CHAPTER 2
Semiconductor Diodes

Objectives

You will be able to:

1. Sketch a diode circuit symbol, identify the terminals, and discuss diode circuit behavior.
2. Explain diode forward and reverse characteristics.
3. List important diode parameters and determine parameter values from the characteristics.
4. Sketch approximate diode characteristics and dc equivalent circuits, and apply them to circuit analysis.
5. Draw dc load lines on diode characteristics to precisely analyze diode circuits.
6. Determine maximum diode power dissipations and forward voltages at various temperatures.
7. Sketch diode ac equivalent circuits and calculate junction capacitance and switching times.
8. Determine diode parameter values from device data sheets.
9. Test diodes, and plot the forward and reverse characteristics.
10. Sketch a Zener diode circuit symbol, identify the terminals, and explain the characteristics.
11. Determine Zener diode parameter values from device characteristics and from data sheets.
12. Analyze basic Zener diode circuits.

INTRODUCTION

The term *diode* refers to a two-electrode, or two-terminal, device. A semiconductor diode is simply a *pn*-junction with a connecting lead on each side. *A diode is a one-way device, offering a low resistance when forward-biased, and behaving almost as an open switch when reverse-biased.* An approximately constant voltage drop occurs across a forward-biased diode, and this simplifies diode circuit analysis. Diode forward and reverse characteristics are graphs of corresponding current and voltage levels. For precise circuit analysis, dc load lines are drawn on the diode forward characteristic.

Some diodes are low-current devices for use in switching circuits. High-current diodes are most often used as rectifiers for ac to dc conversion. Zener diodes are operated in reverse breakdown because they have a very stable breakdown voltage.

2-1 *pn*-JUNCTION DIODE

As explained in Sections 1-5 and 1-6, a *pn*-junction permits substantial current flow when forward biased, and blocks current when reverse-biased. Thus, it can be used as a switch: on when forward-biased and off when biased in reverse. A *pn*-junction provided with copper wire connecting leads becomes an electronic device known as a *diode* (see Fig. 2-1).

The circuit symbol (or *graphic symbol*) for a diode is an arrowhead and bar (Fig. 2-2). The arrowhead indicates the conventional direction of current flow when the diode is forward-biased (from the positive terminal through the device to the negative terminal). The *p*-side of the diode is always the positive terminal for forward bias and is termed the *anode*. The *n*-side, called the *cathode*, is the negative terminal when the device is forward-biased.

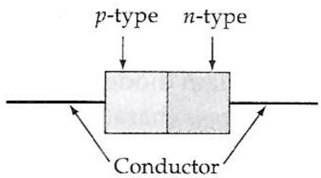


Figure 2-1 A semiconductor diode is a *pn*-junction with conductors on each side of the junction for connecting the device to a circuit.

A *pn*-junction diode can be destroyed if a high level of forward current overheats the device. It can also be destroyed if a large reverse voltage causes the junction to break down. The maximum forward current and reverse voltage for diodes are specified on the manufacturer's data sheets (see Section 2-7). In general, physically large diodes pass the largest currents and survive the largest reverse voltages. Small diodes are limited to low current levels and low reverse voltages.

Figure 2-3 shows the appearance of low-, medium-, and high-current diodes. Since the body of the low-current device in Fig. 2-3a may be only 0.3 cm long, the cathode is usually identified by a coloured band. This type of

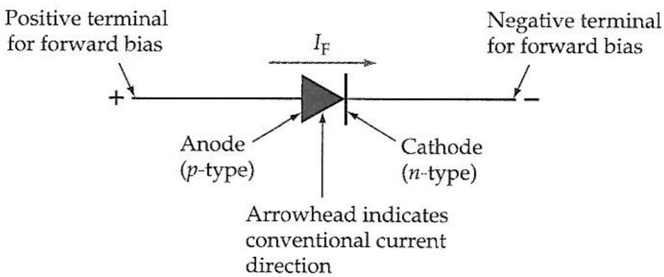
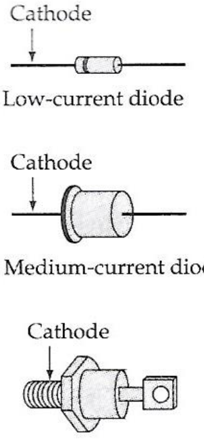


Figure 2-2 Diode circuit symbol. Current flows in the arrowhead direction when the diode is forward-biased: positive (+) on the anode and negative (−) on the cathode.



(a) Low-current diode

(b) Medium-current diode

(c) High-current diode

Figure 2-3 The size and appearance of a diode depend upon the level of forward current that the device is designed to pass.

diode is usually capable of passing a maximum forward current of approximately 100 mA. It can also survive about 75 V reverse bias without breaking down, and its reverse current is usually less than 1 μA at 25°C.

The medium-current diode shown in Fig. 2-3b can usually pass a forward current of about 400 mA and survive over 200 V reverse bias. The anode and cathode terminals may be indicated by a diode symbol on the side of the device.

Low-current and medium-current diodes are usually mounted by soldering the connecting leads to terminals. Power dissipated in the device is then carried away by air convection and by heat conduction along the connecting leads.

High-current diodes, or *power diodes* (see Fig. 2-3c), generate a lot of heat. So air convection would be completely inadequate. Such devices are designed to be connected mechanically to a metal heat sink. Power diodes can pass forward currents of many amperes and can survive several hundred volts of reverse bias.

2-2 CHARACTERISTICS AND PARAMETERS

Forward and Reverse Characteristics

The semiconductor diode is essentially a *pn*-junction, and its characteristics are those discussed in Chapter 1. Figures 2-4 and 2-5 show typical forward and reverse characteristics for low-current silicon and germanium diodes. From the silicon diode characteristics in Fig. 2-4, it is seen that the forward current (I_F) remains very low (less than 100 μA) until the diode forward-bias voltage (V_F) exceeds approximately 0.7 V. At V_F levels greater than 0.7 V, I_F increases almost linearly.

Because the diode reverse current (I_R) is very much smaller than its forward current, the reverse characteristics are plotted with expanded current scales. For a silicon diode, I_R is normally less than 100 nA, and it is almost completely independent of the reverse-bias voltage. As already explained in Chapter 1, I_R is largely a minority charge carrier *reverse saturation current*. A small increase in I_R can occur with increasing reverse-bias voltage, as a result of minority charge carriers leaking along the junction surface. For a diode with the characteristics in Fig. 2-4, the reverse current is usually less than

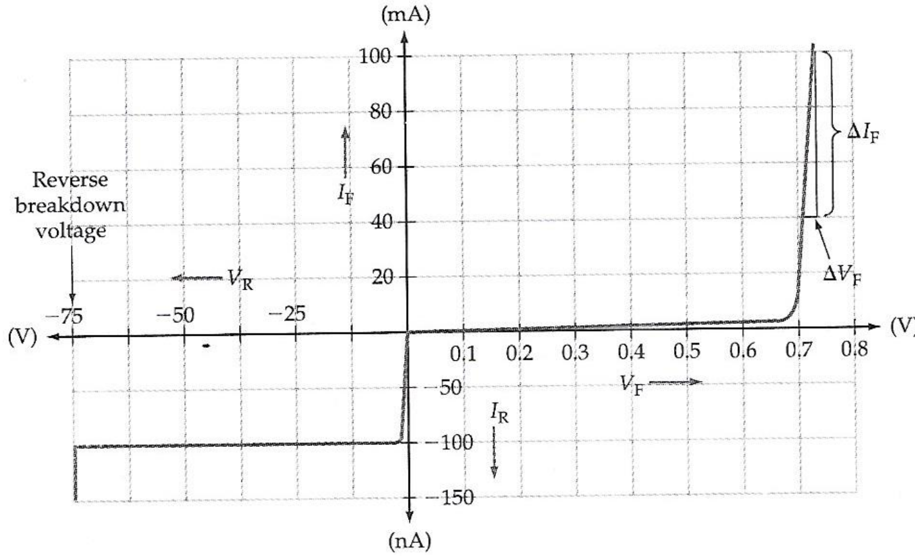


Figure 2-4 Typical forward and reverse characteristics for a silicon diode. There is a substantial forward current (I_F) when the forward voltage (V_F) exceeds approximately 0.7 V.

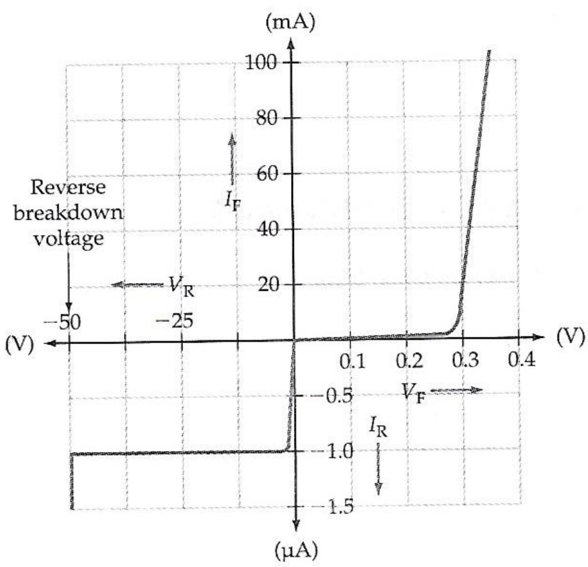


Figure 2-5 Typical forward and reverse characteristics for a germanium diode. Substantial forward current (I_F) flows when the forward voltage (V_F) exceeds approximately 0.3 V.

