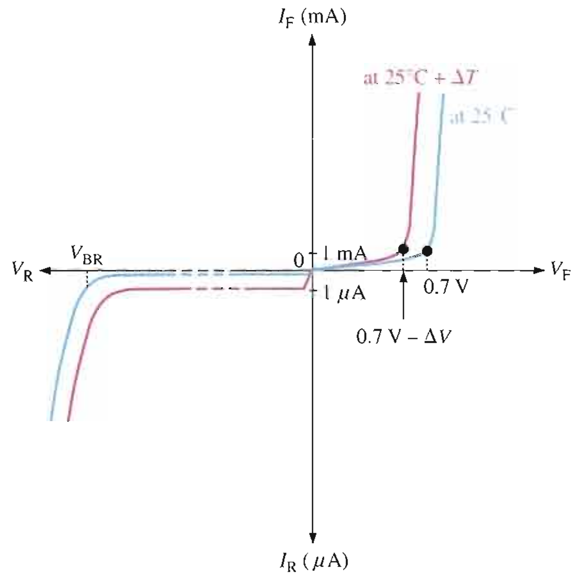
▶ **FIGURE 1–30**

Temperature effect on the diode *V-I* characteristic. The 1 mA and 1 μA marks on the vertical axis are given as a basis for a relative comparison of the current scales.



SECTION 1–8 REVIEW

1. Discuss the significance of the knee of the characteristic curve in forward bias.
2. On what part of the curve is a forward-biased diode normally operated?
3. Which is greater, the breakdown voltage or the barrier potential?
4. On what part of the curve is a reverse-biased diode normally operated?
5. What happens to the barrier potential when the temperature increases?

1–9 DIODE MODELS

You have learned that a diode is a *pn* junction device. In this section, you will learn the electrical symbol for a diode and how the diode can be modeled for circuit analysis using three levels of complexity. Also, diode packaging and terminal identification are introduced.

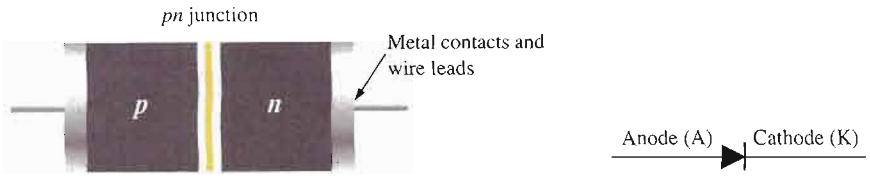
After completing this section, you should be able to

- **Discuss the operation of diodes and explain the three diode models**
- Recognize a diode symbol and indentify the diode terminals
- Recognize diodes in various physical configurations
- Explain the ideal, the practical, and the complete diode models

Diode Structure and Symbol

A diode is a single *pn* junction device with conductive contacts and wire leads connected to each region, as shown in Figure 1–31(a). Part of the diode is an *n*-type semiconductor and the other part is a *p*-type semiconductor.

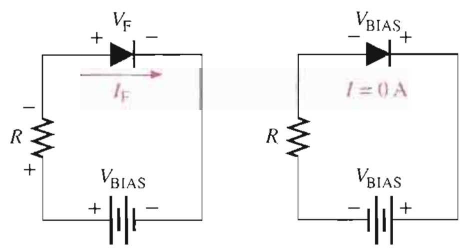
There are several types of diodes, but the schematic symbol for a general-purpose or rectifier diode, such as introduced in this chapter, is shown in Figure 1–31(b). The *n* region is called the **cathode** and the *p* region is called the **anode**. The "arrow" in the symbol points in the direction of conventional current (opposite to electron flow).



(a) Basic diode structure (b) Schematic symbol

FIGURE 1–31
Diode structure and schematic symbol.

Forward-Bias Connection A diode is forward-biased when a voltage source is connected as shown in Figure 1–32(a). The positive terminal of the source is connected to the anode through a current-limiting resistor. The negative terminal of the source is connected to the cathode. The forward current (I_F) is from anode to cathode as indicated. The forward voltage drop (V_F) due to the barrier potential is from positive at the anode to negative at the cathode.



