Of the many applications of diodes, their use in the design of rectifiers (which convert ac to dc) is the most common. Therefore we shall study rectifier circuits in some detail and briefly look at a number of other diode applications. Further nonlinear circuits that utilize diodes and other devices will be found throughout the book, but particularly in Chapter 11.

The junction diode is nothing more than the *pn* junction we studied in Chapter 1, and most of this chapter is concerned with the study of silicon *pn*-junction diodes. In the last section, however, we briefly consider some specialized diode types, including the photodiode and the light-emitting diode.

2.1 THE IDEAL DIODE

2.1.1 Current–Voltage Characteristic

The ideal diode may be considered the most fundamental nonlinear circuit element. It is a two-terminal device having the circuit symbol of Fig. 2.1(a) and the *i–v* characteristic shown in Fig. 2.1(b). The terminal characteristic of the ideal diode can be interpreted as follows: If a negative voltage (relative to the reference direction indicated in Fig. 2.1a) is applied to the diode no current flows and the diode behaves as an open circuit (Fig. 2.1c). Diodes operated in this mode are said to be **reverse biased,** or operated in the reverse direction. An ideal diode has zero current when operated in the reverse direction and is said to be **cut off,** or simply off.

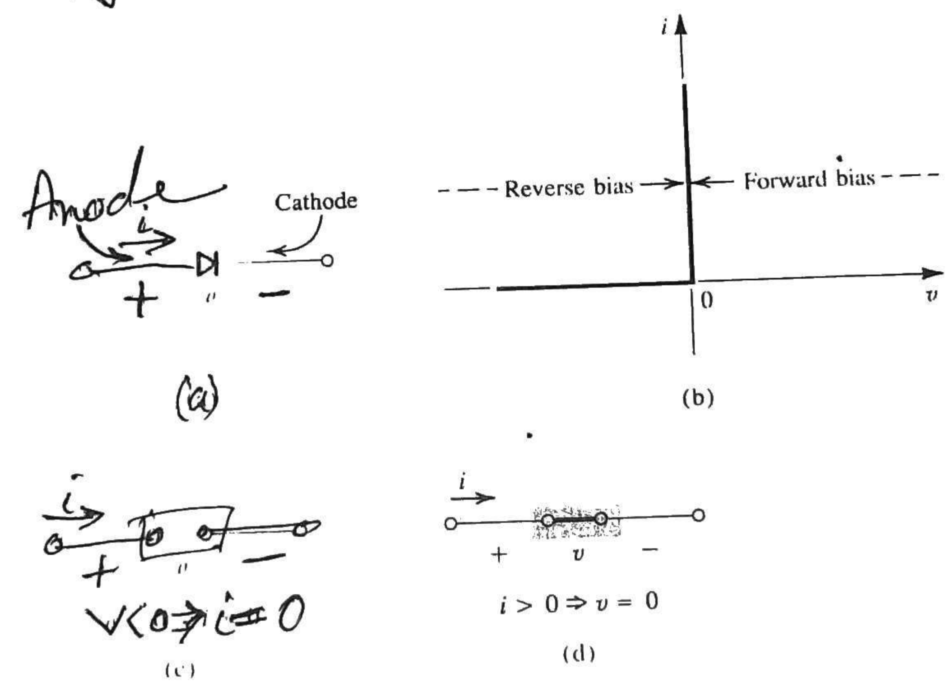

FIGURE 2.1 The ideal diode: (a) diode circuit symbol; (b) *i–v* characteristic; (c) equivalent circuit in the reverse direction; (d) equivalent circuit in the forward direction.

On the other hand, if a positive current (relative to the reference direction indicated in Fig. 2.1a) is applied to the ideal diode, zero voltage drop appears across the diode. In other words, the ideal diode behaves as a short circuit in the *forward* direction (Fig. 2.1d); it passes any current with zero voltage drop. A **forward-biased** diode is said to be **turned on,** or simply **on.**

From the above description it should be noted that the external circuit must be designed to limit the forward current through a conducting diode, and the reverse voltage across a cutoff diode, to predetermined values. Figure 2.2 shows two diode circuits that illustrate this point. In the circuit of Fig. 2.2(a) the diode is obviously conducting. Thus its voltage drop will be zero, and the current through it will be determined by the +10-V supply and the 1-kΩ resistor as 10 mA. The diode in the circuit of Fig. 2.2(b) is obviously cut off, and thus its current will be zero, which in turn means that the entire 10-V supply will appear as reverse bias across the diode.

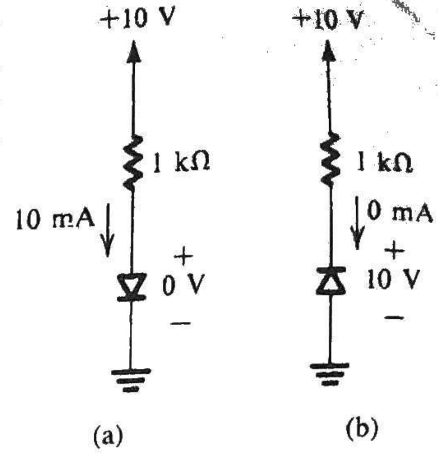

FIGURE 2.2 The two modes of operation of ideal diodes and the use of an external circuit to limit the forward current **(a)** and the reverse voltage **(b)**.

