2–1 DIODE OPERATION

Similar to the solar cell in Chapter 1, a diode is a two-terminal semiconductor device formed by two doped regions of silicon separated by a *pn* junction. In this chapter, the most common category of diode, known as the general-purpose diode, is covered. Other names, such as rectifier diode or signal diode, depend on the particular type of application for which the diode was designed. You will learn how to use a voltage to cause the diode to conduct current in one direction and block it in the other direction. This process is called *biasing*.

After completing this section, you should be able to

- **Use a diode in common applications**
- Recognize the electrical symbol for a diode and several diode package configurations
- Apply forward bias to a diode
  ◆ Define *forward bias* and state the required conditions ◆ Discuss the effect of forward bias on the depletion region ◆ Define *barrier potential* and its effects during forward bias
- Reverse-bias a diode
  ◆ Define *reverse bias* and state the required conditions ◆ Discuss reverse current and reverse breakdown

The Diode

As mentioned, a **diode** is made from a small piece of semiconductor material, usually silicon, in which half is doped as a *p* region and half is doped as an *n* region with a *pn* junction and depletion region in between. The *p* region is called the **anode** and is connected to a conductive terminal. The *n* region is called the **cathode** and is connected to a second conductive terminal. The basic diode structure and schematic symbol are shown in Figure 2–1.

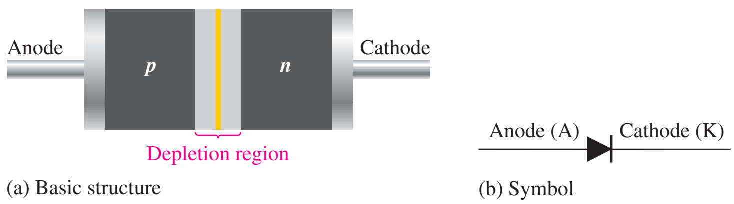


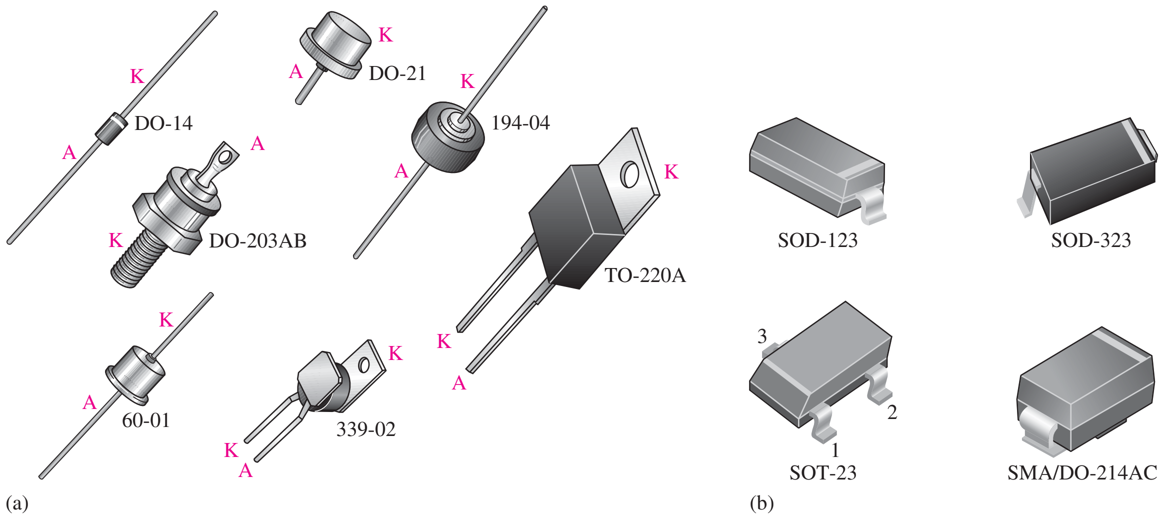
FIGURE 2–1
The diode.

Typical Diode Packages Several common physical configurations of through-hole mounted diodes are illustrated in Figure 2–2(a). The anode (A) and cathode (K) 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.

