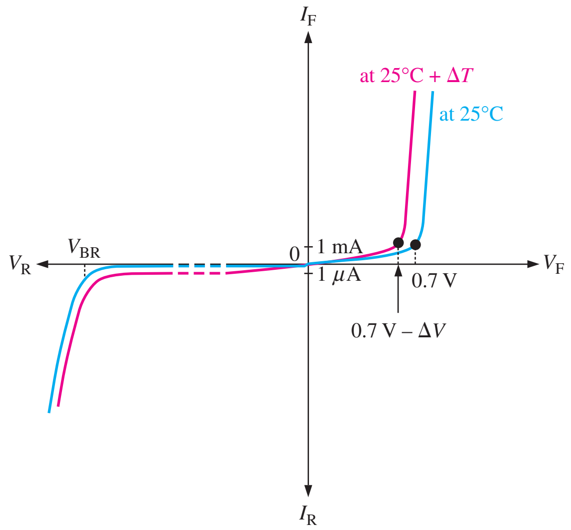
Temperature Effects For a forward-biased diode, as temperature is increased, the forward current increases for a given value of forward voltage. Also, for a given value of forward current, the forward voltage decreases. This is shown with the *V-I* characteristic curves in Figure 2–13. The blue curve is at room temperature (25°C) and the red curve is at an elevated temperature (25°C + ΔT). The barrier potential decreases by 2 mV for each degree increase in temperature.



◀ **FIGURE 2–13**

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.

For a reverse-biased diode, as temperature is increased, the reverse current increases. The difference in the two curves is exaggerated on the graph in Figure 2–13 for illustration. Keep in mind that the reverse current below breakdown remains extremely small and can usually be neglected.

SECTION 2–2 CHECKUP

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?

2–3 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 a diode can be modeled for circuit analysis using any one of three levels of complexity. Also, diode packaging and terminal identification are introduced.

After completing this section, you should be able to

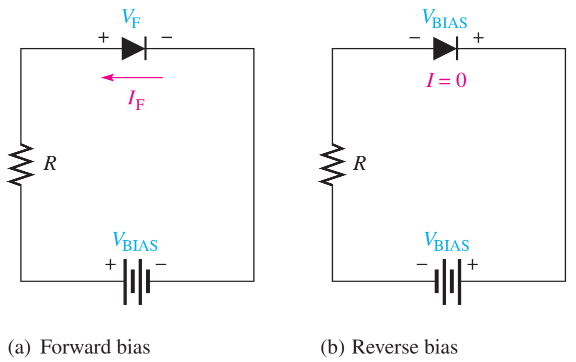
- **Explain how the three diode models differ**
- Discuss bias connections
- Describe the diode approximations
  - Describe the ideal diode model
  - Describe the practical diode model
  - Describe the complete diode model

Bias Connections

Forward-Bias Recall that a diode is forward-biased when a voltage source is connected as shown in Figure 2–14(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 cathode to anode as indicated. The forward voltage drop (V_F) due to the barrier potential is from positive at the anode to negative at the cathode.

▶ FIGURE 2–14

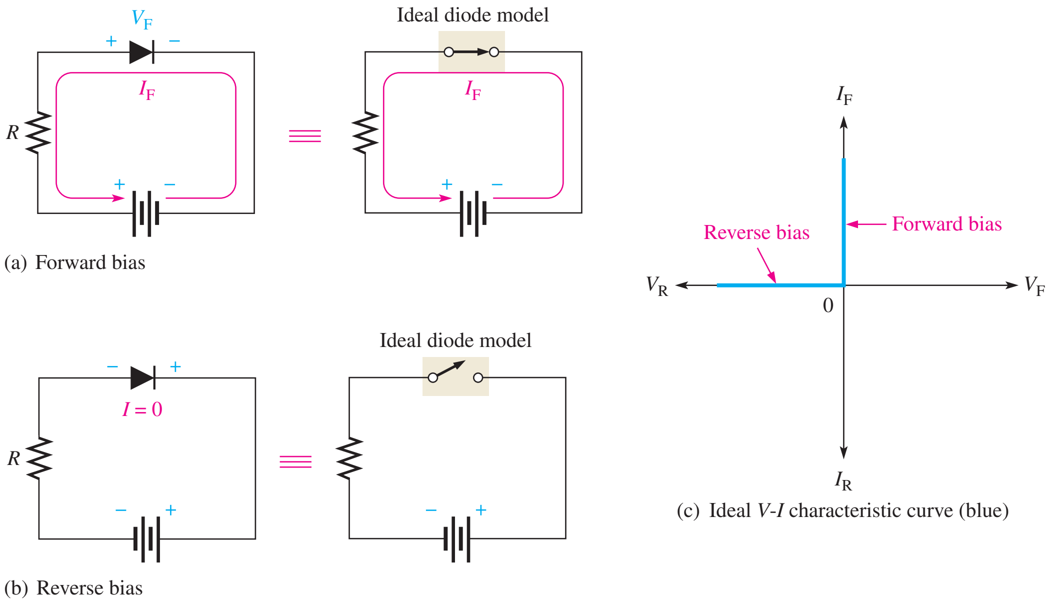
Forward-bias and reverse-bias connections showing the diode symbol.