1/10 000 of the lowest normal forward current level. Therefore, I_R is quite negligible when compared to I_F, and a reverse-biased diode may be treated almost as an open switch. This is investigated further in Ex. 2-1.

Example 2-1

Calculate the forward and reverse resistances offered by a silicon diode with the characteristics in Fig. 2.4 at $I_F = 100$ mA and at $V_R = 50$ V.

Solution

At $I_F = 100$ mA, $V_F \approx 0.75$ V

$$R_F = \frac{V_F}{I_F} = \frac{0.75\ \text{V}}{100\ \text{mA}} \qquad \text{(see Fig. 2-6a)}$$

$$= 7.5\ \Omega$$

At $V_R = 50$ V, $I_R \approx 100$ nA

$$R_R = \frac{V_R}{I_R} = \frac{50\ \text{V}}{100\ \text{nA}} \qquad \text{(see Fig. 2-6b)}$$

$$= 500\ \text{M}\Omega$$

When the diode reverse voltage (V_R) is sufficiently increased, the device goes into *reverse breakdown*. For the characteristics shown in Fig. 2-4, this occurs where $V_R = 75$ V. Reverse breakdown can destroy a diode unless the current is limited by a suitable series-connected resistor. Reverse breakdown is usefully applied in Zener diodes, which are introduced in Section 2-9.

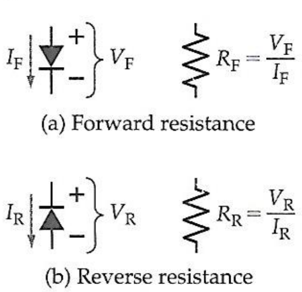


Figure 2-6 Determination of diode forward and reverse resistance.

The characteristics of a germanium diode are similar to those of a silicon diode but with some important differences (see Fig. 2-5). The forward voltage drop of a germanium diode is typically 0.3 V, compared to 0.7 V for silicon. For a germanium device, the reverse saturation current at 25°C may be about 1 μA, which is much larger than the reverse current for a silicon diode. Finally, the reverse breakdown voltage for germanium devices is likely to be substantially lower than that for silicon devices.

The lower forward voltage drop for germanium diodes can be a distinct advantage. However, the lower reverse current and higher reverse breakdown voltage of silicon diodes make them preferable to germanium devices for most applications.

Diode Parameters

The diode parameters of greatest interest are

V_F forward voltage drop

I_R	reverse saturation current
V_{BR}	reverse breakdown voltage
r_d	dynamic resistance
$I_{F(max)}$	maximum forward current

The values of these parameters are normally listed on the diode data sheet provided by device manufacturers (see Section 2-7). Some of the parameters can also be determined directly from the diode characteristics. For the silicon diode characteristics in Fig . 2-4, $V_F \approx 0.7$ V, $I_R = 100$ nA, and $V_{BR} = 75$ V.

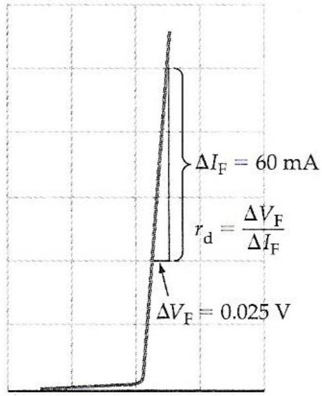


Figure 2-7 Determination of the dynamic resistance (r_d) of a diode from the forward characteristic.

The forward resistance calculated in Ex. 2-1 is a *static quantity*. It is the constant resistance (or dc resistance) of the diode at a particular constant forward current. The *dynamic resistance* of the diode is the resistance offered to changing levels of forward voltage. The dynamic resistance, also known as the *incremental resistance* or *ac resistance*, is the reciprocal of the slope of the forward characteristics beyond the knee. Referring to Figs 2-4 and 2-7,

$$r_d = \frac{\Delta V_F}{\Delta I_F} \tag{2-1}$$

The dynamic resistance can also be calculated from the rule-of-thumb equation

$$r'_d = \frac{26 \text{ mV}}{I_F} \tag{2-2}$$

where I_F is the dc forward current. Thus, for example, the dynamic resistance for a diode passing a 1 mA forward current is $r'_d = 26 \text{ mV}/1 \text{ mA} = 26\ \Omega$.

Equation 2-2 shows that the diode dynamic resistance changes with the level of dc forward current. Since this is not shown in Figs 2-4 and 2-5, the characteristics are approximations of the actual device characteristics. It should also be noted that Eq. 2-2 gives the ac resistance only for the junction. It does not include the dc resistance of the semiconductor material, which might be as large as 2 Ω depending on the design of the device. The resistance derived from the slope of the device characteristic does include the semiconductor dc resistance. So r_d (from the characteristic) should be slightly larger than r'_d calculated from Eq. 2-2.

Example 2-2

Determine the dynamic resistance at a forward current of 70 mA for the diode characteristics given in Fig. 2-4. Using Eq. 2-2, estimate the diode dynamic resistance.

Solution

In Fig. 2-4 at $I_F = 70$ mA,

$$\Delta I_F = 60 \text{ mA} \quad \text{and} \quad \Delta V_F \approx 0.025 \text{ V}$$

Eq. 2-1:

$$r_d = \frac{\Delta V_F}{\Delta I_F} = \frac{0.025 \text{ V}}{60 \text{ mA}} \qquad \text{(see Fig. 2-7)}$$

$$= 0.42\ \Omega$$

Eq. 2-2:

$$r'_d = \frac{26 \text{ mV}}{I_F} = \frac{26 \text{ mV}}{70 \text{ mA}}$$

$$= 0.37\ \Omega$$

Practice Problems

2-2.1 Calculate the resistances offered by a diode with the characteristics in Fig. 2.5 at 30 V reverse bias and at 60 mA of forward current.

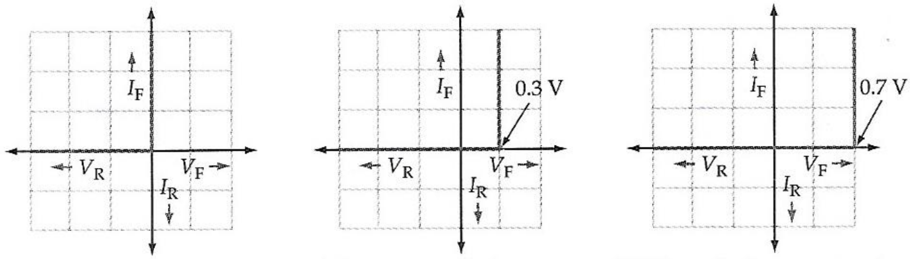
2-2.2 Determine the dynamic resistance at a 50 mA forward current for a diode with the characteristics in Fig. 2-5. Use Eq. 2-2 to estimate the diode dynamic resistance.

2-3 DIODE APPROXIMATIONS

Ideal Diodes and Practical Diodes

As already explained, a diode is essentially a one-way device, offering a low resistance when forward-biased and a high resistance when biased in reverse. An *ideal diode* (or perfect diode) would have zero forward resistance and zero forward voltage drop. It would also have an infinitely high reverse resistance, which would result in zero reverse current. Figure 2-8a shows the current/voltage characteristics of an ideal diode.

Although an ideal diode does not exist, there are many applications where diodes can be assumed to be near-ideal devices. In circuits with supply voltages much larger than the diode forward voltage drop, V_F can be assumed to be constant without introducing any serious error. Also, the diode reverse current is normally so much smaller than the forward current that the reverse current can be ignored. These assumptions lead to the near-ideal, or approximate, characteristics for silicon and germanium diodes shown in Figs 2-8b and c. Example 2-3 investigates a situation where the diode V_F is assumed to be constant.



(a) Ideal diode characteristics (b) Germanium diode approximate characteristics (c) Silicon diode approximate characteristics

Figure 2-8 An ideal diode has $V_F = 0$ and $I_R = 0$. Practical diodes can be treated as near-ideal devices if the forward voltage drop is taken into account.

Example 2-3

A silicon diode is used in the circuit shown in Fig. 2-9. Calculate the diode current.