Surface-Mount Diode Packages Figure 2–2(b) shows typical diode packages for surface mounting on a printed circuit board. The SOD and SOT packages have gull-wing shaped leads. The SMA package has L-shaped leads that bend under the package. The SOD and SMA types have a band on one end to indicate the cathode. The SOT type is a three-terminal package in which there are either one or two diodes. In a single-diode SOT package, pin 1 is usually the anode and pin 3 is the cathode. In a dual-diode SOT package, pin 3 is the common terminal and can be either the anode or the cathode. Always check the datasheet for the particular diode to verify the pin configurations.

GREENTECH NOTE

The diodes covered in this chapter are based on the *pn* junction just like the solar cell, also known as the photovoltaic cell or PV cell, that was introduced in Chapter 1. A solar cell is basically a diode with a different geometric construction than rectifier and signal diodes. The *p* and *n* regions in the solar cell are much thinner to allow light energy to activate the photovoltaic effect, and a solar cell's exposed surface is transparent.



▲ **FIGURE 2–2**

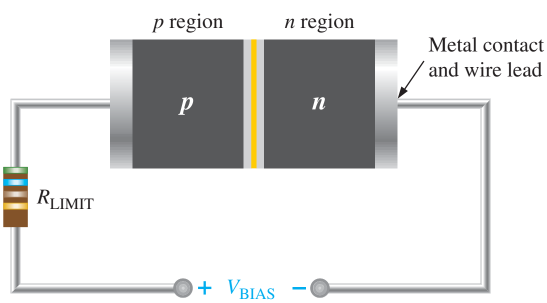
Typical diode packages with terminal identification. The letter K is used for cathode to avoid confusion with certain electrical quantities that are represented by *C*. Case type numbers are indicated for each diode.

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 2–3 shows a dc voltage source connected by conductive material (contacts and wire) across a diode in the direction to produce forward bias. This external bias voltage is designated as V_{BIAS}. The resistor limits the forward current to a value that will not damage the diode. Notice that the negative side of V_{BIAS} is connected to the *n* region of the diode and the positive side is connected to the *p* region. This is one requirement for forward bias. A second requirement is that the bias voltage, V_{BIAS}, must be greater than the **barrier potential**.

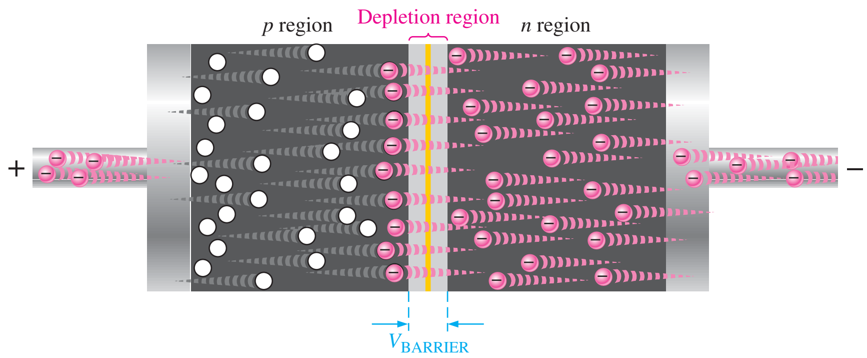
▶ **FIGURE 2–3**

A diode connected for forward bias.



A fundamental picture of what happens when a diode is forward-biased is shown in Figure 2–4. Because like charges repel, the negative side of the bias-voltage source “pushes” the free electrons, which are the majority carriers in the *n* region, toward the *pn* junction. This flow of free electrons is called *electron current.* The negative side of the source also provides a continuous flow of electrons through the external connection (conductor) and into the *n* region as shown.

The bias-voltage source imparts sufficient energy to the free electrons for them to overcome the barrier potential of the depletion region and move on through into the *p* region. Once in the *p* region, these conduction electrons have lost enough energy to immediately combine with holes in the valence band.



