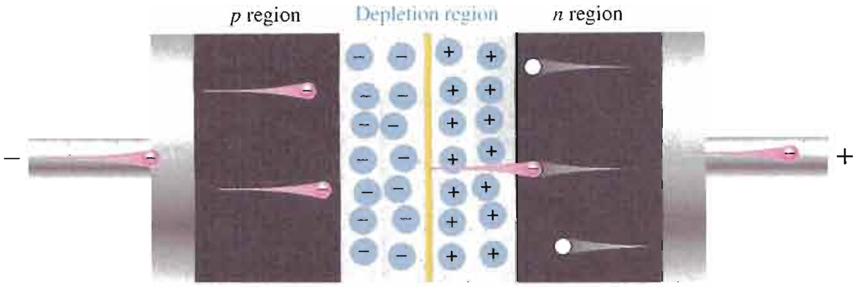
FIGURE 1–25

The extremely small reverse current in a reverse-biased diode is due to the minority carriers from thermally generated electron-hole pairs.



This is what happens. The high reverse-bias voltage imparts energy to the free minority electrons so that as they speed through the *p* region, they collide with atoms with enough energy to knock valence electrons out of orbit and into the conduction band. The newly created conduction electrons are also high in energy and repeat the process. If one electron knocks only two others out of their valence orbit during its travel through the *p* region, the numbers quickly multiply. As these high-energy electrons go through the depletion region, they have enough energy to go through the *n* region as conduction electrons, rather than combining with holes.

The multiplication of conduction electrons just discussed is known as **avalanche** and results in a very high reverse current that can damage the diode because of excessive heat dissipation.

SECTION 1–7 REVIEW

1. Describe forward bias of a diode.
2. Explain how to forward-bias a diode.
3. Describe reverse bias of a diode.
4. Explain how to reverse-bias a diode.
5. Compare the depletion regions in forward bias and reverse bias.
6. Which bias condition produces majority carrier current?
7. How is reverse current in a diode produced?
8. When does reverse breakdown occur in a diode?
9. Define *avalanche* as applied to diodes.

1–8 VOLTAGE-CURRENT CHARACTERISTIC OF A DIODE

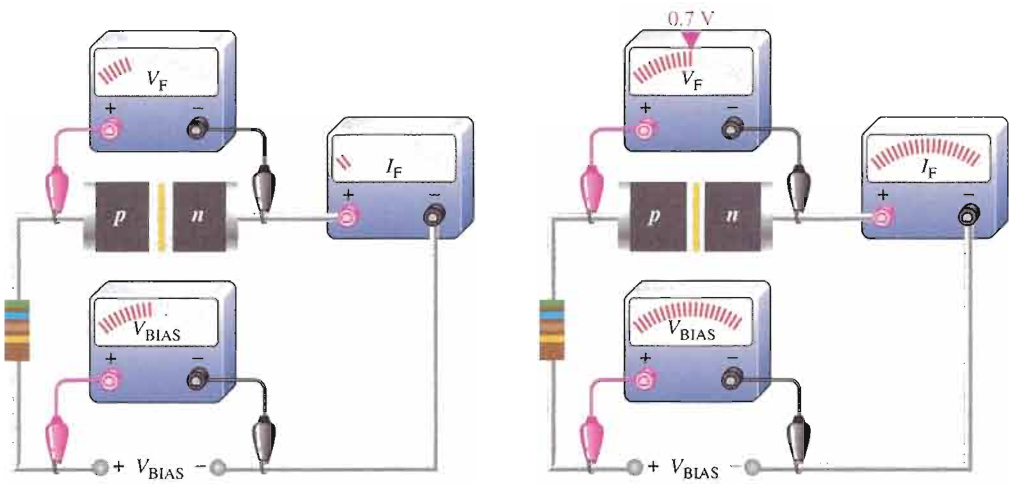
As you have learned, forward bias produces current through a diode and reverse bias essentially prevents current, except for a negligible reverse current. Reverse bias prevents current as long as the reverse-bias voltage does not equal or exceed the breakdown voltage of the junction. In this section, we will examine more closely the relationship between the voltage and the current in a diode on a graphical basis.

After completing this section, you should be able to

- **Analyze the voltage-current (*V-I*) characteristic curve of a diode**
- Explain the forward-bias portion of the *V-I* characteristic curve
- Explain the reverse-bias portion of the *V-I* characteristic curve
- Identify the barrier potential
- Identify the breakdown voltage
- Discuss temperature effects on a diode

V-I Characteristic for Forward Bias

When a forward-bias voltage is applied across a diode, there is current. This current is called the *forward current* and is designated I_F. Figure 1–26 illustrates what happens as the forward-bias voltage is increased positively from 0 V. The resistor is used to limit the forward current to a value that will not overheat the diode and cause damage.