The positive terminal of the diode is called the **anode** and the negative terminal the **cathode,** a carryover from the days of vacuum-tube diodes. The *i–v* characteristic of the ideal diode (conducting in one direction and not in the other) should explain the choice of its arrow-like circuit symbol.

As should be evident from the preceding description, the *i–v* characteristic of the ideal diode is highly nonlinear; although it consists of two straight-line segments, they are at 90° to one another. A nonlinear curve that consists of straight-line segments is said to be **piecewise linear.** If a device having a piecewise-linear characteristic is used in a particular application in such a way that the signal across its terminals swings along only one of the linear segments, then the device can be considered a linear circuit element as far as that particular circuit application is concerned. On the other hand, if signals swing past one or more of the break points in the characteristic, linear analysis is no longer possible.

2.1.2 A Simple Application: The Rectifier

A fundamental application of the diode, one that makes use of its severely nonlinear *i–v* curve, is the rectifier circuit shown in Fig. 2.3(a). The circuit consists of the series connection of a diode D and a resistor R. Let the input voltage v_I be the sinusoid shown in Fig. 2.3(b), and assume the diode to be ideal. During the positive half-cycles of the input sinusoid, the positive v_I will cause current to flow through the diode in its forward direction. It follows that the diode voltage v_D will be very small—ideally zero. Thus the circuit will have the equivalent shown in Fig. 2.3(c), and the output voltage v_O will be equal to the input voltage v_I. On the other hand, during the negative half-cycles of v_I, the diode will not conduct. Thus the circuit will have the equivalent shown in Fig. 2.3(d), and v_O will be zero. Thus the output voltage will have the waveform shown in Fig. 2.3(e). Note that while v_I alternates in polarity and has a zero average value, v_O is unidirectional and has a finite average value or a *dc component*. Thus the circuit of Fig. 2.3(a) **rectifies** the signal and hence is called a **rectifier.** It can be used to generate dc from ac. We will study rectifier circuits in Section 2.5.

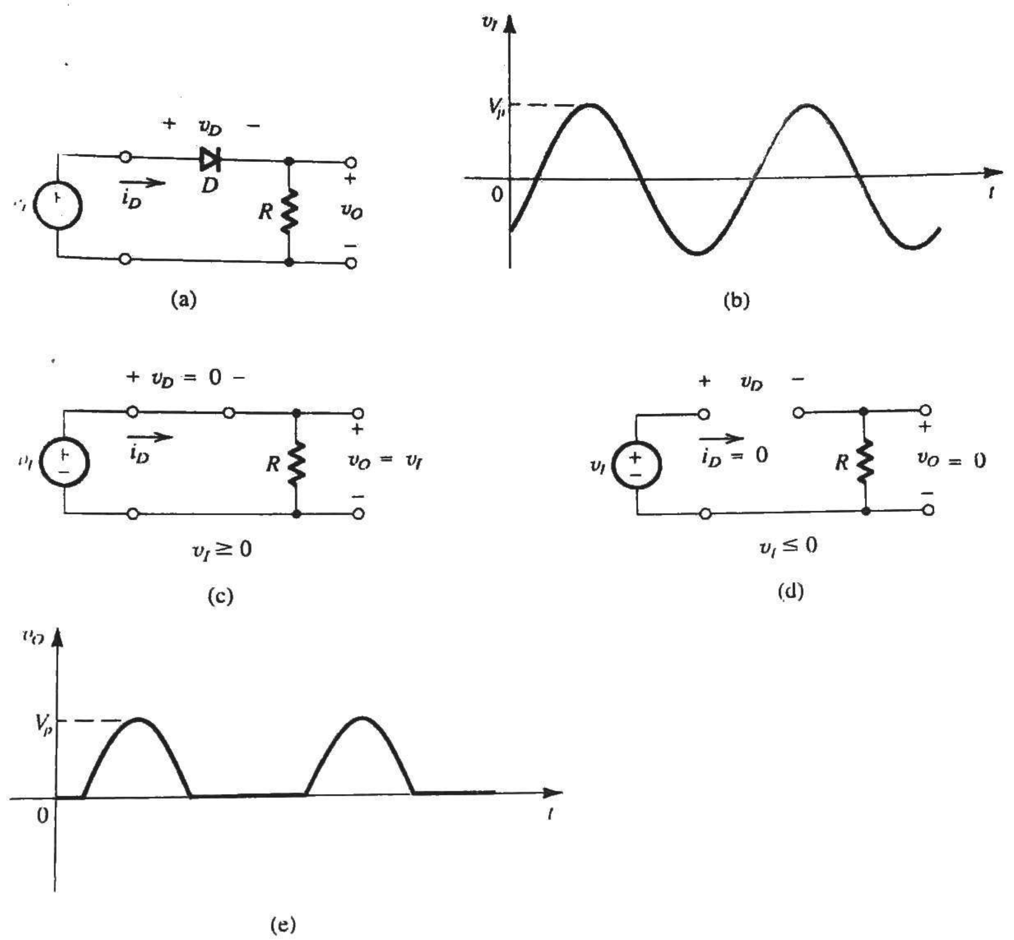

FIGURE 2.3 **(a)** Rectifier circuit. **(b)** Input waveform. **(c)** Equivalent circuit when $v_I \geq 0$. **(d)** Equivalent circuit when $v_I \leq 0$. **(e)** Output waveform.