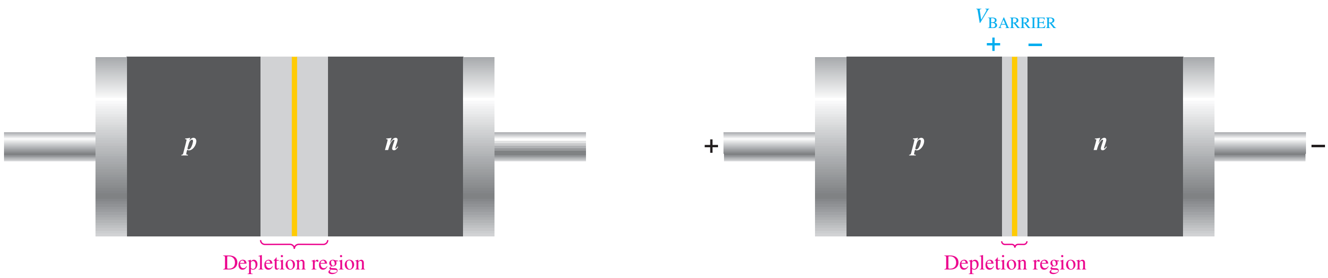
▲ FIGURE 2–4

A forward-biased diode showing the flow of majority carriers and the voltage due to the barrier potential across the depletion region.

Now, the electrons are in the valence band in the *p* region, simply because they have lost too much energy overcoming the barrier potential to remain in the conduction band. Since unlike charges attract, the positive side of the bias-voltage source attracts the valence electrons toward the left end of the *p* region. The holes in the *p* region provide the medium or "pathway" for these valence electrons to move through the *p* region. The valence electrons move from one hole to the next toward the left. The holes, which are the majority carriers in the *p* region, effectively (not actually) move to the right toward the junction, as you can see in Figure 2–4. This *effective* flow of holes is the hole current. You can also view the hole current as being created by the flow of valence electrons through the *p* region, with the holes providing the only means for these electrons to flow.

As the electrons flow out of the *p* region through the external connection (conductor) and to the positive side of the bias-voltage source, they leave holes behind in the *p* region; at the same time, these electrons become conduction electrons in the metal conductor. Recall that the conduction band in a conductor overlaps the valence band so that it takes much less energy for an electron to be a free electron in a conductor than in a semiconductor and that metallic conductors do not have holes in their structure. There is a continuous availability of holes effectively moving toward the *pn* junction to combine with the continuous stream of electrons as they come across the junction into the *p* region.

The Effect of Forward Bias on the Depletion Region As more electrons flow into the depletion region, the number of positive ions is reduced. As more holes effectively flow into the depletion region on the other side of the *pn* junction, the number of negative ions is reduced. This reduction in positive and negative ions during forward bias causes the depletion region to narrow, as indicated in Figure 2–5.



(a) At equilibrium (no bias)

(b) Forward bias narrows the depletion region and produces a voltage drop across the *pn* junction equal to the barrier potential.

▲ FIGURE 2–5

The depletion region narrows and a voltage drop is produced across the *pn* junction when the diode is forward-biased.

The Effect of the Barrier Potential During Forward Bias Recall that the electric field between the positive and negative ions in the depletion region on either side of the junction creates an "energy hill" that prevents free electrons from diffusing across the junction at equilibrium. This is known as the *barrier potential.*

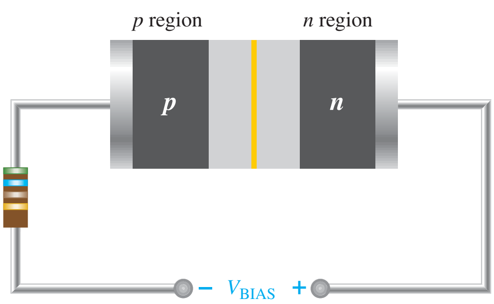
When forward bias is applied, the free electrons are provided with enough energy from the bias-voltage source to overcome the barrier potential and effectively "climb the energy hill" and cross the depletion region. The energy that the electrons require in order to pass through the depletion region is equal to the barrier potential. In other words, the electrons give up an amount of energy equivalent to the barrier potential when they cross the depletion region. This energy loss results in a voltage drop across the *pn* junction equal to the barrier potential (0.7 V), as indicated in Figure 2–5(b). An additional small voltage drop occurs across the *p* and *n* regions due to the internal resistance of the material. For doped semiconductive material, this resistance, called the **dynamic resistance,** is very small and can usually be neglected. This is discussed in more detail in Section 2–2.