Solution

$$E = I_F R_1 + V_F$$

or

$$I_F = \frac{E - V_F}{R_1} = \frac{15\text{ V} - 0.7\text{ V}}{4.7\text{ k}\Omega}$$

$$= 3.04\text{ mA}$$

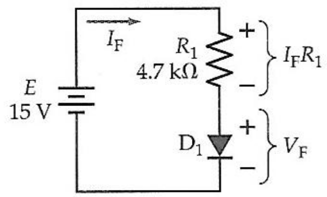


Figure 2-9 Circuit for Ex. 2-3.

Piecewise Linear Characteristic

When the forward characteristic of a diode is not available, a straight-line approximation called the *piecewise linear characteristic* may be employed. To construct the piecewise linear characteristic, V_F is first marked on the horizontal axis, as shown in Fig. 2-10. Then, from V_F, a straight line is drawn with a slope equal to the diode dynamic resistance. Example 2-4 demonstrates the process.

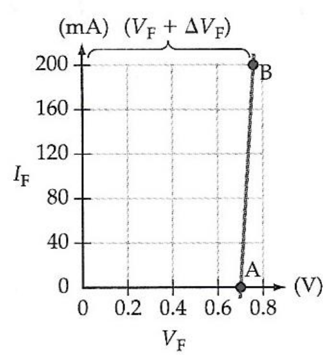


Figure 2-10 Diode piecewise linear characteristic, or straight-line approximation of the diode forward characteristic.

Example 2-4

Construct the piecewise linear characteristic for a silicon diode which has a 0.25 Ω dynamic resistance and a 200 mA maximum forward current.

Solution

Plot point A on the horizontal axis at

$$V_F = 0.7\text{ V} \qquad \text{(see Fig. 2-10)}$$

$$\Delta V_F = \Delta I_F \times r_d = 200\text{ mA} \times 0.25\ \Omega$$
$$= 0.05\text{ V}$$

Plot point B (on Fig. 2-10) at

$$I_F = 200\text{ mA} \quad \text{and} \quad V_F = (0.7\text{ V} + 0.05\text{ V})$$

Draw the characteristic through points A and B.

DC Equivalent Circuits

An *equivalent circuit* for a device is a circuit that represents the device behavior. Usually, the equivalent circuit is made up of a number of components, such as resistors and voltage cells. A diode equivalent circuit may be substituted for the device when investigating a circuit containing the diode. Equivalent circuits may also be used as device *models* for computer analysis.

In Ex. 2-3, a forward-biased diode is assumed to have a constant forward voltage drop (V_F) and negligible series resistance. In this case the diode equivalent circuit is assumed to be a voltage cell with a voltage V_F (see Fig. 2-11a). This simple dc equivalent circuit is quite suitable for a great many diode applications.

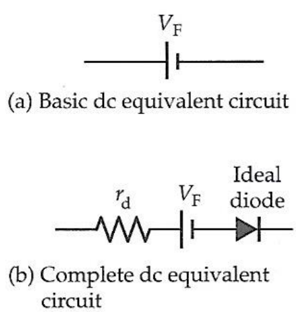


Figure 2-11 DC equivalent circuits for a junction diode.

A more accurate equivalent circuit includes the diode dynamic resistance (r_d) in series with the voltage cell, as shown in Fig. 2-11b. This takes account of the small variations in V_F that occur with change in forward current. An ideal diode is also included to show that current flows only in one direction. The equivalent circuit without r_d assumes that the diode has the approximate characteristics illustrated in Fig. 2-8b or c. With r_d included, the equivalent circuit represents a diode with the type of piecewise linear characteristic shown in Fig. 2-10. Consequently, the circuit in Fig. 2-11b is termed the *piecewise linear equivalent circuit*.

Example 2-5

Calculate I_F for the diode circuit in Fig. 2-12a assuming that the diode has $V_F = 0.7$ V and $r_d = 0$. Then recalculate the current taking $r_d = 0.25\ \Omega$.

Solution

Substituting V_F as the diode equivalent circuit (Fig. 2-12b),

$$I_F = \frac{E - V_F}{R_1} = \frac{1.5\text{ V} - 0.7\text{ V}}{10\ \Omega}$$
$$= 80\text{ mA}$$

Substituting V_F and r_d as the diode equivalent circuit (Fig. 2-12c),

$$I_F = \frac{E - V_F}{R_1 + r_d} = \frac{1.5\text{ V} - 0.7\text{ V}}{10\ \Omega + 0.25\ \Omega}$$
$$= 78\text{ mA}$$

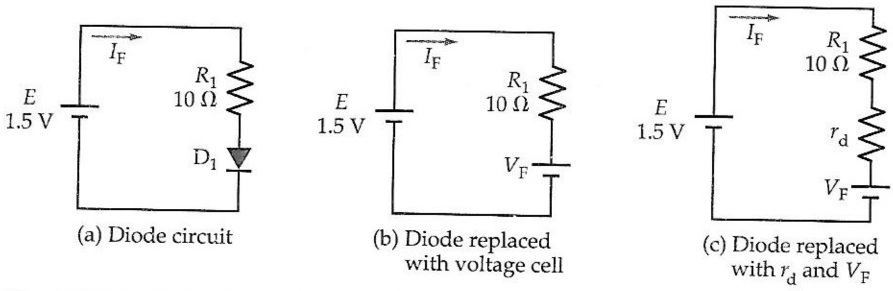


Figure 2-12 Diode circuits for Ex. 2-5.

Practice Problems

2-3.1 Calculate the new level of diode current in the circuit in Fig. 2-9 when D_1 is replaced with two series-connected silicon diodes.

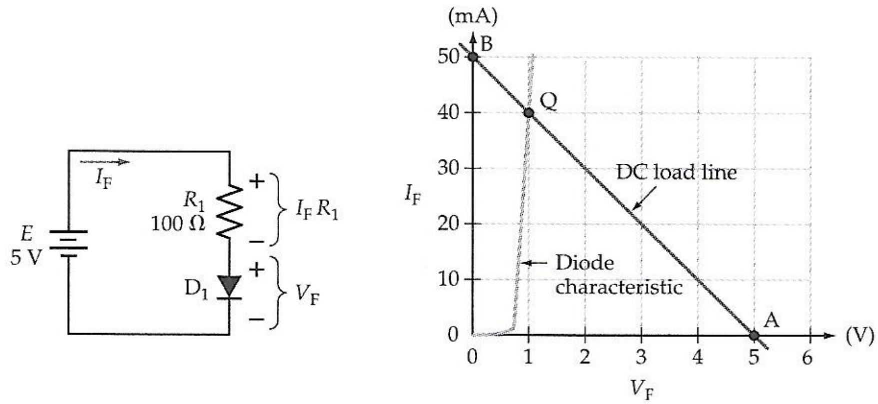
2-3.2 A germanium diode has a maximum forward current of 100 mA and a 0.5 Ω dynamic resistance. Construct the piecewise linear characteristics for this diode on Fig. 2-10.

2-3.3 Calculate the circuit current when the diode in Problem 2-3.2 is forward-biased in series with a 15 Ω resistor and a 3 V battery.

2-4 DC LOAD LINE ANALYSIS

DC Load Line

Figure 2-13a shows a diode in series with a 100 Ω resistor (R_1) and a supply voltage (E). The polarity of E is such that the diode is forward-biased, so that there is a diode forward current (I_F). As already discussed, the circuit current can be determined approximately by assuming a constant diode forward voltage drop (V_F). When the precise levels of the diode current and voltage must be calculated, *graphical analysis* (also termed *dc load line analysis*) is employed.



(a) Diode-resistor series circuit

(b) Plotting the dc load line on the diode characteristics

Figure 2-13 Drawing a dc load line on the diode characteristic.

For graphical analysis, a dc load line is drawn on the diode forward characteristics (Fig. 2-13b). This is a straight line that illustrates all dc conditions that could exist within the circuit. Because the load line is always straight, it can be constructed by plotting any two corresponding current and voltage points and then drawing a straight line through them. To determine two points on the load line, an equation relating voltage, current, and resistance is first derived for the circuit. From Fig. 2-13a,

$$E = (I_F R_1) + V_F \tag{2-3}$$

Any two convenient levels of I_F can be substituted into Eq. 2-3 to calculate corresponding V_F levels, or vice versa. As demonstrated in Ex. 2-6, it is convenient to calculate V_F when $I_F = 0$, and to determine I_F when $V_F = 0$.

Example 2-6

Draw the dc load line for the circuit in Fig. 2-13a on the diode forward characteristic given in Fig. 2-13b.

Solution

Substitute $I_F = 0$ into Eq. 2-3,

$$E = (I_F R_1) + V_F = 0 + V_F$$

or

$$V_F = E = 5\text{ V}$$

Plot point A on the diode characteristic at

$$I_F = 0 \text{ and } V_F = 5\text{ V}$$

Now substitute $V_F = 0$ into Eq. 2-3,

$$E = (I_F R_1) + 0$$

giving

$$I_F = \frac{E}{R_1} = \frac{5\text{ V}}{100\ \Omega}$$

$$= 50\text{ mA}$$

Plot point B on the diode characteristic at

$$I_F = 50\text{ mA and } V_F = 0$$

Draw the dc load line through points A and B.