(a) Small forward-bias voltage ($V_F < 0.7$ V), very small forward current.

(b) Forward voltage reaches and remains at approximately 0.7 V. Forward current continues to increase as the bias voltage is increased.

FIGURE 1–26

Forward-bias measurements show general changes in V_F and I_F as V_{BIAS} is increased.

With 0 V across the diode, there is no forward current. As you gradually increase the forward-bias voltage, the forward current *and* the voltage across the diode gradually increase, as shown in Figure 1–26(a). A portion of the forward-bias voltage is dropped across the limiting resistor. When the forward-bias voltage is increased to a value where the voltage across the diode reaches approximately 0.7 V (barrier potential), the forward current begins to increase rapidly, as illustrated in Figure 1–26(b).

As you continue to increase the forward-bias voltage, the current continues to increase very rapidly, but the voltage across the diode increases only gradually above 0.7 V. This small increase in the diode voltage above the barrier potential is due to the voltage drop across the internal dynamic resistance of the semiconductive material.

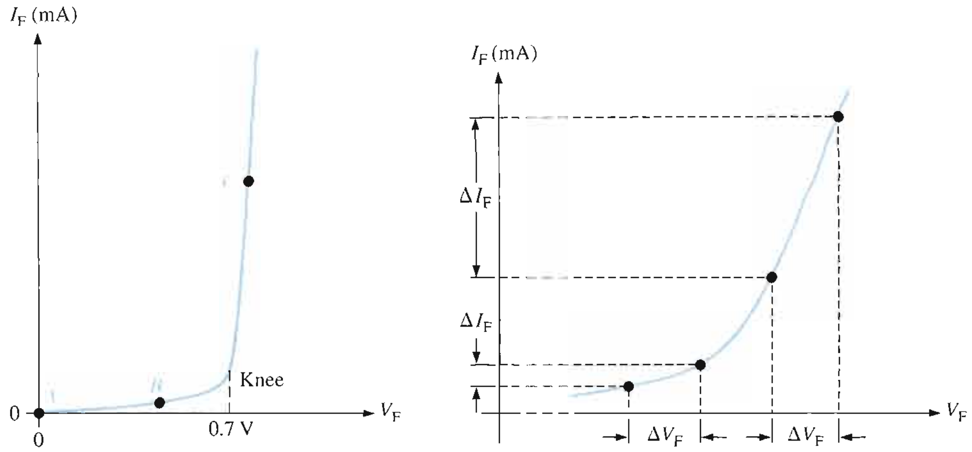
Graphing the V-I Curve If you plot the results of the type of measurements shown in Figure 1–26 on a graph, you get the ***V-I* characteristic** curve for a forward-biased diode, as shown in Figure 1–27(a). The diode forward voltage (V_F) increases to the right along the horizontal axis, and the forward current (I_F) increases upward along the vertical axis.

As you can see in Figure 1–27(a), the forward current increases very little until the forward voltage across the *pn* junction reaches approximately 0.7 V at the knee of the curve. After this point, the forward voltage remains at approximately 0.7 V, but I_F increases rapidly. As previously mentioned, there is a slight increase in V_F above 0.7 V as the current increases due mainly to the voltage drop across the dynamic resistance. *Normal operation for a forward-biased diode is above the knee of the curve.* The I_F scale is typically in mA, as indicated.

Three points *A*, *B*, and *C* are shown on the curve in Figure 1–27(a). Point *A* corresponds to a zero-bias condition. Point *B* corresponds to Figure 1–26(a) where the forward voltage is less than the barrier potential of 0.7 V. Point *C* corresponds to Figure 1–26(a) where the

FIGURE 1–27

Relationship of voltage and current in a forward-biased diode.



(a) *V-I* characteristic curve for forward bias.

(b) Expanded view of a portion of the curve in part (a). The dynamic resistance r'_d decreases as you move up the curve, as indicated by the decrease in the value of $\Delta V_F/\Delta I_F$.

forward voltage *approximately* equals the barrier potential. As the external bias voltage and forward current continue to increase above the knee, the forward voltage will increase slightly above 0.7 V. In reality, the forward voltage can be as much as approximately 0.90 V, depending on the forward current.

Dynamic Resistance Figure 1–27(b) is an expanded view of the *V-I* characteristic curve in part (a) and illustrates dynamic resistance. Unlike a linear resistance, the resistance of the forward-biased diode is not constant over the entire curve. Because the resistance changes as you move along the *V-I* curve, it is called *dynamic* or *ac resistance*. Internal resistances of electronic devices are usually designated by lowercase italic r with a prime, instead of the standard R. The dynamic resistance of a diode is designated r'_d.

Below the knee of the curve the resistance is greatest because the current increases very little for a given change in voltage ($r'_d = \Delta V_F/\Delta I_F$). The resistance begins to decrease in the region of the knee of the curve and becomes smallest above the knee where there is a large change in current for a given change in voltage.