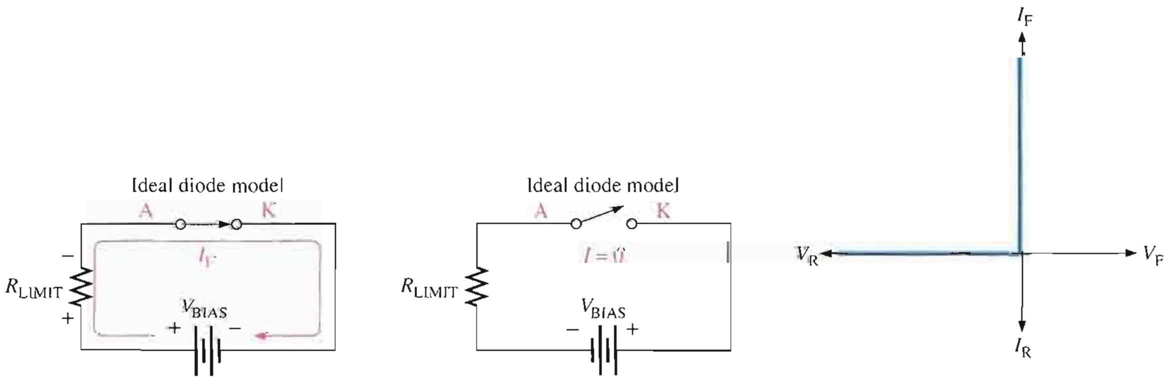
(a) Forward bias (b) Reverse bias

FIGURE 1–32
Forward-bias and reverse-bias connections showing the diode symbol.

Reverse-Bias Connection A diode is reverse-biased when a voltage source is connected as shown in Figure 1–32(b). The negative terminal of the source is connected to the anode side of the circuit, and the positive terminal is connected to the cathode side. A resistor is not necessary in reverse bias but it is shown for circuit consistency. The reverse current is extremely small and can be considered to be zero. Notice that the entire bias voltage (V_{BIAS}) appears across the diode.

The Ideal Diode Model

The ideal model of a diode is a simple switch. When the diode is forward-biased, it acts like a closed (on) switch, as shown in Figure 1–33(a). When the diode is reverse-biased, it acts like an open (off) switch, as shown in part (b). The barrier potential, the forward dynamic resistance, and the reverse current are all neglected.



(a) Forward bias (b) Reverse bias (c) Ideal characteristic curve (blue)

FIGURE 1–33
The ideal model of a diode.

In Figure 1–33(c), the ideal *V-I* characteristic curve graphically depicts the ideal diode operation. Since the barrier potential and the forward dynamic resistance are neglected, the diode is assumed to have a zero voltage across it when forward-biased, as indicated by the portion of the curve on the positive vertical axis.

$$V_F = 0\text{ V}$$

The forward current is determined by the bias voltage and the limiting resistor using Ohm's law.

Equation 1–2

$$I_F = \frac{V_{BIAS}}{R_{LIMIT}}$$

Since the reverse current is neglected, its value is assumed to be zero, as indicated in Figure 1–33(c) by the portion of the curve on the negative horizontal axis.