Q-Point

The relationship between the diode forward voltage and current in the circuit in Fig. 2-13a is defined by the device characteristic. Consequently, there is only one point on the dc load line where the diode voltage and current are compatible with the circuit conditions. That is *point Q*, termed the *quiescent point* or *dc bias point*, where the load line intersects the characteristic. This may be checked by substituting the levels of I_F and V_F at point Q into Eq. 2-3. From the Q point on Fig. 2-13b, $I_F = 40$ mA and $V_F = 1$ V. Equation 2-3 states that $E = (I_F R_1) + V_F$. Therefore,

$$E = (40\text{ mA} \times 100\ \Omega) + 1\text{ V}$$

$$= 5\text{ V}$$

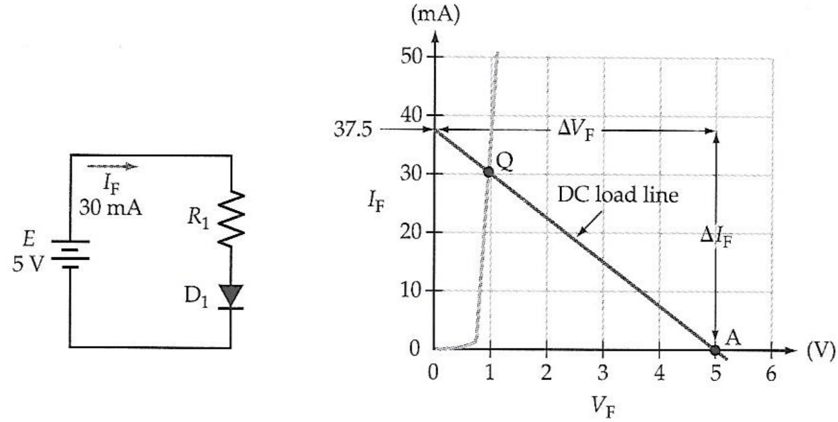
So, with $E = 5$ V and $R_1 = 100\ \Omega$, the only levels of I_F and V_F that can satisfy Eq. 2-3 on the diode characteristics in Fig. 2-13b are 40 mA and 1 V.

Note that, although 0 and 5 V were used for V_F when the dc load line was drawn in Ex. 2-6, no functioning semiconductor diode would have a 5 V forward voltage drop. This is simply a convenient theoretical level for plotting the dc load line.

Calculating Load Resistance and Supply Voltage

In a diode series circuit (see Fig. 2-14a), resistor R_1 dictates the slope of the dc load line, and supply voltage E determines point A on the load line. So the circuit conditions can be altered by changing either R_1 or E.

When designing a diode circuit, it may be necessary to use a given supply voltage and set up a specified forward current. In this case, points A and Q are first plotted and the load line is drawn. Resistor R_1 is then calculated from the slope of the load line. The problem could also occur in another way. For example, R_1 and the required I_F are known, and the supply voltage is to be



(a) Diode-resistor circuit

(b) Resistor determination

Figure 2-14 Determination of the required circuit series resistance R_1 from the slope of the dc load line.

determined. This problem is solved by plotting point Q and drawing the load line with slope $1/R_1$. The supply voltage is then read at point A.

Example 2-7

Using the device characteristics in Fig. 2-14b, determine the required load resistance for the circuit in Fig. 2-14a to give $I_F = 30$ mA.

Solution

From Eq. 2-3, $\quad V_F = E - (I_F R_1)$

Substituting $I_F = 0$, $\quad V_F = E - 0 = 5\text{ V}$

Plot point A on the diode characteristic in Fig. 2-14b at

$$I_F = 0 \text{ and } V_F = 5\text{ V}$$

Now plot point Q in Fig. 2-14b at

$$I_F = 30\text{ mA}$$

Draw the dc load line through points A and Q. From the load line,

$$R_1 = \frac{\Delta V_F}{\Delta I_F} = \frac{5\text{ V}}{37.5\text{ mA}}$$

$$= 133\ \Omega$$

Example 2-8

Determine a new supply voltage for the circuit in Fig. 2-14a to give a 50 mA diode forward current when $R_1 = 100\ \Omega$.

Solution

Plot point Q on the diode characteristic in Fig. 2-15 at

$$I_F = 50 \text{ mA}$$

From the characteristic, read

$$V_F = 1.1 \text{ V}$$

From Eq. 2-3, $\quad V_F = E - (I_F R_1)$

When I_F changes from 50 mA to 0,

$$\Delta I_F = 50 \text{ mA} \qquad \text{(see Fig. 2-15)}$$

and

$$\Delta V_F = I_F R_1 = 50 \text{ mA} \times 100\ \Omega \qquad \text{(see Fig. 2-15)}$$

$$= 5 \text{ V}$$

The new supply voltage is

$$E = V_F + \Delta V_F = 1.1 \text{ V} + 5 \text{ V}$$

$$= 6.1 \text{ V}$$

Point A may now be plotted (on Fig. 2-15) at $I_F = 0$ and $E = 6.1$ V, and the new dc load line may be drawn through points A and Q.

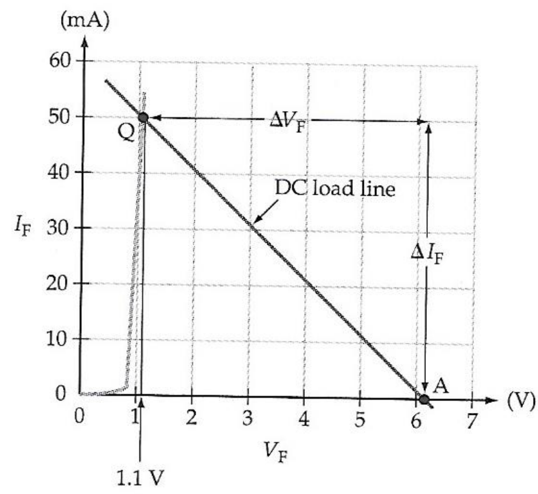


Figure 2-15 Determination of the required supply voltage for a diode-resistor circuit with a given resistor and a specified load current.

Practice Problems

2-4.1 A diode with the characteristics in Fig. 2-15 is connected in series with a 3 V supply and a 100 Ω resistor. Draw the dc load line for the circuit, and determine the forward current level.

2-4.2 Calculate a new load resistance for the circuit in Problem 2-4.1 to produce a 40 mA diode forward current.

2-4.3 A diode with the characteristics in Fig. 2-15 is to have a 35 mA forward current when connected in series with a 70 Ω resistor. Determine the required supply voltage.

2-5 TEMPERATURE EFFECTS

Diode Power Dissipation

The power dissipation in a diode is simply calculated as the device terminal voltage multiplied by the current level:

$$P = V_F I_F \tag{2-4}$$

Device manufacturers specify a maximum power dissipation for each type of diode. If the specified level is exceeded, the device will overheat and may short-circuit or open-circuit. The maximum power that may be dissipated in a diode (or any other electronic device) is normally specified for an ambient temperature of 25°C or, sometimes, for a 25°C case temperature. When the temperature exceeds this level, the device maximum power dissipation must be derated.

Figure 2-16 shows the type of power-versus-temperature graph provided on device data sheets. The maximum power dissipation for any temperature

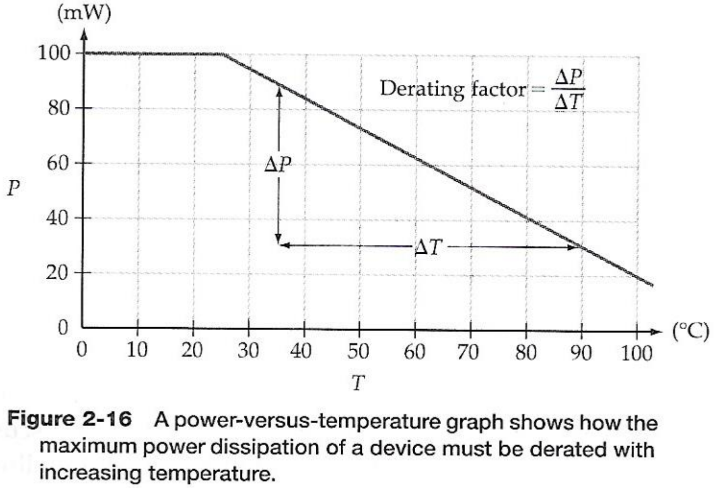


Figure 2-16 A power-versus-temperature graph shows how the maximum power dissipation of a device must be derated with increasing temperature.

is simply read from the graph; then the maximum forward current level is calculated from Eq. 2-4. Instead of a power-versus-temperature graph, some rectifier diode data sheet have a current-versus-temperature graph, which directly gives the maximum forward current at any temperature in the range of operation.