EXERCISES

2.1 For the circuit in Fig. 2.3(a), sketch the transfer characteristic v_O versus v_I.

Ans. See Fig. E2.1.

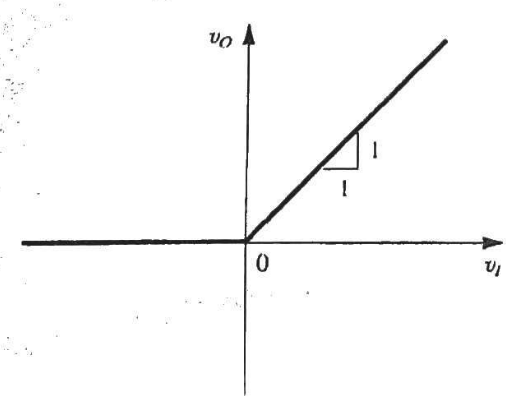

FIGURE E2.1

2.2 For the circuit in Fig. 2.3(a), sketch the waveform of v_D.
Ans. See Fig. E2.2.

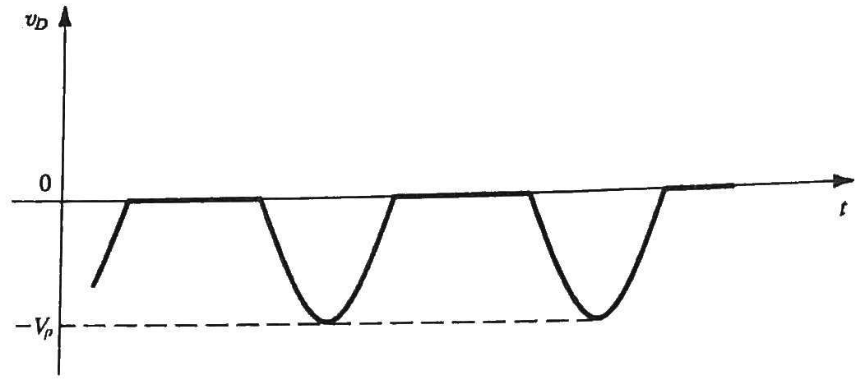

FIGURE E2.2

2.3 In the circuit of Fig. 2.3(a), let v_I have a peak value of 10 V and $R = 1$ kΩ. Find the peak value of i_D and the dc component of v_O.
Ans. 10 mA; 3.18 V

EXAMPLE 2.1

Figure 2.4(a) shows a circuit for charging a 12-V battery. If v_S is a sinusoid with 24-V peak amplitude, find the fraction of each cycle during which the diode conducts. Also, find the peak value of the diode current and the maximum reverse-bias voltage that appears across the diode.

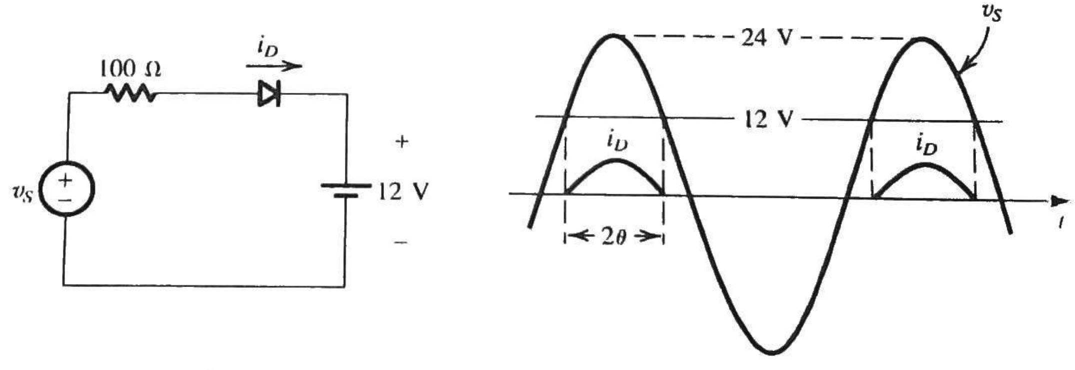

FIGURE 2.4 Circuit and waveforms for Example 2.1.

Solution

The diode conducts when v_S exceeds 12 V, as shown in Fig. 2.4(b). The conduction angle is 2θ, where θ is given by

$$24 \cos \theta = 12$$

Thus $\theta = 60°$ and the conduction angle is 120°, or one-third of a cycle.