V-I Characteristic for Reverse Bias

When a reverse-bias voltage is applied across a diode, there is only an extremely small reverse current (I_R) through the *pn* junction. With 0 V across the diode, there is no reverse current. As you gradually increase the reverse-bias voltage, there is a very small reverse current and the voltage across the diode increases. When the applied bias voltage is increased to a value where the reverse voltage across the diode (V_R) reaches the breakdown value (V_{BR}), the reverse current begins to increase rapidly.

As you continue to increase the bias voltage, the current continues to increase very rapidly, but the voltage across the diode increases very little above V_{BR}. *Breakdown, with exceptions, is not a normal mode of operation for most pn junction devices.*

Graphing the V-I Curve If you plot the results of reverse-bias measurements on a graph, you get the *V-I* characteristic curve for a reverse-biased diode. A typical curve is shown in Figure 1–28. The diode reverse voltage (V_R) increases to the left along the horizontal axis, and the reverse current (I_R) increases downward along the vertical axis.

There is very little reverse current (usually μA or nA) until the reverse voltage across the diode reaches approximately the breakdown value (V_{BR}) at the knee of the curve. After this

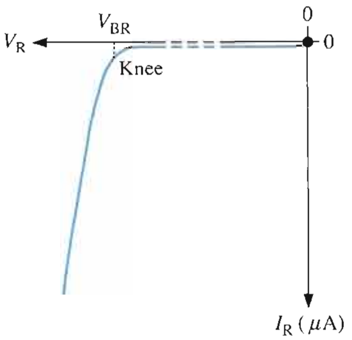


FIGURE 1–28

V-I characteristic curve for a reverse-biased diode.

point, the reverse voltage remains at approximately V_{BR}, but I_R increases very rapidly, resulting in overheating and possible damage. The breakdown voltage for a typical silicon diode can vary, but a minimum value of 50 V is not unusual.

The Complete *V-I* Characteristic Curve

Combine the curves for both forward bias and reverse bias, and you have the complete *V-I* characteristic curve for a diode, as shown in Figure 1–29. Notice that the I_F scale is in mA compared to the I_R scale in μA.

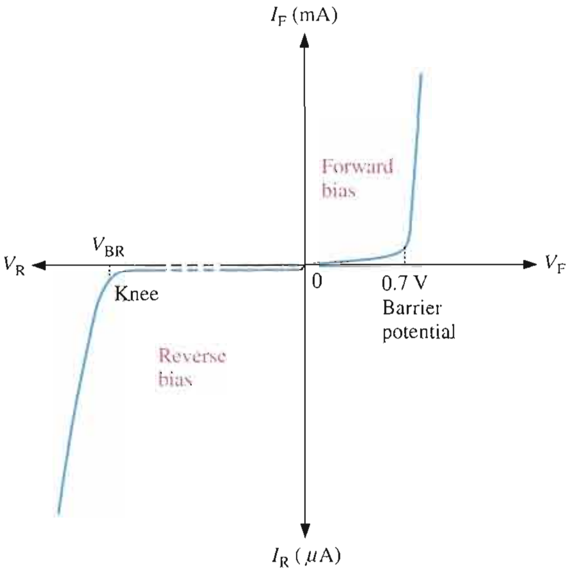


FIGURE 1–29

The complete *V-I* characteristic curve for a diode.

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 1–30. The blue curve is at room temperature (25°C) and the red curve is at an elevated temperature (25°C + ΔT). Notice that the barrier potential decreases as temperature increases.

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 1–30 for illustration. Keep in mind that the reverse current below breakdown remains extremely small and can usually be neglected.

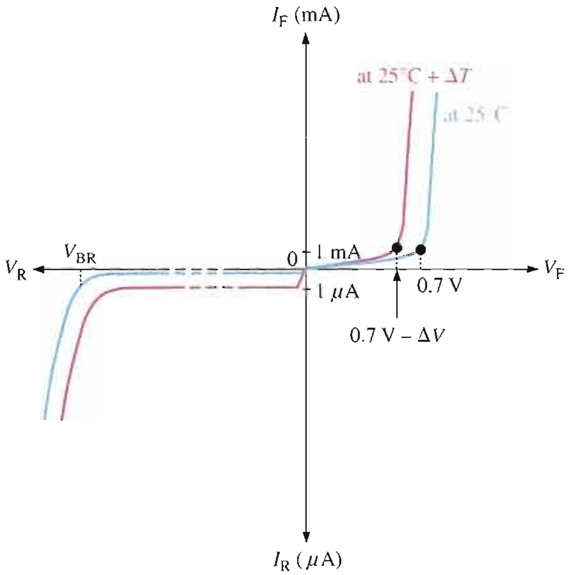


FIGURE 1–30

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).