Reverse-Bias Connection A diode is reverse-biased when a voltage source is connected as shown in Figure 2–14(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.

Diode Approximations

The Ideal Diode Model The ideal model of a diode is the least accurate approximation and can be represented by a simple switch. When the diode is forward-biased, it ideally acts like a closed (on) switch, as shown in Figure 2–15(a). When the diode is reverse-biased, it



▲ FIGURE 2–15

The ideal model of a diode.

ideally acts like an open (off) switch, as shown in part (b). Although the barrier potential, the forward dynamic resistance, and the reverse current are all neglected, this model is adequate for most troubleshooting when you are trying to determine if the diode is working properly.

In Figure 2–15(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.

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

Equation 2–1

Since the reverse current is neglected, its value is assumed to be zero, as indicated in Figure 2–15(c) by the portion of the curve on the negative horizontal axis.

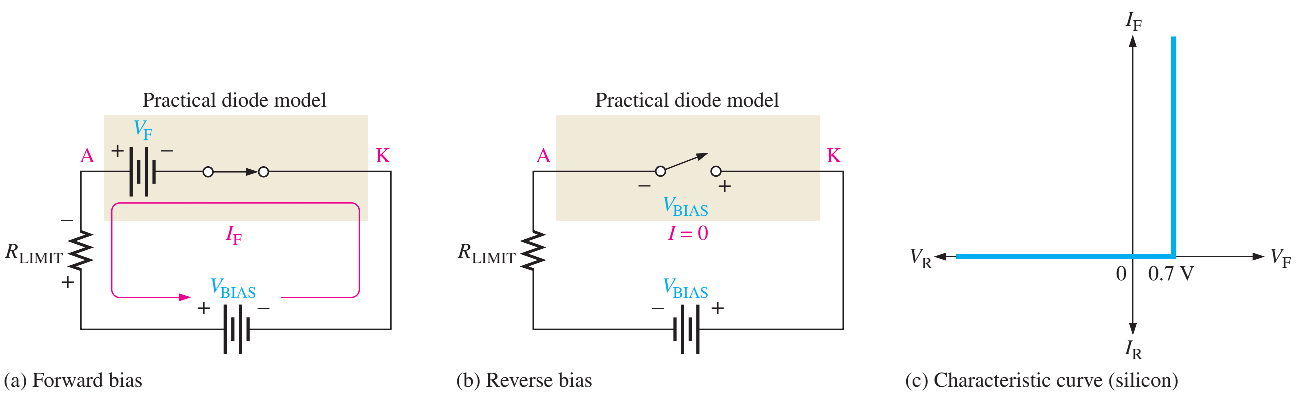
$$I_R = 0\text{ A}$$

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 includes the barrier potential. When the diode is forward-biased, it is equivalent to a closed switch in series with a small equivalent voltage source (V_F) equal to the barrier potential (0.7 V) with the positive side toward the anode, as indicated in Figure 2–16(a). This equivalent voltage source represents the barrier potential that must be exceeded by the bias voltage before the diode will conduct and is not an active source of voltage. When conducting, a voltage drop of 0.7 V appears across the diode.



▲ **FIGURE 2–16**

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 2–16(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 2–16(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 2–16(a):

$$V_{\text{BIAS}} - V_{\text{F}} - V_{R_{\text{LIMIT}}} = 0$$
$$V_{R_{\text{LIMIT}}} = I_{\text{F}} R_{\text{LIMIT}}$$

Substituting and solving for I_{F},

Equation 2–2

$$I_{\text{F}} = \frac{V_{\text{BIAS}} - V_{\text{F}}}{R_{\text{LIMIT}}}$$

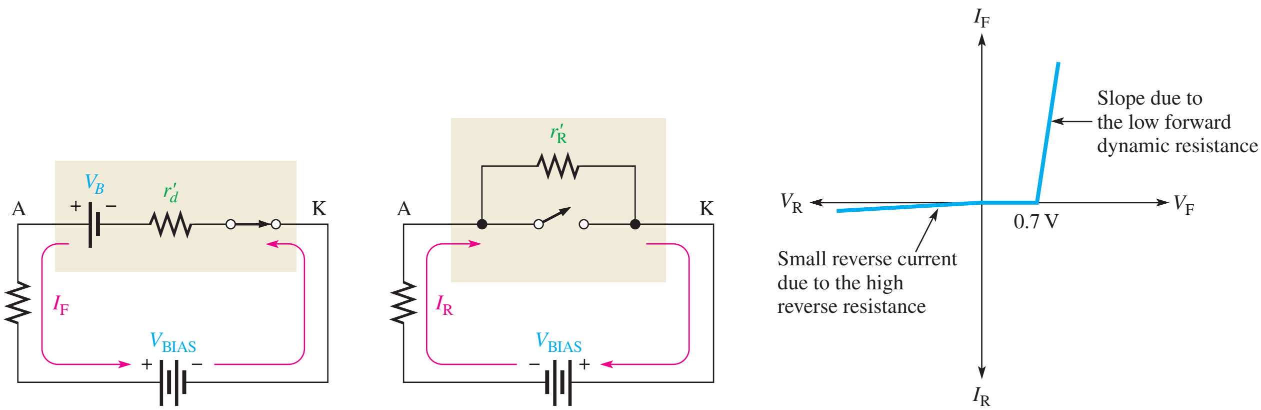
The diode is assumed to have zero reverse current, as indicated by the portion of the curve on the negative horizontal axis.