The peak value of the diode current is given by

$$I_d = \frac{24 - 12}{100} = 0.12 \text{ A}$$

The maximum reverse voltage across the diode occurs when v_S is at its negative peak and is equal to 24 + 12 = 36 V.

2.1.3 Another Application: Diode Logic Gates

Diodes together with resistors can be used to implement digital logic functions. Figure 2.5 shows two diode logic gates. To see how these circuits function, consider a positive-logic system in which voltage values close to 0 V correspond to logic 0 (or low) and voltage values close to +5 V correspond to logic 1 (or high). The circuit in Fig. 2.5(a) has three inputs, v_A, v_B, and v_C. It is easy to see that diodes connected to +5 V inputs will conduct, thus clamping the output v_Y to a value equal to +5 V. This positive voltage at the output will keep the diodes whose inputs are low (around 0 V) cut off. Thus the output will be high if one or more of the inputs are high. The circuit therefore implements the **logic OR function,** which in Boolean notation is expressed as

$$Y = A + B + C$$

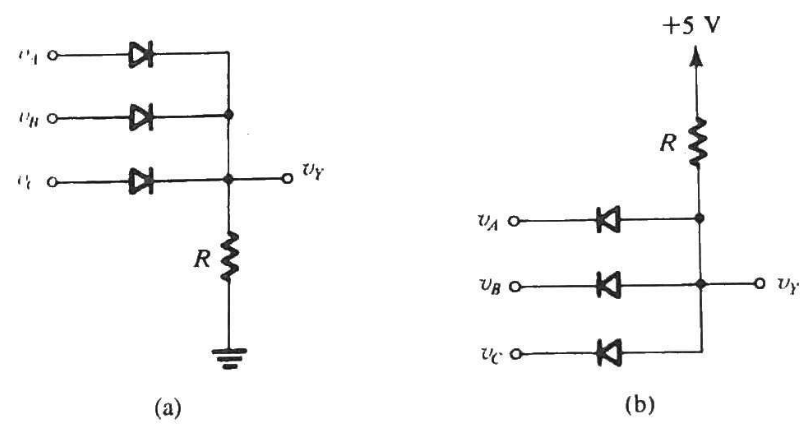

FIGURE 2.5 Diode logic gates: **(a)** OR gate; **(b)** AND gate (in a positive-logic system).

Similarly, the reader is encouraged to show that using the same logic system mentioned above, the circuit of Fig. 2.5(b) implements the **logic AND function,**

$$Y = A \cdot B \cdot C$$

EXAMPLE 2.2

Assuming the diodes to be ideal, find the values of I and V in the circuits of Fig. 2.6.

Solution

In these circuits it might not be obvious at first sight whether none, one, or both diodes are conducting. In such a case, we make a plausible assumption, proceed with the analysis, and then

$I = \frac{10-0}{10}$

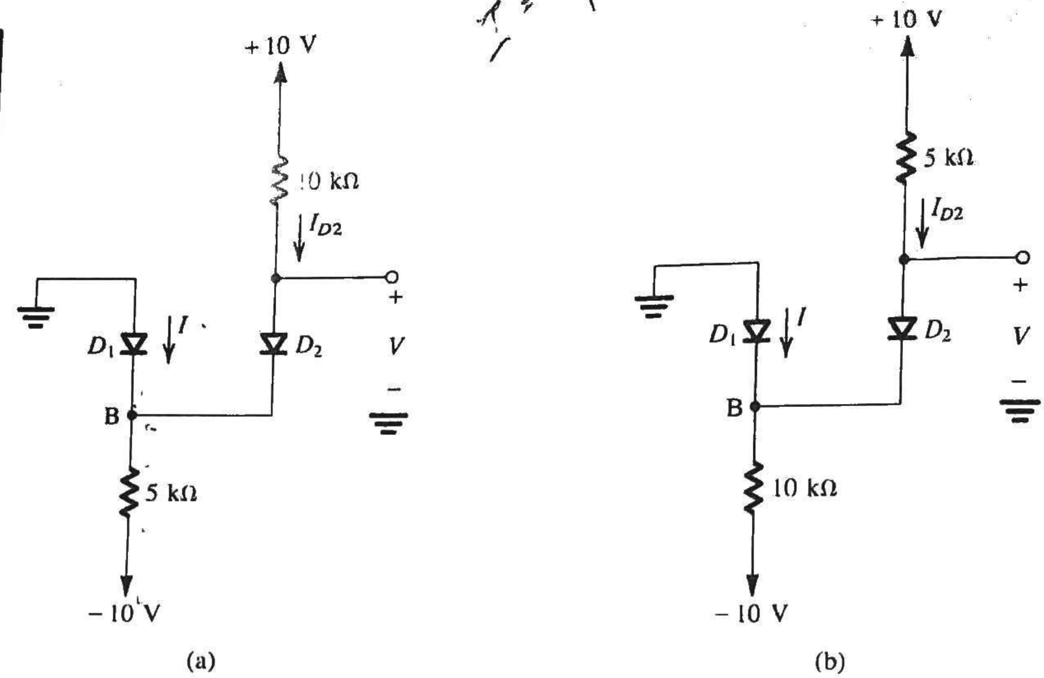

FIGURE 2.6 Circuits for Example 2.2.