As an alternative to power or current graphs, a *derating factor* is often listed on device data sheets. The derating factor defines the slope of the power-versus-temperature graph (see Fig. 2-16); it can be employed to draw the graph or used directly without reference to the graph. The equation for the maximum power dissipation when the temperature changes involves the specified power at the specified temperature (P_1 at T_1), the derating factor (D), and the temperature change (ΔT).

$$P_2 = (P_1 \text{ at } T_1) - (D \times \Delta T) \qquad \textbf{(2-5)}$$

Example 2-9

A diode with 700 mW maximum power dissipation at 25°C has a 5 mW/°C derating factor. If the forward voltage drop remains constant at 0.7 V, calculate the maximum forward current at 25°C and at 65°C.

Solution

At 25°C:

From Eq. 2-4,
$$I_F = \frac{P}{V_F} = \frac{700 \text{ mW}}{0.7 \text{ V}}$$
$$= 1 \text{ A}$$

At 65°C:

Eq. 2-5:
$$P_2 = (P_1 \text{ at } T_1) - (D \times \Delta T)$$
$$= 700 \text{ mW} - [5 \text{ mW/°C} \times (65\text{°C} - 25\text{°C})]$$
$$= 500 \text{ mW}$$

From Eq. 2-4,
$$I_F = \frac{P_2}{V_F} = \frac{500 \text{ mW}}{0.7 \text{ V}}$$
$$= 714 \text{ mA}$$

Forward Voltage Drop

Sometimes it is important to know the precise level of a diode forward voltage drop. In these cases, the graphical analysis techniques discussed in Section 2-4 can be used. However, as explained in Section 1-6 and illustrated

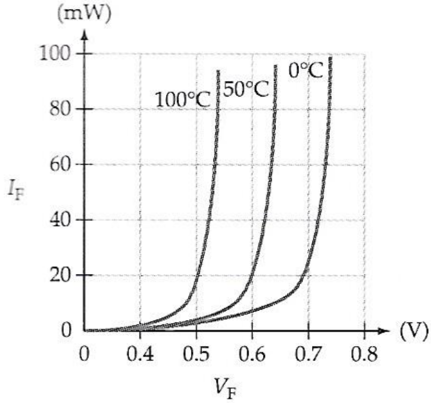


Figure 2-17 The forward voltage drop across a diode decreases by approximately 2 mV/°C as the device temperature increases.

in Fig. 2-17, the voltage drop across a forward-biased *pn*-junction changes with temperature by approximately −1.8 mV/°C for a silicon device and by −2.02 mV/°C for germanium. A diode forward voltage drop at any temperature can be calculated from a knowledge of V_F at the starting temperature (V_{F1} at T_1), the temperature change (ΔT), and the voltage/temperature coefficient (ΔV_F/°C).

$$V_{F2} = (V_{F1} \text{ at } T_1) + [\Delta T\,(\Delta V_F/°\text{C})] \qquad \textbf{(2-6)}$$

Dynamic Resistance

Equation 2-2 for calculating the dynamic resistance of a forward-biased diode is correct only for a junction temperature of 25°C. For higher or lower temperatures, the equation must be modified to

$$r'_d = \frac{26\text{ mV}}{I_F}\left(\frac{T + 273°\text{C}}{298°\text{C}}\right) \qquad \textbf{(2-7)}$$

where T is the junction temperature in degrees Celsius.

Example 2-10

A silicon diode with a 0.7 V forward voltage drop at 25°C is to be operated with a constant forward current up to a temperature of 100°C. Calculate the diode V_F at 100°C. Also, determine the junction dynamic resistance at 25°C and at 100°C if the forward current is 26 mA.

Solution

Eq. 2-6:

$$\begin{aligned} V_{F2} &= (V_{F1} \text{ at } T_1) + [\Delta T\,(\Delta V_F/°\text{C})] \\ &= 0.7\text{ V} + [(100°\text{C} - 25°\text{C})(-1.8\text{ mV}/°\text{C})] \\ &= 0.565\text{ V (at 100°C)} \end{aligned}$$

At 25°C:

Eq. 2-7:
$$r'_d = \frac{26\text{ mV}}{I_F}\left[\frac{T + 273°\text{C}}{298°\text{C}}\right] = \frac{26\text{ mV}}{26\text{ mA}}\left[\frac{25°\text{C} + 273°\text{C}}{298°\text{C}}\right]$$
$$= 1\ \Omega$$

At 100°C:

$$r'_d = \frac{26\text{ mV}}{26\text{ mA}}\left[\frac{100°\text{C} + 273°\text{C}}{298°\text{C}}\right]$$
$$= 1.25\ \Omega$$

Practice Problems

2-5.1 A diode with a constant 0.65 V forward drop has the power-versus-temperature graph in Fig. 2-16. Calculate the maximum forward current that may be passed at 25°C and at 80°C.

2-5.2 Calculate the maximum and minimum levels of V_F for a germanium diode with $V_F = 0.3$ V at 25°C when operated over a temperature range of 10°C to 80°C. Determine the device dynamic resistances at the temperature extremes if I_F is 20 mA.

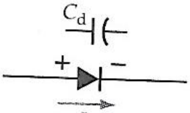
2-5.3 A diode with a 1 W maximum power dissipation at 25°C has a 4 mW/°C derating factor. Calculate the maximum power that may be dissipated in the diode when its temperature is 80°C.

2-6 DIODE AC MODELS

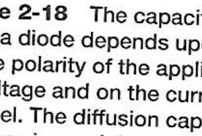
Junction Capacitances

The depletion region of a *pn*-junction (see Section 1-6) is a layer depleted of charge carriers situated between two blocks of low-resistance material. Since this is also the description of a capacitor, the junction depletion region clearly has a capacitance. The *depletion layer capacitance* (C_{pn}) (also known as the *transition capacitance*) may be calculated from the equation for a parallel-plate capacitor if the junction dimensions are known. Typically, C_{pn} is 4 pF for a low-current diode.

The depletion layer capacitance is essentially the capacitance of a reverse-biased *pn*-junction (Fig. 2-18a). Consider the forward-biased junction in Fig. 2-18b. If the applied



(a) A depletion layer capacitance occurs at a reverse-biased diode



(b) A diffusion capacitance is present at a forward-biased diode

Figure 2-18 The capacitance of a diode depends upon the polarity of the applied voltage and on the current level. The diffusion capacitance is much larger than the depletion layer capacitance.

voltage is suddenly reversed, forward current I_F ceases immediately, leaving some majority charge carriers in the depletion region. These charge carriers must flow back out of the depletion region, which is widened when the junction is reverse-biased. The result is that, when a forward-biased junction is suddenly reversed, there is a reverse current, which is large at first and which slowly decreases to the level of the reverse saturation current. The effect may be likened to the discharge of a capacitor, and so it is represented by a capacitance known as the *diffusion capacitance* (C_d) (also termed the *storage capacitance*).

The equation for the diffusion capacitance is

$$C_d \approx \frac{\tau I_F}{V_F} \tag{2-8}$$

where I_F and V_F are the forward current and voltage, and τ is the *transist time* of charge carriers. The transit time is dependent on the doping density of the semiconductor material, and on whether the p-side or the n-side of the junction is most heavily doped. It is to be expected that C_d would be directly proportional to I_F since the quantity of charge carriers in the depletion region is dependent on the forward current level.

Example 2-11

Calculate the diffusion capacitance for a silicon diode with a 10 mA forward current if the charge carrier transit time is 70 ns.

Solution

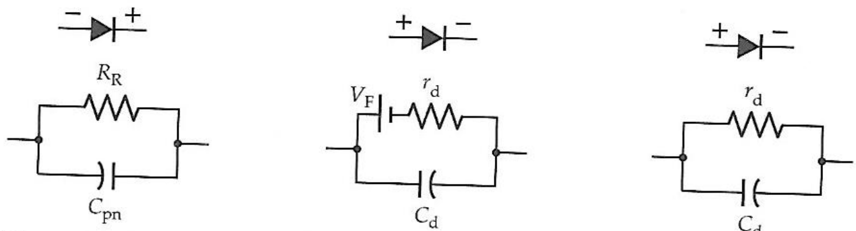
Eq. 2-8:

$$C_d \approx \frac{\tau I_F}{V_F} \approx \frac{70\text{ ns} \times 10\text{ mA}}{0.7\text{ V}}$$
$$\approx 1\text{ nF}$$

AC Equivalent Circuits (Reverse-Biased and Forward-Biased)

A reverse-biased diode can be simply represented by the high reverse resistance R_R in parallel with the depletion layer capacitance C_{pn} (see Fig. 2-19a). The equivalent circuit (or model) for a forward-biased diode consists of the dynamic resistance r_d in series with a voltage cell representing V_F, as discussed in Section 2-3. To allow for the effect of the diffusion capacitance, C_d is included in parallel to give the complete equivalent circuit shown in Fig. 2-19b.