$$I_R = 0\text{ A}$$

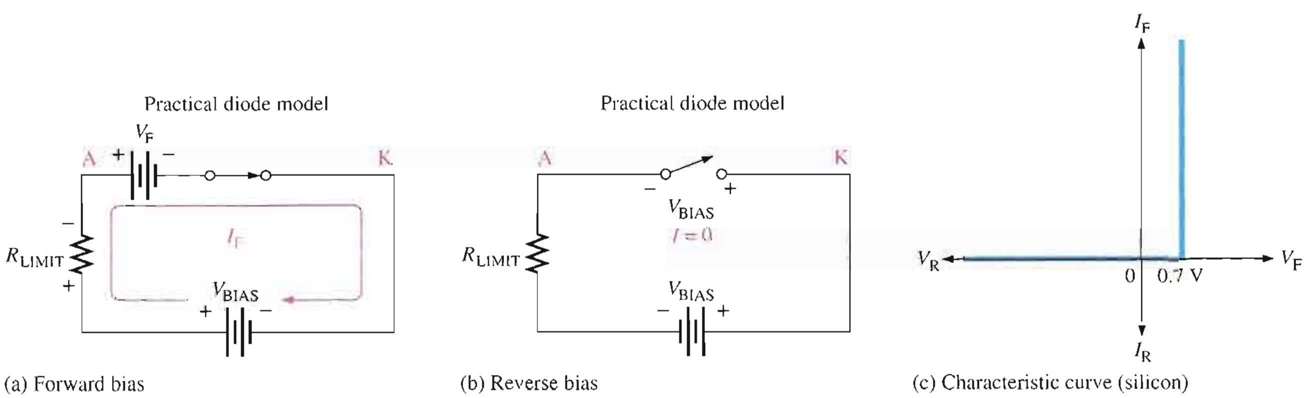
The reverse voltage equals the bias voltage.

$$V_R = V_{BIAS}$$

You may want to use the ideal model when you are troubleshooting or trying to figure out the operation of a circuit and are not concerned with more exact values of voltage or current.

The Practical Diode Model

The practical model adds the barrier potential to the ideal switch model. When the diode is forward-biased, it is equivalent to a closed switch in series with a small equivalent voltage source equal to the barrier potential (0.7 V) with the positive side toward the anode, as indicated in Figure 1–34(a). This equivalent voltage source represents the fixed voltage drop (V_F) produced across the forward-biased *pn* junction of the diode and is not an active source of voltage.



▲ FIGURE 1–34

The practical model of a diode.

When the diode is reverse-biased, it is equivalent to an open switch just as in the ideal model, as shown in Figure 1–34(b). The barrier potential does not affect reverse bias, so it is not a factor.

The characteristic curve for the practical diode model is shown in Figure 1–34(c). Since the barrier potential is included and the dynamic resistance is neglected, the diode is assumed to have a voltage across it when forward-biased, as indicated by the portion of the curve to the right of the origin.

$$V_F = 0.7\text{ V}$$

The forward current is determined as follows by first applying Kirchhoff's voltage law to Figure 1–34(a):

$$V_{BIAS} - V_F - V_{R_{LIMIT}} = 0$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT}$$

Substituting and solving for I_F,

$$I_F = \frac{V_{BIAS} - V_F}{R_{LIMIT}}$$

Equation 1–3

The diode is assumed to have zero reverse current, as indicated by the portion of the curve on the negative horizontal axis.