Reverse Bias

Reverse bias is the condition that essentially prevents current through the diode. Figure 2–6 shows a dc voltage source connected across a diode in the direction to produce reverse bias. This external bias voltage is designated as V_{BIAS} just as it was for forward bias. Notice that the positive side of V_{BIAS} is connected to the *n* region of the diode and the negative side is connected to the *p* region. Also note that the depletion region is shown much wider than in forward bias or equilibrium.

▶ FIGURE 2–6

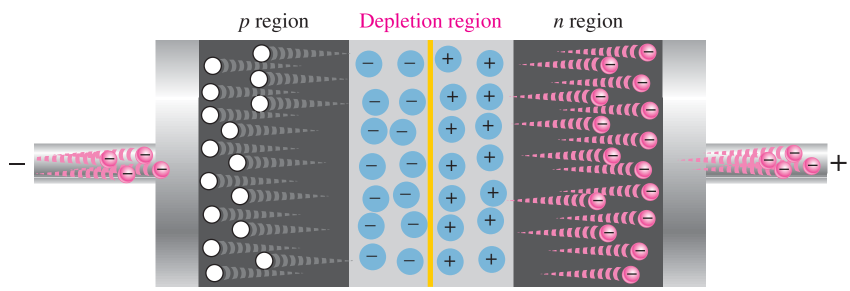
A diode connected for reverse bias. A limiting resistor is shown although it is not important in reverse bias because there is essentially no current.



An illustration of what happens when a diode is reverse-biased is shown in Figure 2–7. Because unlike charges attract, the positive side of the bias-voltage source "pulls" the free electrons, which are the majority carriers in the *n* region, away from the *pn* junction. As the electrons flow toward the positive side of the voltage source, additional positive ions are created. This results in a widening of the depletion region and a depletion of majority carriers.

▶ FIGURE 2–7

The diode during the short transition time immediately after reverse-bias voltage is applied.

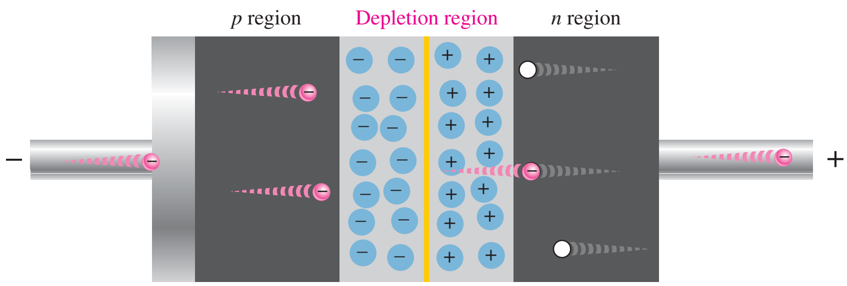


In the *p* region, electrons from the negative side of the voltage source enter as valence electrons and move from hole to hole toward the depletion region where they create additional negative ions. This results in a widening of the depletion region and a depletion of majority carriers. The flow of valence electrons can be viewed as holes being "pulled" toward the positive side.

The initial flow of charge carriers is transitional and lasts for only a very short time after the reverse-bias voltage is applied. As the depletion region widens, the availability of majority carriers decreases. As more of the *n* and *p* regions become depleted of majority carriers, the electric field between the positive and negative ions increases in strength until the potential across the depletion region equals the bias voltage, V_{BIAS}. At this point, the transition current essentially ceases except for a very small reverse current that can usually be neglected.

Reverse Current The extremely small current that exists in reverse bias after the transition current dies out is caused by the minority carriers in the *n* and *p* regions that are produced by thermally generated electron-hole pairs. The small number of free minority electrons in the *p* region are "pushed" toward the *pn* junction by the negative bias voltage. When these electrons reach the wide depletion region, they "fall down the energy hill" and combine with the minority holes in the *n* region as valence electrons and flow toward the positive bias voltage, creating a small hole current.

The conduction band in the *p* region is at a higher energy level than the conduction band in the *n* region. Therefore, the minority electrons easily pass through the depletion region because they require no additional energy. Reverse current is illustrated in Figure 2–8.