The complete equivalent circuit for the forward-biased diode may be modified into an *ac equivalent circuit*, which can be used for diodes that are maintained in a forward-biased condition while subjected to small variations in I_F and V_F. The ac equivalent circuit is created simply by removing the voltage cell representing V_F from the complete equivalent circuit (Fig. 2-19c).



(a) Equivalent circuit for a reverse-biased diode

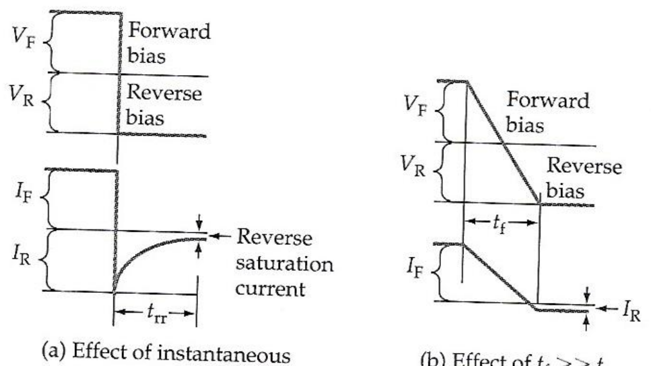
(b) Equivalent circuit for a forward-biased diode

(c) AC equivalent circuit for a forward-biased diode

Figure 2-19 Equivalent circuits (or models) for reverse-biased and forward-biased diodes.

Reverse Recovery Time

In many applications, diodes must switch rapidly between forward and reverse bias. Most diodes switch very quickly into the forward-biased condition; however, there is a longer *turnoff* time owing to the junction diffusion capacitance.



(a) Effect of instantaneous reverse bias

(b) Effect of $t_f >> t_{rr}$

Figure 2-20 The minimum on-off switching time of a diode is limited by the reverse recovery time (t_{rr}). The reverse saturation current can be minimized by using a pulse with $t_f >> t_{rr}$.

Figure 2-20 illustrates the effect of a voltage pulse on the diode forward current. When the pulse switches from positive to negative, the diode conducts in reverse instead of switching off sharply (see Fig. 2-20a). The reverse current (I_R) initially equals the forward current (I_F); then it gradually decreases toward zero. The high level of reverse current occurs because at the instant of reverse bias there are charge carriers crossing the junction depletion region, and these must be removed. (This is the same effect that produces diffusion capacitance.) The *reverse recovery time* (t_{rr}) is the time required for the current to decrease to the reverse saturation current level.

Typical values of t_{rr} for switching diodes range from 4 ns to 50 ns. The diode reverse current can be kept to a minimum if the *fall time* (t_f) of the applied voltage pulse is much larger than the diode reverse recovery time. This is illustrated in Fig. 2-20b. Typically

$$t_{f(min)} = 10\,t_{rr} \tag{2-9}$$

Example 2-12

Calculate the minimum fall times for voltage pulses applied to a circuit using 1N915 and 1N917 diodes to keep the diode reverse current to a minimum.

Solution

From diode data sheets,

$$t_{rr} = 10 \text{ ns for the 1N915} \quad \text{and} \quad t_{rr} = 3 \text{ ns for the 1N917}$$

For the 1N915:

Eq. 2-9: $$t_{f(min)} = 10\,t_{rr} = 10 \times 10 \text{ ns}$$
$$= 100 \text{ ns}$$

For the 1N917:

Eq. 2-9: $$t_{f(min)} = 10\,t_{rr} = 10 \times 3 \text{ ns}$$
$$= 30 \text{ ns}$$

Practice Problems

2-6.1 Determine the maximum reverse recovery time for satisfactory operation of a diode with an applied voltage pulse which has a 0.5 μs fall time.

2-6.2 Estimate a suitable minimum fall time for a pulse which switches a diode from *on* to *off* if the reverse recovery time of the diode is 15 ns.

2-6.3 Determine the charge carrier transit time for a silicon diode which has a capacitance of 11 nF when the forward current is $I_F = 50$ mA.

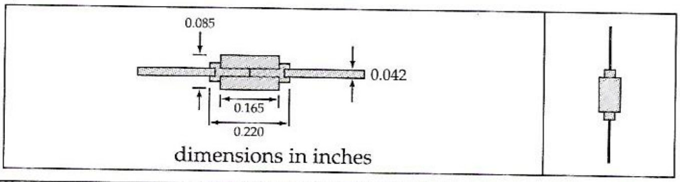
2-7 DIODE SPECIFICATIONS

Diode Data Sheets

To select a suitable diode for a particular application, the *data sheets*, or *specifications*, provided by device manufacturers must be consulted. Portions of typical diode data sheets are shown in Fig. 2-21 and as data sheets 1 to 3 in Appendix A.

Type 1N914 Through 1N917 Silicon Switching Diodes

Mechanical data



Absolute maximum ratings at 25°C ambient temperature

		1N914	1N915	1N916	1N917	Unit
V_R	Reverse voltage	75	50	75	30	V
I_o	Average rectified forward current	75	75	75	50	mA
I_{FRM}	Repetitive peak forward current	225	225	225	150	mA
P	Power dissipation	250	250	250	250	mW

Figure 2-21 Part of data sheet for type 1N914 to 1N917 diodes.

Most data sheets start with the device type number at the top of the page, such as '1N914 through 1N917' or '1N5391 through 1N5399'. The 1 (one) in the type number signifies a one-junction device: a diode. This is followed by a short descriptive title, for example, *silicon switching diode* or *silicon rectifier*. *Mechanical data* are also given, usually in the form of an illustration showing the shape and dimensions of the package. The *maximum ratings* at 25°C are then listed (see Fig. 2-21).

The maximum ratings are the maximum voltages, currents, and so on, that can be applied without destroying the device. It is very important that these ratings not be exceeded; otherwise the diode is quite likely to fail. *For reliability, the maximum ratings should not even be approached.* If a diode is to survive a 50 V reverse bias, a device that has a 75 V peak reverse voltage should be selected. If the diode peak forward current is to be 100 mA, a device that can handle 150 mA should be used. It is also important to note that the maximum ratings must be adjusted downward for operation at temperatures greater than 25°C (see Section 2-5).

A list of other electrical characteristics for the device normally follows the maximum ratings. An understanding of all the parameters specified on a data sheet will not be achieved until the data sheets have been consulted frequently. However, some of the most important parameters are considered below.

V_R or V_{RRM} — *Peak reverse voltage* (also termed *peak inverse voltage* and *dc blocking voltage*). This is the maximum reverse voltage that may be applied across the diode.

I_o or $I_{F(AV)}$	*Steady-state forward current*. The maximum current that may be passed continuously through the diode.
I_{FSM}	*Non-repetitive peak surge current*. This current may be passed for a specified time. The non-repetitive surge current is very much higher than the normal maximum forward current. It is a current that may be allowed to flow briefly when a circuit is first switched *on*.
I_{FRM}	*Repetitive peak surge current*. Peak current that may be repeated over and over again, for example, during each cycle of a rectified waveform.
V_F	*Static forward voltage drop*. The maximum forward volt drop for a given forward current and device temperature.
P	*Continuous power dissipation at 25°C*. The maximum power that the device can safely dissipate continuously in free air. This rating must be downgraded at higher temperatures (see Section 2-5).

Low-Power Diodes

The data sheet portion in Fig. 2-21 identifies the 1N914 to 1N917 devices as *switching diodes*. The average rectified forward current is listed as 75 mA (except for the 1N917). Maximum reverse voltage ranges from 30 V to 75 V. Thus, these diodes are intended for relatively low-current, low-voltage applications, in which they may be required to switch rapidly between on and off states.

Rectifier Diodes

The low-power rectifier data sheets (see Appendix A, data sheets A-2 and A-3) show that the 1N4000 range of rectifiers can pass an average forward current of 1 A, and that the 1N5390 range can pass 1.5 A. Both types have maximum reverse voltages ranging from 50 V to 1000 V. Unlike data sheet A-1, for switching diodes, the rectifier data sheet does not list the reverse recovery time. Rectifier diodes are generally intended for low-frequency applications (60 Hz to perhaps 400 Hz) in which switching time is not important.

Example 2-13

Referring to Fig. 2-21, determine the following quantities for a 1N915 diode: peak reverse voltage, steady-state forward current, peak repetitive forward current and power dissipation.

Solution

For the 1N915:

$$\text{PIV} = V_R = 50 \text{ V}$$

$$I_o = 75 \text{ mA}$$

$$I_{FRM} = 225 \text{ mA}$$
$$P = 250 \text{ mW}$$

Practice Problems

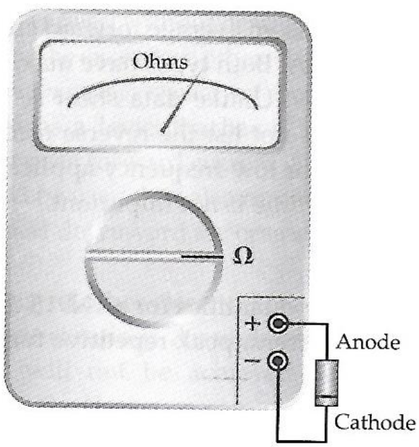
2-7.1 Referring to Appendix A, data sheet A-3, determine the following quantities for a 1N5397 diode: peak reverse voltage, steady-state forward current, and non-repetitive forward current.