check whether we end up with a consistent solution. For the circuit in Fig. 2.6(a), we shall assume that both diodes are conducting. It follows that $V_B = 0$ and $V = 0$. The current through D_2 can now be determined from

$$I_{D2} = \frac{10-0}{10} = 1 \text{ mA}$$

Writing a node equation at B,

$$I + 1 = \frac{0-(-10)}{5}$$

results in $I = 1$ mA. Thus D_1 is conducting as originally assumed, and the final result is $I = 1$ mA and $V = 0$ V.

For the circuit in Fig. 2.6(b), if we assume that both diodes are conducting, then $V_B = 0$ and $V = 0$. The current in D_2 is obtained from

$$I_{D2} = \frac{10-0}{5} = 2 \text{ mA}$$

The node equation at B is

$$I + 2 = \frac{0-(-10)}{10}$$

which yields $I = -1$ mA. Since this is not possible, our original assumption is not correct. We start again, assuming that D_1 is off and D_2 is on. The current I_{D2} is given by

$$I_{D2} = \frac{10-(-10)}{15} = 1.33 \text{ mA}$$

and the voltage at node B is

$$V_B = -10 + 10 \times 1.33 = +3.3 \text{ V}$$

Thus D_1 is reverse biased as assumed, and the final result is $I = 0$ and $V = 3.3$ V.

EXERCISES

2.4 Find the values of I and V in the circuits shown in Fig. E2.4.

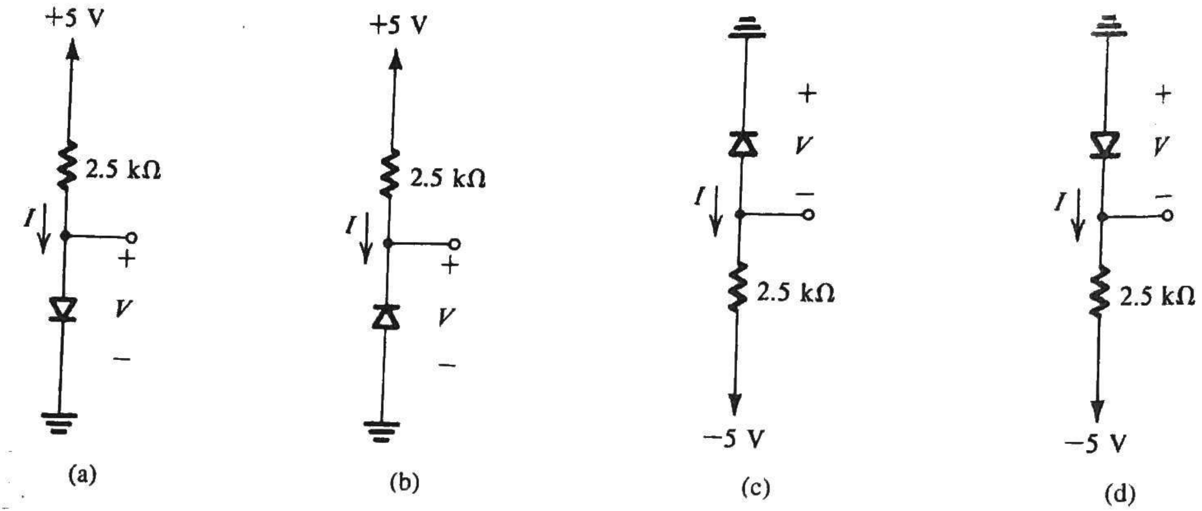

FIGURE E2.4

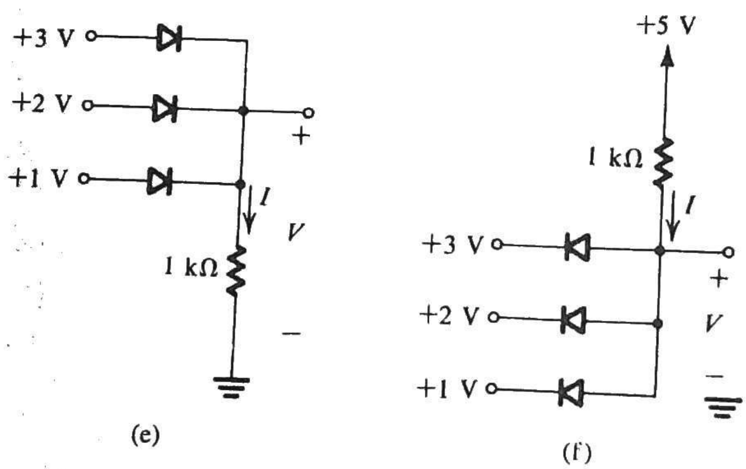

FIGURE E2.4 *(Continued)*

Ans. (a) 2 mA, 0 V; (b) 0 mA, 5 V; (c) 0 mA, 5 V; (d) 2 mA, 0 V; (e) 3 mA, +3 V; (f) 4 mA, +1 V.