$$I_{\text{R}} = 0\text{ A}$$
$$V_{\text{R}} = V_{\text{BIAS}}$$

The practical model is useful when you are troubleshooting in lower-voltage circuits. In these cases, the 0.7 V drop across the diode may be significant and should be taken into account. The practical model is also useful when you are designing basic diode circuits.

The Complete Diode Model The complete model of a diode is the most accurate approximation and includes 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 equivalent barrier potential voltage (V_B) and the small forward dynamic resistance (r'_d), as indicated in Figure 2–17(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 2–17(b). The barrier potential does not affect reverse bias, so it is not a factor.



(a) Forward bias (b) Reverse bias (c) *V-I* characteristic curve

▲ **FIGURE 2–17**

The complete model of a diode.

The characteristic curve for the complete diode model is shown in Figure 2–17(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:

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

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

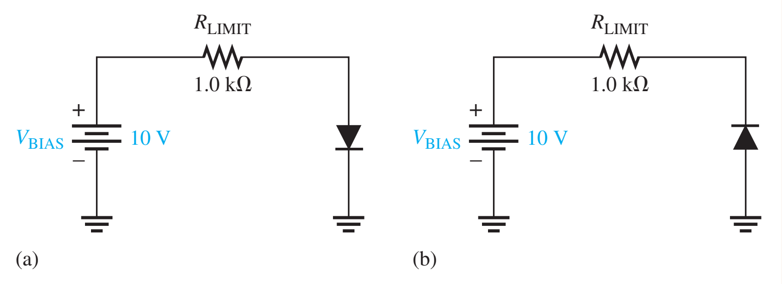
The reverse current is taken into account with the parallel resistance and is indicated by the portion of the curve to the left of the origin. The breakdown portion of the curve is not shown because breakdown is not a normal mode of operation for most diodes.

For troubleshooting work, it is unnecessary to use the complete model, as it involves complicated calculations. This model is generally suited to design problems using a computer for simulation. The ideal and practical models are used for circuits in this text, except in the following example, which illustrates the differences in the three models.

EXAMPLE 2–1

(a) Determine the forward voltage and forward current for the diode in Figure 2–18(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 2–18(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 2–18

Solution

(a) Ideal model:

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

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

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

Practical model:

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

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

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

Complete model:

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

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

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

(b) Ideal model:

$$I_R = \mathbf{0\ A}$$
$$V_R = V_{BIAS} = \mathbf{10\ V}$$
$$V_{R_{LIMIT}} = \mathbf{0\ V}$$

Practical model:

$$I_R = \mathbf{0\ A}$$
$$V_R = V_{BIAS} = \mathbf{10\ V}$$
$$V_{R_{LIMIT}} = \mathbf{0\ V}$$

Complete model:

$$I_R = \mathbf{1\ \mu A}$$
$$V_{R_{LIMIT}} = I_R R_{LIMIT} = (1\ \mu A)(1.0\ k\Omega) = \mathbf{1\ mV}$$
$$V_R = V_{BIAS} - V_{R_{LIMIT}} = 10\ V - 1\ mV = \mathbf{9.999\ V}$$

*Related Problem** Assume that the diode in Figure 2–18(a) fails open. What is the voltage across the diode and the voltage across the limiting resistor?

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*Answers can be found at www.pearsonhighered.com/floyd.

Open the Multisim file E02-01 in the Examples folder on the companion website. Measure the voltages across the diode and the resistor in both circuits and compare with the calculated results in this example.

SECTION 2–3 CHECKUP

1. What are the two conditions under which a diode is operated?
2. Under what condition is a diode never intentionally operated?
3. What is the simplest way to visualize a diode?
4. To more accurately represent a diode, what factors must be included?
5. Which diode model represents the most accurate approximation?

2–4 HALF-WAVE RECTIFIERS

Because of their ability to conduct current in one direction and block current in the other direction, diodes are used in circuits called rectifiers that convert ac voltage into dc voltage. Rectifiers are found in all dc power supplies that operate from an ac voltage source. A power supply is an essential part of each electronic system from the simplest to the most complex.

After completing this section, you should be able to

- **Explain and analyze the operation of half-wave rectifiers**
- Describe a basic dc power supply
- Discuss half-wave rectification
  - Determine the average value of a half-wave voltage
- Explain how the barrier potential affects a half-wave rectifier output
  - Calculate the output voltage
- Define *peak inverse voltage*
- Explain the operation of a transformer-coupled rectifier