2-7.2 A rectifier has to pass an average current of 600 mA and survive a repetitive reverse voltage of 75 V. Choose a suitable diode from Appendix A, data sheets A-1 to A-3.

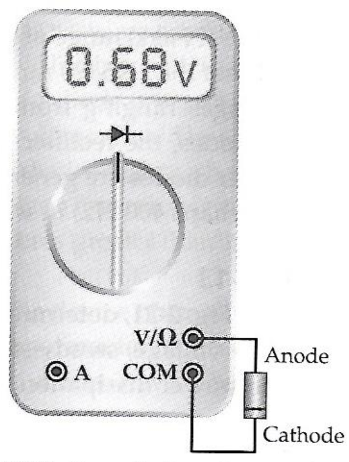
2-8 DIODE TESTING

Ohmmeter Tests

Diode failure is usually the result of passing excessive forward current through the device, or application of excessive reverse voltage. Both situations can result in devices that offer either an open circuit or a short circuit. Several methods are available for testing diodes. One of the simplest and quickest tests can be made by using an ohmmeter to measure the forward and reverse resistance (see Fig. 2-22a). The diode should offer a low resistance when forward-biased and a high resistance when reverse-biased. A diode is short-circuited when it displays a low resistance for both forward



(a) Testing a diode with an ohmmeter



(b) Testing a diode with a digital multimeter

Figure 2-22 Analog or digital multimeters may be used for diode testing. When forward-biased, the diode should display a low resistance, or the typical forward voltage drop. When reverse biased, it should indicate a high reverse resistance.

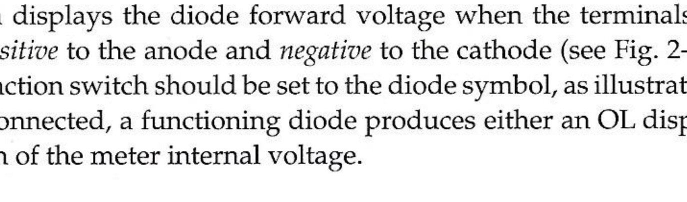
and reverse bias, and open-circuited if a high resistance is measured with both bias polarities. In the case of an analog ohmmeter with a 1.5 V battery, the low resistance indicated is normally about half the selected range. It is important to note that *when some multi-function instruments are used as ohmmeters, the voltage polarity at the terminals may not be the same as the polarity marked on the instrument*. A voltmeter can be used to check the ohmmeter terminal polarity.

Use of a Digital Meter

Many portable multi-function digital instruments have a diode-testing facility which displays the diode forward voltage when the terminals are connected *positive* to the anode and *negative* to the cathode (see Fig. 2-22b). The meter function switch should be set to the diode symbol, as illustrated. When reverse-connected, a functioning diode produces either an OL display or an indication of the meter internal voltage.

Plotting Diode Characteristics

The forward characteristics of a diode can be obtained by use of the circuit illustrated in Fig. 2-23a. The diode voltage is set at a series of convenient levels, and the corresponding current levels are measured and recorded. The characteristics are then plotted from the resulting table of quantities. The reverse characteristics can be derived in the same way, except that a very sensitive microammeter is required in order to measure the reverse current (Fig. 2-23b). The microammeter must be connected directly in series with the diode, as shown; otherwise the voltmeter current may introduce a serious error.



(a) Circuit for obtaining diode forward characteristics

(b) Circuit for obtaining diode reverse characteristics

Figure 2-23 Diode characteristics can be plotted from a table of corresponding current and voltage measurements, obtained by varying the applied voltage in steps and measuring V and I at each step.

Figure 2-24 shows a method of using an *XY recorder* for drawing the forward characteristics of a diode. The resistor voltage (V_{R1}) is directly proportional to the diode forward current (I_F). So V_{R1} is applied to the vertical input terminals of the XY recorder, as illustrated. The diode forward voltage (V_F) goes to the horizontal input terminals. When the power supply voltage is slowly increased from zero, the diode forward characteristic is traced out by the pen on the XY recorder.

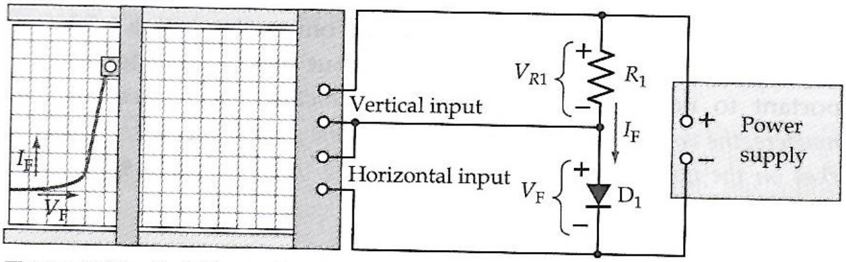


Figure 2-24 An XY recorder can be used for directly plotting diode characteristics.

If R_1 in Fig. 2-24 is a 1 kΩ resistor, there is a 1 V drop across it for every 1 mA of diode current. Therefore, with the vertical scale of the XY recorder set to 1 V/cm, the (vertical) current coordinate of the graph is 1 mA/cm. A convenient scale for the (horizontal) voltage coordinate is 0.1 V/cm. Diode characteristics can also be investigated by means of a *curve tracer,* and by computer graphic analysis software.

Example 2-14

The arrangement shown in Fig. 2-24 is to be used to plot the characteristics of a 1N914 diode. Select a suitable resistor for R_1, and determine appropriate V/cm scales for the XY recorder.

Solution

From Fig. 2-21, $I_o = 75 \text{ mA}$ (for the 1N914)

Select a vertical scale of 5 mA/cm for the characteristic so that

$$\text{Vertical scale length (for } I_F) = \frac{75 \text{ mA}}{5 \text{ mA/cm}}$$

$$= 15 \text{ cm}$$

Select a vertical scale of 1 V/cm for the XY recorder, so that 15 cm represents 15 V as well as 75 mA.

$$R_1 = \frac{15 \text{ V}}{75 \text{ mA}}$$

$$= 200\ \Omega$$

and

$$P_{R1(\max)} = (I_{F(\max)})^2 R_1 = (75 \text{ mA})^2 \times 200\ \Omega$$

$$= 1.1 \text{ W}$$

V_F might be as large as 0.8 V, so select a horizontal scale of 0.1 V/cm so that

$$\text{Horizontal scale length (for } V_F) = \frac{0.8\text{ V}}{0.1\text{V/cm}}$$
$$= 8\text{ cm}$$

Practice Problems

2-8.1 Plot the forward characteristics for a silicon diode from the following experimental data:

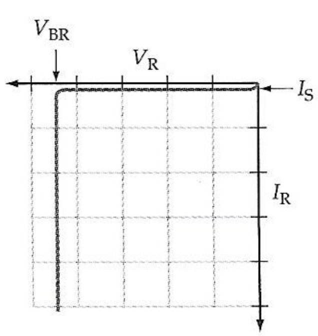
V_F (V)	0.6	0.62	0.64	0.66	0.68	0.7	0.72	0.74	0.76
I_F (mA)	1	1.4	1.8	2.5	10	50	90	130	170

2-8.2 An XY recorder is used (as in Fig. 2-24) to plot silicon diode forward characteristics to approximately fill a 10 cm by 10 cm square. If the maximum forward current is to be 100 mA, select suitable V/cm scales for the recorder and a suitable resistance for R_1.

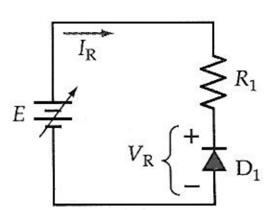
2-9 ZENER DIODES

Junction Breakdown

When a junction diode is reverse-biased, there is normally only a very small reverse saturation current: I_S on the reverse characteristic in Fig. 2-25a. When the reverse voltage is sufficiently increased, the junction *breaks down* and a large reverse current flows. If the reverse current is limited by means of a suitable series-connected resistor (R_1 in the circuit in Fig. 2-25b), the power dissipation in the diode can be kept to a level that will not destroy the device. In this case, the diode may be operated continuously in reverse breakdown. The reverse current returns to its normal level when the voltage is reduced below the reverse breakdown level.



