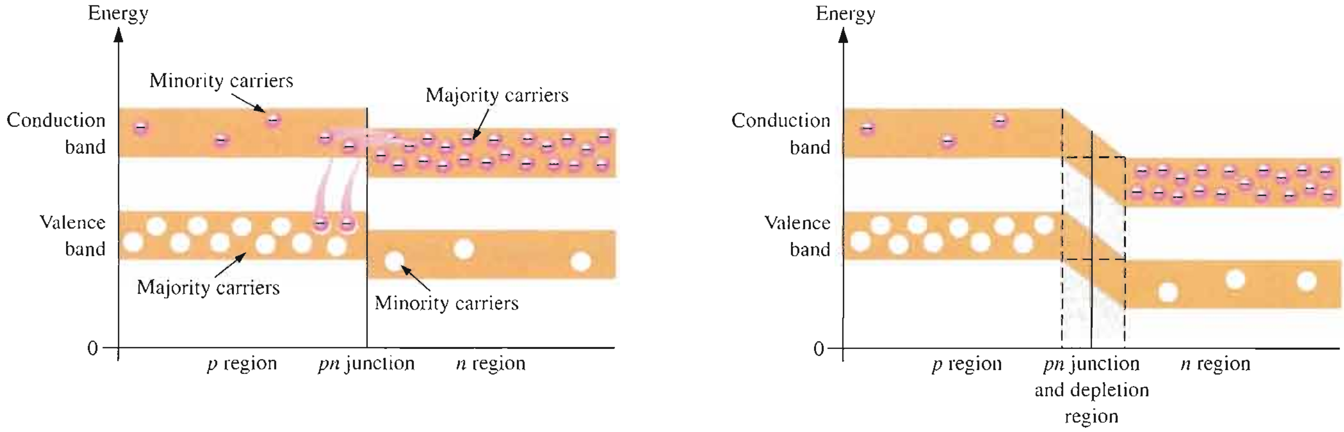
The potential difference of the electric field across the depletion region is the amount of voltage required to move electrons through the electric field. This potential difference is called the **barrier potential** and is expressed in volts. Stated another way, a certain amount of voltage equal to the barrier potential and with the proper polarity must be applied across a *pn* junction before electrons will begin to flow across the junction. You will learn more about this when we discuss *biasing* in Section 1–7.

The barrier potential of a *pn* junction depends on several factors, including the type of semiconductive material, the amount of doping, and the temperature. The typical barrier potential is approximately 0.7 V for silicon and 0.3 V for germanium at 25°C. Throughout the rest of the book, silicon will be used unless otherwise stated.

## Energy Diagrams of the *PN* Junction and Depletion Region

The valence and conduction bands in an *n*-type material are at slightly lower energy levels than the valence and conduction bands in a *p*-type material. This is due to differences in the atomic characteristics of the pentavalent and the trivalent impurity atoms.

An energy diagram for a *pn* junction at the instant of formation is shown in Figure 1–19(a). As you can see, the valence and conduction bands in the *n* region are at lower energy levels than those in the *p* region, but there is a significant amount of overlapping.



(a) At the instant of junction formation

(b) At equilibrium

▲ **FIGURE 1–19**

Energy diagrams illustrating the formation of the *pn* junction and depletion region.

The free electrons in the *n* region that occupy the upper part of the conduction band in terms of their energy can easily diffuse across the junction (they do not have to gain additional energy) and temporarily become free electrons in the lower part of the *p*-region conduction band. After crossing the junction, the electrons quickly lose energy and fall into the holes in the $p$-region valence band as indicated in Figure 1–19(a).

As the diffusion continues, the depletion region begins to form and the energy level of the $n$-region conduction band decreases. The decrease in the energy level of the conduction band in the $n$ region is due to the loss of the higher-energy electrons that have diffused across the junction to the $p$ region. Soon, there are no electrons left in the $n$-region conduction band with enough energy to get across the junction to the $p$-region conduction band, as indicated by the alignment of the top of the $n$-region conduction band and the bottom of the $p$-region conduction band in Figure 1-19(b). At this point, the junction is at equilibrium; and the depletion region is complete because diffusion has ceased. There is an energy gradiant across the depletion region which acts as an "energy hill" that an $n$-region electron must climb to get to the $p$ region.

Notice that as the energy level of the $n$-region conduction band has shifted downward, the energy level of the valence band has also shifted downward. It still takes the same amount of energy for a valence electron to become a free electron. In other words, the energy gap between the valence band and the conduction band remains the same.

### SECTION 1-6 REVIEW

1. What is a *pn* junction?
2. Explain what diffusion is.
3. Describe the depletion region.
4. Explain what the barrier potential is and how it is created.
5. What is the typical value of the barrier potential for a silicon diode?
6. What is the typical value of the barrier potential for a germanium diode?

## 1–7 BIASING A DIODE

As you have learned, no electrons move through the *pn* junction at equilibrium. Generally the term *bias* refers to the use of a dc voltage to establish certain operating conditions for an electronic device. In relation to a diode, there are two bias conditions: forward and reverse. Either of these bias conditions is established by connecting a sufficient dc voltage of the proper polarity across the *pn* junction.

After completing this section, you should be able to

- **Discuss the bias of a diode**
- Define *forward bias* and state the required conditions
- Define *reverse bias* and state the required conditions
- Discuss the effect of barrier potential on forward bias
- Explain how current is produced in forward bias
- Explain reverse current
- Describe reverse breakdown of a diode
- Explain forward bias and reverse bias in terms of energy diagrams

### Forward Bias

To bias a diode, you apply a dc voltage across it. Forward bias is the condition that allows current through the *pn* junction. Figure 1–20 shows a dc voltage source connected by con-