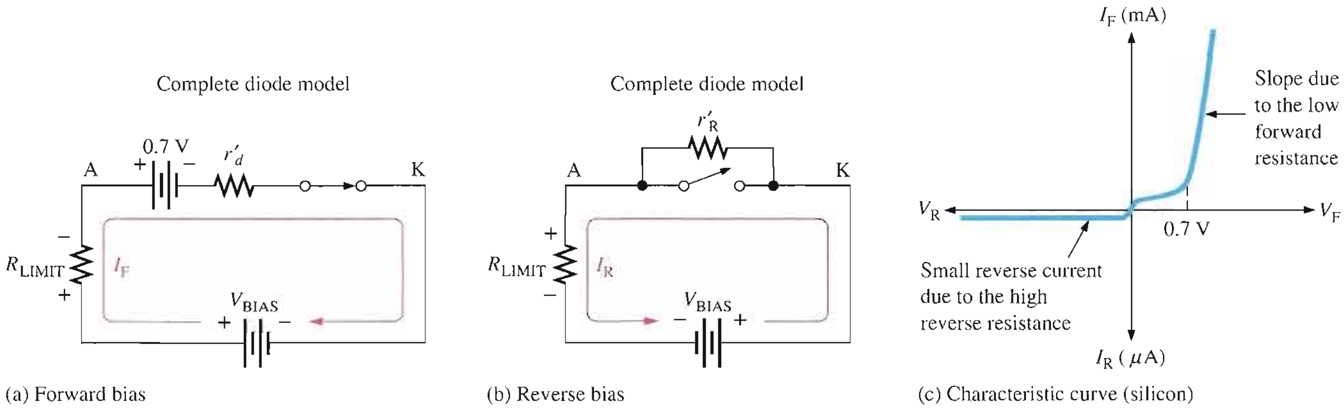
$$I_R = 0 \text{ A}$$

$$V_R = V_{BIAS}$$

The Complete Diode Model

The complete model of a diode consists of the barrier potential, the small forward dynamic resistance (r'_d), and the large internal reverse resistance (r'_R). The reverse resistance is taken into account because it provides a path for the reverse current, which is included in this diode model.

When the diode is forward-biased, it acts as a closed switch in series with the barrier potential voltage and the small forward dynamic resistance (r'_d), as indicated in Figure 1–35(a). When the diode is reverse-biased, it acts as an open switch in parallel with the large internal reverse resistance (r'_R), as shown in Figure 1–35(b). The barrier potential does not affect reverse bias, so it is not a factor.



▲ FIGURE 1–35

The complete model of a diode.

The characteristic curve for the complete diode model is shown in Figure 1–35(c). Since the barrier potential and the forward dynamic resistance are included, the diode is assumed to have a voltage across it when forward-biased. This voltage (V_F) consists of the barrier potential voltage plus the small voltage drop across the dynamic resistance, as indicated by the portion of the curve to the right of the origin. The curve slopes because the voltage drop due to dynamic resistance increases as the current increases. For the complete model of a silicon diode, the following formulas apply:

$$V_F = 0.7 \text{ V} + I_F r'_d$$

Equation 1–4

$$I_F = \frac{V_{BIAS} - 0.7 \text{ V}}{R_{LIMIT} + r'_d}$$

Equation 1–5

The reverse current is taken into account with the parallel resistance and is indicated by the portion of the curve to the left of the origin. The breakdown portion of the curve is not shown because breakdown is not a normal mode of operation for most diodes.

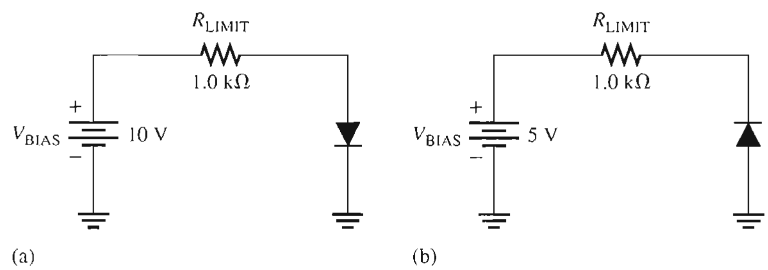
Although the ideal and practical models are predominately used in this textbook, the following example illustrates the differences in all three diode models in the analysis of a simple circuit.

EXAMPLE 1–1

(a) Determine the forward voltage and forward current for the diode in Figure 1–36(a) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume $r'_d = 10\ \Omega$ at the determined value of forward current.

(b) Determine the reverse voltage and reverse current for the diode in Figure 1-36(b) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume $I_R = 1\ \mu A$.