◄ FIGURE 2–8

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

Reverse Breakdown Normally, the reverse current is so small that it can be neglected. However, if the external reverse-bias voltage is increased to a value called the *breakdown voltage,* the reverse current will drastically increase.

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 the **avalanche effect,** and reverse current can increase dramatically if steps are not taken to limit the current. When the reverse current is not limited, the resulting heating will permanently damage the diode. Most diodes are not operated in reverse breakdown, but if the current is limited (by adding a series-limiting resistor for example), there is no permanent damage to the diode.

SECTION 2–1 CHECKUP
Answers can be found at www.pearsonhighered.com/floyd.

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 effect* as applied to diodes.

2–2 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 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 of a diode**
- Explain the *V-I* characteristic for forward bias
  - ◆ Graph the *V-I* curve for forward bias ◆ Describe how the barrier potential affects the *V-I* curve ◆ Define *dynamic resistance*
- Explain the *V-I* characteristic for reverse bias
  - ◆ Graph the *V-I* curve for reverse bias
- Discuss the complete *V-I* characteristic curve
  - ◆ Describe the effects of temperature on the diode characteristic

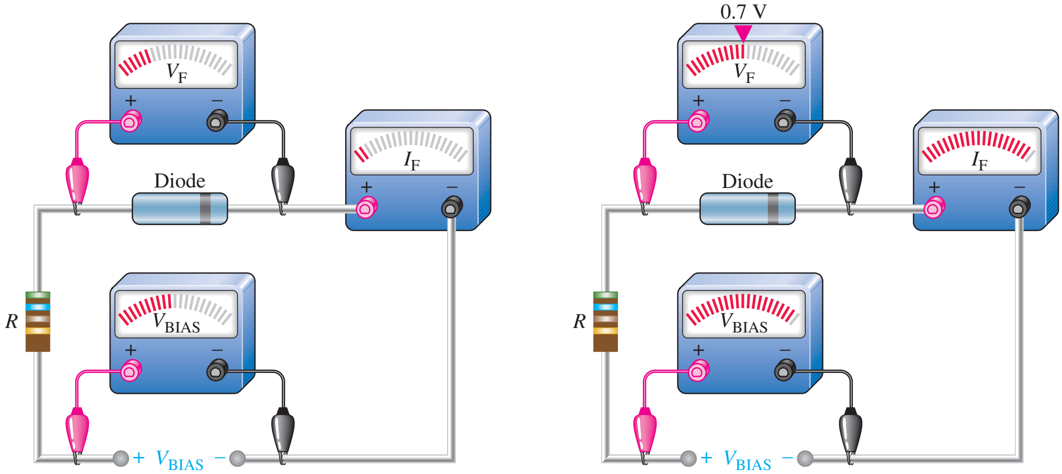
V-I Characteristic for Forward Bias

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 2–9 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.

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 2–9(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 2–9(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 2–9 on a graph, you get the ***V-I* characteristic** curve for a forward-biased diode, as shown in Figure 2–10(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.

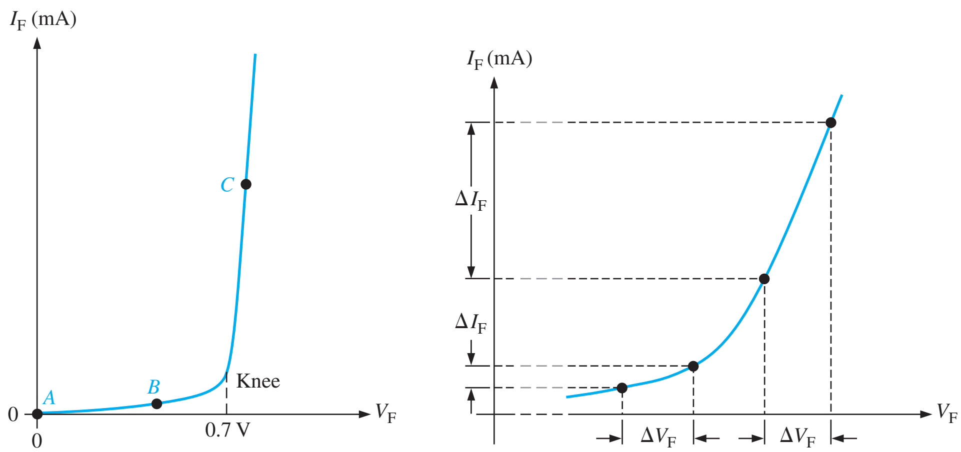


(a) Small forward-bias voltage ($V_F < 0.7$ V), very small forward current.