2.5 Figure E2.5 shows a circuit for an ac voltmeter. It utilizes a moving-coil meter that gives a full-scale reading when the *average* current flowing through it is 1 mA. The moving-coil meter has a 50-Ω resistance.

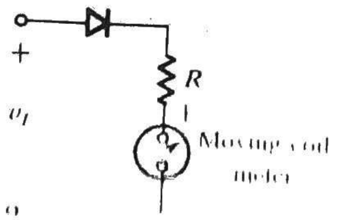

FIGURE E2.5

[illegible] when the input sine-wave [illegible] V_p/π.)

Ans. [illegible]

2.2 TERMINAL CHARACTERISTICS OF JUNCTION DIODES

The most common implementation of the diode utilizes a *pn* junction. We have studied the physics of the *pn* junction and derived its *i–v* characteristic in Chapter 1. That the *pn* junction is used to implement the diode function should come as no surprise: the *pn* junction can conduct substantial current in the forward direction and almost no current in the reverse direction. In this section we study the *i–v* characteristic of the *pn* junction diode in detail in order to prepare ourselves for diode circuit applications.

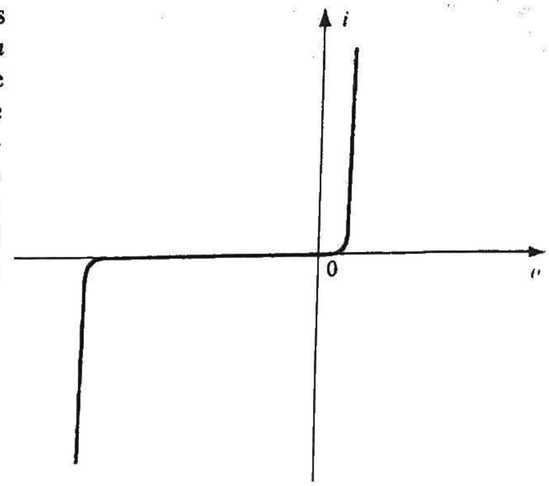

FIGURE 2.7 The *i–v* characteristic of a silicon junction diode.

Figure 2.7 shows the *i–v* characteristic of a silicon junction diode. The same characteristic is shown in Fig. 2.8 with some scales expanded and others compressed to reveal details. Note that the scale changes have resulted in the apparent discontinuity at the origin.

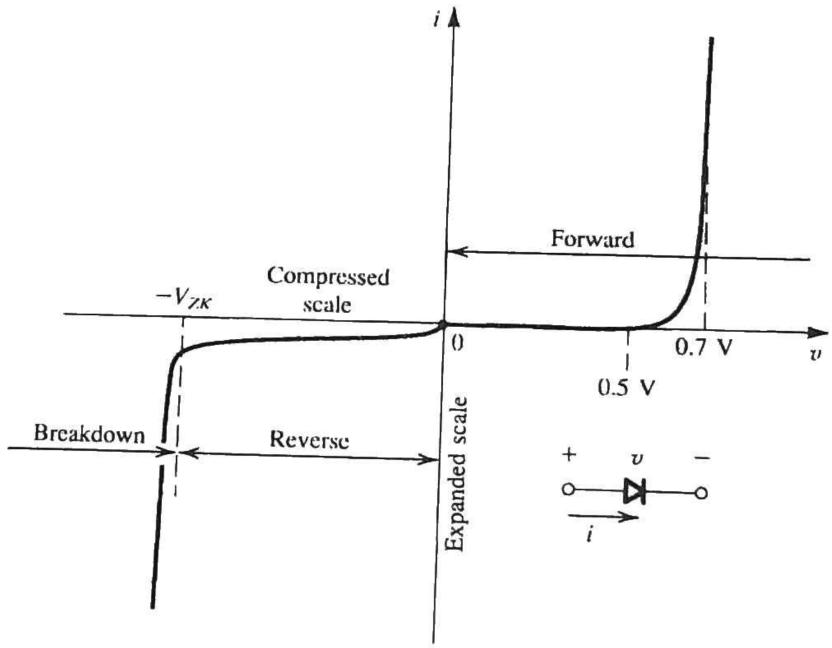

FIGURE 2.8 The diode *i–v* relationship with some scales expanded and others compressed in order to reveal details.

As indicated, the characteristic curve consists of three distinct regions:

1. The forward-bias region, determined by $v > 0$
2. The reverse-bias region, determined by $v < 0$
3. The breakdown region, determined by $v < -V_{ZK}$

These three regions of operation are described in the following sections.