► FIGURE 1–36



Solution **(a)** Ideal model:

$$V_F = \mathbf{0\ V}$$

$$I_F = \frac{V_{BIAS}}{R_{LIMIT}} = \frac{10\ V}{1.0\ k\Omega} = \mathbf{10\ mA}$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT} = (10\ mA)(1.0\ k\Omega) = \mathbf{10\ V}$$

Practical model:

$$V_F = \mathbf{0.7\ V}$$

$$I_F = \frac{V_{BIAS} - V_F}{R_{LIMIT}} = \frac{10\ V - 0.7\ V}{1.0\ k\Omega} = \frac{9.3\ V}{1.0\ k\Omega} = \mathbf{9.3\ mA}$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT} = (9.3\ mA)(1.0\ k\Omega) = \mathbf{9.3\ V}$$

Complete model:

$$I_F = \frac{V_{BIAS} - 0.7\ V}{R_{LIMIT} + r'_d} = \frac{10\ V - 0.7\ V}{1.0\ k\Omega + 10\ \Omega} = \frac{9.3\ V}{1010\ \Omega} = \mathbf{9.21\ mA}$$

$$V_F = 0.7\ V + I_F r'_d = 0.7\ V + (9.21\ mA)(10\ \Omega) = \mathbf{792\ mV}$$

$$V_{R_{LIMIT}} = I_F R_{LIMIT} = (9.21\ mA)(1.0\ k\Omega) = \mathbf{9.21\ V}$$

$$I_R = \mathbf{0\ A}$$
$$V_R = V_{BIAS} = \mathbf{5\ V}$$
$$V_{R_{LIMIT}} = \mathbf{0\ V}$$

Practical model:

$$I_R = \mathbf{0\ A}$$
$$V_R = V_{BIAS} = \mathbf{5\ V}$$
$$V_{R_{LIMIT}} = \mathbf{0\ V}$$

Complete model:

$$I_R = \mathbf{1\ \mu A}$$
$$V_{R_{LIMIT}} = I_R R_{LIMIT} = (1\ \mu A)(1.0\ k\Omega) = \mathbf{1\ mV}$$
$$V_R = V_{BIAS} - V_{R_{LIMIT}} = 5\ V - 1\ mV = \mathbf{4.999\ V}$$

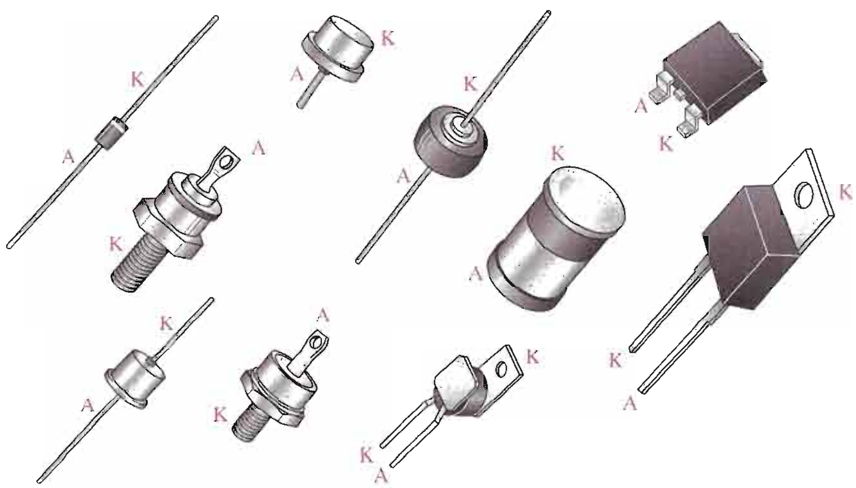
Related Problem* Assume that the diode in Figure 1–36(a) fails open. What is the voltage across the diode and the voltage across the limiting resistor?

*Answers are at the end of the chapter.

Open the Multisim file E01-01 in the Examples folder on your CD-ROM. Measure the voltages across the diode and the resistor in both circuits and compare with the calculated results in this example.

Typical Diodes

Several common physical configurations of diodes are illustrated in Figure 1–37. The anode and cathode are indicated on a diode in several ways, depending on the type of package. The cathode is usually marked by a band, a tab, or some other feature. On those packages where one lead is connected to the case, the case is the cathode. Always check the data sheet, which will be introduced in Chapter 2, for the pin configuration if there is uncertainty.



◄ **FIGURE 1–37**

Typical diode packages with terminal identification.