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

▲ **FIGURE 2–9**

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



(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 $\Delta V_F/\Delta I_F$.

◀ **FIGURE 2–10**

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

As you can see in Figure 2–10(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 nearly constant 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. The I_F scale is typically in mA, as indicated.

Three points *A*, *B*, and *C* are shown on the curve in Figure 2–10(a). Point *A* corresponds to a zero-bias condition. Point *B* corresponds to Figure 2–10(a) where the forward voltage is less than the barrier potential of 0.7 V. Point *C* corresponds to Figure 2–10(a) where the 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 1 V, depending on the forward current.

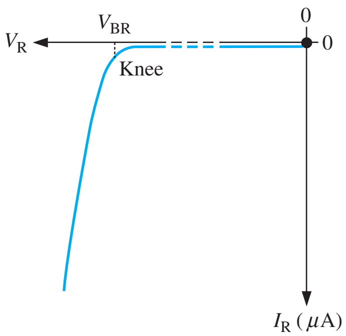
Dynamic Resistance Figure 2–10(b) is an expanded view of the *V-I* characteristic curve in part (a) and illustrates dynamic resistance. Unlike a linear resistance, the resistance of the forward-biased diode is not constant over the entire curve. Because the resistance changes as you move along the *V-I* 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.



▲ FIGURE 2–11

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

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 2–11. 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.

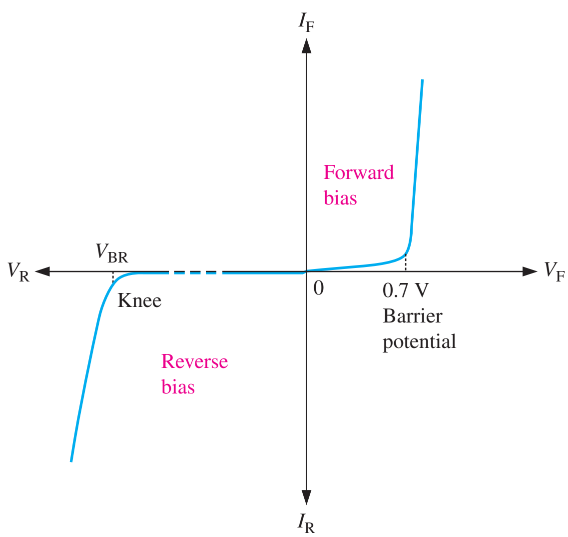
There is very little reverse current (usually μA or nA) until the reverse voltage across the diode reaches approximately the breakdown value (V_{BR}) at the knee of the curve. After this point, the reverse voltage remains at approximately V_{BR}, but I_R increases very rapidly, resulting in overheating and possible damage if current is not limited to a safe level. The breakdown voltage for a diode depends on the doping level, which the manufacturer sets, depending on the type of diode. A typical rectifier diode (the most widely used type) has a breakdown voltage of greater than 50 V. Some specialized diodes have a breakdown voltage that is only 5 V.

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 2–12.

▶ FIGURE 2–12

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 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.