2.2.1 The Forward-Bias Region

The forward-bias—or simply forward—region of operation is entered when the terminal voltage v is positive. In the forward region the i–v relationship is closely approximated by

$$i = I_S(e^{v/V_T} - 1) \tag{2.1}$$

In this equation[1] I_S is a constant for a given diode at a given temperature. A formula for I_S in terms of the diode's physical parameters and temperature has been given in Chapter 1. The current I_S is usually called the **saturation current** (for reasons that will become apparent shortly). Another name for I_S, and one that we will occasionally use, is the **scale current.** This name arises from the fact that I_S is directly proportional to the cross-sectional area of the diode. Thus doubling of the junction area results in a diode with double the value of I_S and, as the diode equation indicates, double the value of current i for a given forward voltage v. For "small-signal" diodes, which are small-size diodes intended for low-power applications, I_S is on the order of 10^{-15} A. The value of I_S is, however, a very strong function of temperature. As a rule of thumb, I_S doubles in value for every 5°C rise in temperature.

The voltage V_T in Eq. (2.1) is a constant called the **thermal voltage** and is given by

$$V_T = \frac{kT}{q} \tag{2.2}$$

where

k = Boltzmann's constant = 1.38×10^{-23} joules/kelvin

T = the absolute temperature in kelvins = 273 + temperature in °C

q = the magnitude of electronic charge = 1.60×10^{-19} coulomb

Substituting $k = 8.62 \times 10^{-5}$ eV/K into Eq. (2.2) gives

$$V_T = 0.0862T, \text{ mV} \tag{2.2a}$$

At room temperature (20°C) the value of V_T is 25.3 mV. In rapid approximate circuit analysis we shall use $V_T \simeq 25$ mV at room temperature.[2]

For appreciable current i in the forward direction, specifically for $i \gg I_S$, Eq. (2.1) can be approximated by the exponential relationship

$$i \simeq I_S e^{v/nV_T} \tag{2.3}$$

This relationship can be expressed alternatively in the logarithmic form

$$v = nV_T \ln \frac{i}{I_S} \tag{2.4}$$

where ln denotes the natural (base e) logarithm.

The exponential relationship of the current i to the voltage v holds over many decades of current (a span of as many as seven decades—i.e., a factor of 10^7—can be found). This is

---

[1] Equation (2.1), the diode equation, is sometimes written to include a constant n in the exponential,

$$i = I_S(e^{qv/nkT} - 1)$$

with n having a value between 1 and [illegible] depending on the material and the physical structure of the diode. [illegible]

[2] [illegible]

quite a remarkable property of junction diodes, one that is also found in bipolar junction transistors and that has been exploited in many interesting applications.

Let us consider the forward i–v relationship in Eq. (2.3) and evaluate the current I_1 corresponding to a diode voltage V_1:

$$I_1 = I_S e^{V_1/nV_T}$$

Similarly, if the voltage is V_2, the diode current I_2 will be

$$I_2 = I_S e^{V_2/nV_T}$$

These two equations can be combined to produce

$$\frac{I_2}{I_1} = e^{(V_2 - V_1)/nV_T}$$

which can be rewritten as

$$V_2 - V_1 = nV_T \ln \frac{I_2}{I_1}$$

or, in terms of base-10 logarithms,

$$V_2 - V_1 = 2.3nV_T \log \frac{I_2}{I_1} \tag{2.5}$$

This equation simply states that for a decade (factor of 10) change in current, the diode voltage drop changes by $2.3nV_T$, which is approximately 60 mV for $n = 1$ and 120 mV for $n = 2$. This also suggests that the diode i–v relationship is most conveniently plotted on semilog paper. Using the vertical, linear axis for v and the horizontal, log axis for i, one obtains a straight line with a slope of 60 mV per decade of current. Finally, it should be mentioned that not knowing the exact value of n (which can be obtained from a simple experiment), circuit designers use the convenient approximate number of 0.1 V/decade for the slope of the diode logarithmic characteristic.

A glance at the i–v characteristic in the forward region (Fig. 2.8) reveals that the current is negligibly small for v smaller than about 0.5 V. This value is usually referred to as the **cut-in voltage**. It should be emphasized, however, that this apparent threshold in the characteristic is simply a consequence of the exponential relationship. Another consequence of this relationship is the rapid increase of i. Thus, for a "fully conducting" diode, the voltage drop lies in a narrow range, approximately 0.6 V to 0.8 V. This gives rise to a simple "model" for the diode where it is assumed that a conducting diode has approximately a 0.7-V drop across it. Diodes with different current ratings (i.e., different areas and correspondingly different I_S) will exhibit the 0.7-V drop at different currents. For instance, a small-signal diode may be considered to have a 0.7-V drop at $i = 1$ mA, while a higher-power diode may have a 0.7-V drop at $i = 1$ A. We will study the topics of diode-circuit analysis and diode models in the next section.

EXAMPLE 2.3

A silicon diode said to be a 1-mA device displays a forward voltage of 0.7 V at a current of 1 mA. Evaluate the junction scaling constant I_S in the event that n is either 1 or 2. What scaling constants would apply for a 1-A diode of the same manufacture that conducts 1 A at 0.7 V?