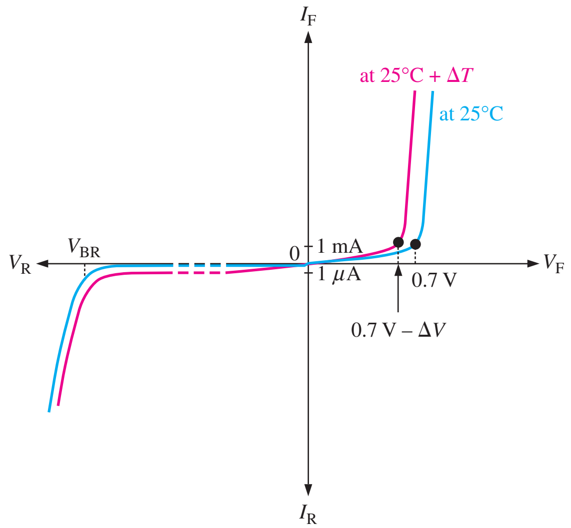


FIGURE 2–13

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

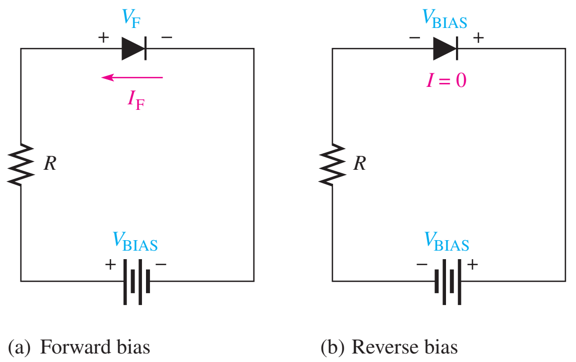
- **Explain how the three diode models differ**
- Discuss bias connections
- Describe the diode approximations
  - Describe the ideal diode model
  - Describe the practical diode model
  - Describe the complete diode model

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

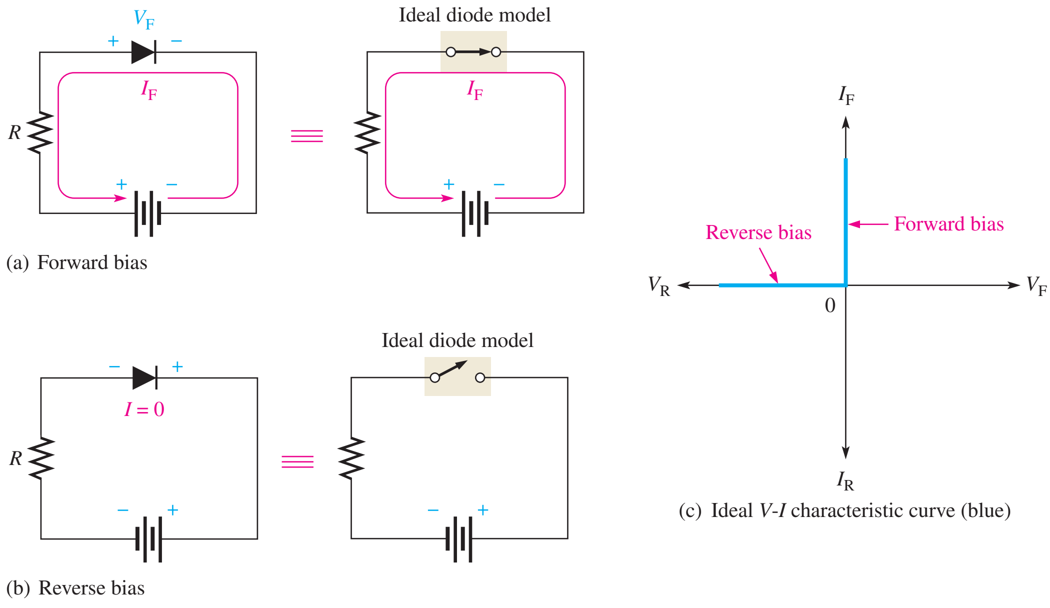
Forward-bias and reverse-bias connections showing the diode symbol.



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.

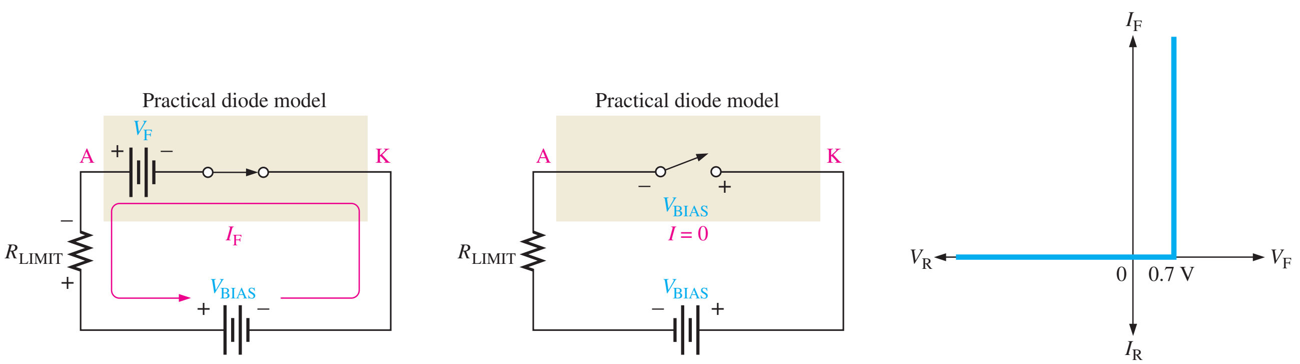
$$I_R = 0\text{ A}$$

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.



(a) Forward bias (b) Reverse bias (c) Characteristic curve (silicon)

▲ 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

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

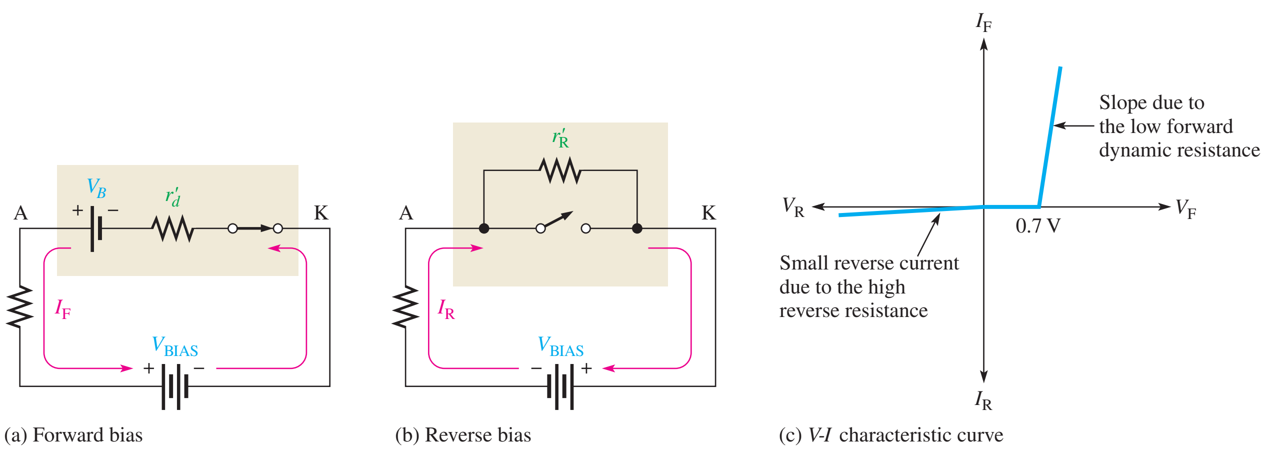
The diode is assumed to have zero reverse current, as indicated by the portion of the curve on the negative horizontal axis.

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

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.



▲ 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:

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

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

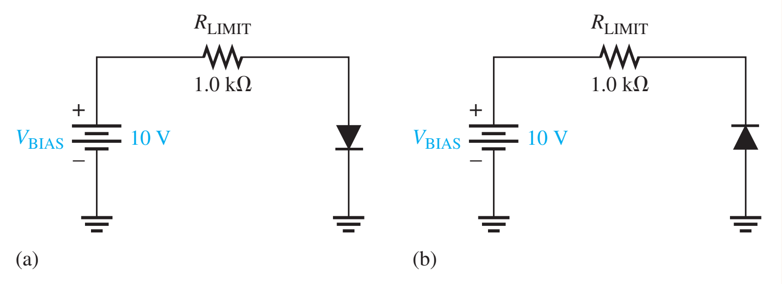
The reverse current is taken into account with the parallel resistance and is indicated by the portion of the curve to the left of the origin. The breakdown portion of the curve is not shown because breakdown is not a normal mode of operation for most diodes.

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 $I_R = 1\ \mu\text{A}$.



▲ 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?

*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