Solution

Since

$$i = I_S e^{v/nV_T}$$

then

$$I_S = i e^{-v/nV_T}$$

For the 1-mA diode:

If $n = 1$: $I_S = 10^{-3} e^{-700/25} = 6.9 \times 10^{-16}$ A, or about 10^{-15} A

If $n = 2$: $I_S = 10^{-3} e^{-700/50} = 8.3 \times 10^{-10}$ A, or about 10^{-9} A

The diode conducting 1 A at 0.7 V corresponds to one-thousand 1-mA diodes in parallel with a total junction area 1000 times greater. Thus I_S is also 1000 times greater,

$I_S = 6.9 \times 10^{-13}$ A for $n = 1$

$I_S = 8.3 \times 10^{-7}$ A for $n = 2$

From this example it should be apparent that the value of n used can be quite important.

Since both I_S and V_T are functions of temperature, the forward i–v characteristic varies with temperature, as illustrated in Fig. 2.9. At a given constant diode current the voltage drop across the diode decreases by approximately 2 mV for every 1°C increase in temperature. The change in diode voltage with temperature has been exploited in the design of electronic thermometers.

EXERCISES

2.6 Consider a silicon diode with $n = 1.5$. Find the change in voltage if the current changes from 0.1 mA to 10 mA.

Ans. 172.5 mV

2.7 A silicon junction diode with $n = 1$ has $v = 0.7$ V at $i = 1$ mA. Find the voltage drop at $i = 0.1$ mA and $i = 10$ mA.

Ans. 0.64 V; 0.76 V

2.8 Using the fact that a silicon diode has $I_S = 10^{-14}$ A at 25°C and that I_S increases by 15% per °C rise in temperature, find the value of I_S at 125°C.

Ans. 1.17×10^{-8} A

2.2.2 The Reverse-Bias Region

The reverse-bias region of operation is entered when the diode voltage v is made negative. Equation (2.1) predicts that if v is negative and a few times larger than V_T (25 mV) in magnitude, the exponential term becomes negligibly small compared to unity, and the diode current becomes

$$i \simeq -I_S$$

That is, the current in the reverse direction is constant and equal to I_S. This constancy is the reason behind the term *saturation current*.

Real diodes exhibit reverse currents that, though quite small, are much larger than I_S. For instance, a small-signal diode whose I_S is on the order of 10^{-14} A to 10^{-15} A could show a reverse current on the order of 1 nA. The reverse current also increases somewhat with the increase in magnitude of the reverse voltage. Note that because of the very small magnitude of the current, these details are not clearly evident on the diode i–v characteristic of Fig. 2.8.

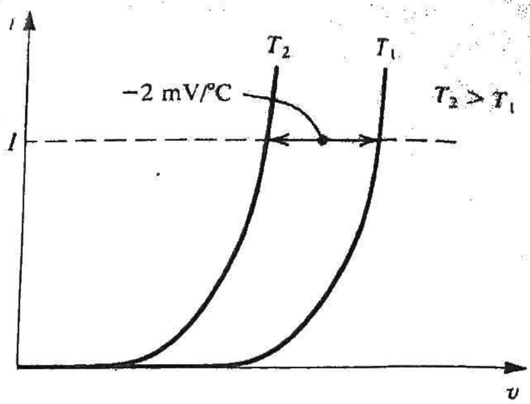

FIGURE 2.9 Illustrating the temperature dependence of the diode forward characteristic. At a constant current, the voltage drop decreases by approximately 2 mV for every 1°C increase in temperature.

A large part of the reverse current is due to leakage effects. These leakage currents are proportional to the junction area, just as I_S is. Their dependence on temperature, however, is different from that of I_S. Thus, whereas I_S doubles for every 5°C rise in temperature, the corresponding rule of thumb for the temperature dependence of the reverse current is that it doubles for every 10°C rise in temperature.

EXERCISE

2.9 The diode in the circuit of Fig. E2.9 is a large high-current device whose reverse leakage is reasonably independent of voltage. If $V = 1$ V at 20°C, find the value of V at 40°C and at 0°C.

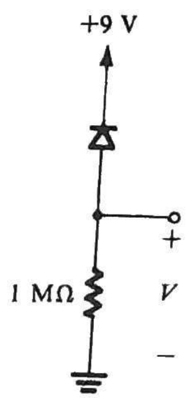

FIGURE E2.9

Ans. 4 V; 0.25 V

2.2.3 The Breakdown Region

The third distinct region of diode operation is the breakdown region, which can be easily identified on the diode i–v characteristic in Fig. 2.8. The breakdown region is entered when the magnitude of the reverse voltage exceeds a threshold value that is specific to the particular diode, called the **breakdown voltage.** This is the voltage at the "knee" of the i–v curve in Fig. 2.8 and is denoted V_{ZK}, where the subscript Z stands for zener (to be explained shortly) and K denotes knee.