(a) Diode reverse characteristic



(b) Diode-resistor circuit

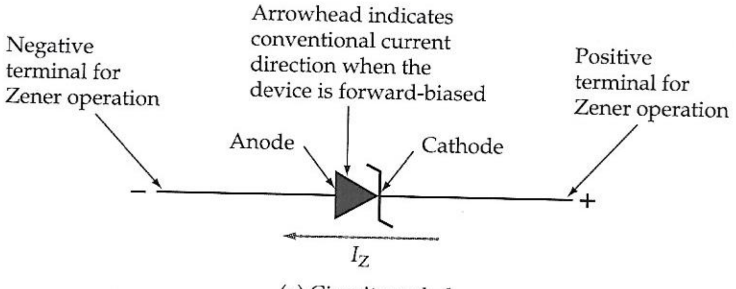
Figure 2-25 A diode can be operated in reverse breakdown if the current is limited by means of a series-connected resistor. Zener diodes are designed for operation in reverse breakdown.

Diodes designed for operation in reverse breakdown are found to have a breakdown voltage that remains extremely stable over a wide range of current levels. This property gives the *breakdown diode* many useful applications as a voltage reference source. There are two mechanisms that cause breakdown in a reverse biased *pn*-junction. With a very narrow depletion region, the electric field strength (volts/width) produced by a reverse bias voltage can be very high. The high-intensity electric field causes electrons to break away from their atoms, thus converting the depletion region from an insulating material into a conductor. This is *ionization by electric field*, also called Zener breakdown, and it usually occurs with reverse bias voltages less than 5 V.

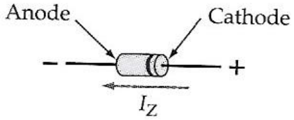
In cases where the depletion region is too wide for Zener breakdown, the electrons in the reverse saturation current can be given sufficient energy to cause other electrons to break free when they strike atoms within the depletion region. This is termed *ionization by collision*. The electrons released in this way collide with other atoms to produce more free electrons in an *avalanche* effect. *Avalanche breakdown* is normally produced by reverse voltage levels above 5 V. Although *Zener* and *avalanche* are two different types of breakdown, the name *Zener diode* is commonly applied to all breakdown diodes.

Circuit Symbol and Package

The circuit symbol for a Zener diode in Fig. 2-26a is the same as that for an ordinary diode but with the cathode bar approximately in the shape of a letter Z. The arrowhead on the symbol still points in the (conventional) direction of forward current when the device is forward-biased. As illustrated, for operation in reverse bias, the voltage drop (V_Z) is positive (+) on the cathode and negative (−) on the anode.



(a) Circuit symbol



(b) Low-current Zener diode

Figure 2-26 Zener diode circuit symbol and low-current Zener diode package.

Low-power Zener diodes are available in a variety of packages. For the device package shown in Fig. 2-26b, the coloured band identifies the cathode terminal, as in the case of an ordinary low-current diode. High-current Zener diodes are also available in the type of package that allows for mounting on a heat sink.

Characteristics and Parameters

The typical characteristics of a Zener diode are shown in detail in Fig. 2-27. Note that the forward characteristic is simply that of an ordinary forward-biased diode. Some important points on the reverse characteristic are

V_Z	Zener breakdown voltage
I_{ZT}	Test current for measuring V_Z
I_{ZK}	Reverse current near the knee of the characteristic, the minimum reverse current to sustain breakdown
I_{ZM}	Maximum Zener current, limited by the maximum power dissipation

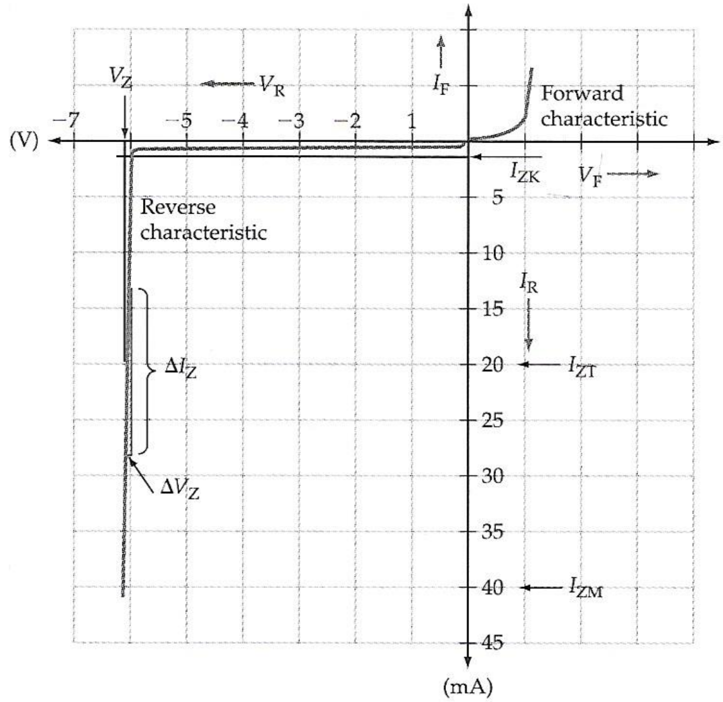


Figure 2-27 Typical characteristics for a Zener diode. The most important parameters are the Zener voltage V_Z, the knee current I_{ZK}, the test current I_{ZT}, and the maximum current I_{ZM}.

The *dynamic impedance* (Z_Z) is another important parameter that may be derived from the characteristics:

$$Z_Z = \frac{\Delta V_Z}{\Delta I_Z} \tag{2-10}$$

As illustrated in Fig. 2-27, Z_Z defines how V_Z changes with variations in diode reverse current. When measured at I_{ZT}, the dynamic impedance is designated (Z_{ZT}). The dynamic impedance measured at the knee of the characteristic (Z_{ZK}) is substantially larger than Z_{ZT}.

The Zener diode may be operated at any (reverse) current level between I_{ZK} and I_{ZM}. For greatest voltage stability, the diode is normally operated at the test current (I_{ZT}). Many low-power Zener diodes have a test current specified as 20 mA; however, some devices have lower test currents.

Data Sheet

A portion of a data sheet for low-power Zener diodes with voltages ranging from 3.3 V to 12 V is shown in Fig. 2-28. (See also data sheet A-4 for 2.4 V to 110 V Zener diodes in Appendix A.) Note in Fig. 2-28 that the V_Z tolerance is stated as ±5% or ±10%. This means that the devices can be purchased with either a ±5% or ±10% tolerance on V_Z. For a 1N753 with a ±10% tolerance, the actual V_Z is 6.2 V ±10%, or 5.58 V to 6.82 V. The Zener voltage remains stable at whatever it happens to be within this range.

Type 1N746 Through 1N759 Silicon Zener Diodes

3.3 V to 12 V (±5% or ±10%)
P_D = 400 mW (derate linearly above 50°C at 3.2 mW/°C)

Electrical characteristics at 25°C ambient temperature

Type number	Nominal Zener voltage V_Z (V)	Test current I_Z (mA)	Zener impedance Z_{ZT} (Ω)	Leakage current I_R (μA)	Reverse temperature coefficient α_Z (%/°C)
IN746	3.3	20	28	10	−0.062
IN747	3.6	20	24	10	−0.055
IN753	6.2	20	7	0.1	+0.022
IN755	7.5	20	6	0.1	+0.045
IN757	9.1	20	10	0.1	+0.056
IN759	12.0	20	30	0.1	+0.060

Figure 2-28 Portions of a data sheet for low-power Zener diodes.

The data sheet also lists the dynamic impedance (Z_{ZT}); reverse leakage current (I_R), which is the reverse current before breakdown; and the temperature coefficient (α_Z) for the V_Z of each device. The Zener voltages at any temperature can be calculated as follows:

$$V_{Z2} = (V_{Z1} \text{ at } T_1) + [\Delta T \, \alpha_Z \, V_Z/100)] \quad \textbf{(2-11)}$$

Temperature-compensated Zener diodes are also available with extremely low temperature coefficients.

Low-power Zener diodes are generally limited to a maximum power dissipation of 400 mW (P_D in Fig. 2-28). Higher power devices are available. All of the power dissipations must be derated with temperature increase, exactly as explained in Section 2-5. When the maximum Zener current is not listed on the device data sheet, it may be calculated from the power dissipation equation:

$$P_D = V_Z I_{ZM} \quad \textbf{(2-12)}$$

Example 2-15

Calculate the maximum current that may be allowed to flow through a 1N755 Zener diode at device temperatures of 50°C and 100°C.

Solution

From data sheet A-4 in Appendix A, it can be seen that for the 1N755 Zener diode, $V_Z = 7.5$ V, $P_D = 400$ mW at 50°C, and the derating factor = 3.2 mW/°C.

At 50°C:

From Eq. 2-12,
$$I_{ZM} = \frac{P_D}{V_Z} = \frac{400 \text{ mV}}{7.5 \text{ V}}$$
$$= 53.3 \text{ mA}$$

At 100°C:

Eq. 2-5:
$$P_2 = (P_1 \text{ at } T_1) - [\Delta T \times \text{derating factor}]$$
$$= 400 \text{ mW} - [(100°\text{C} - 50°\text{C}) \times 3.2 \text{ mW}/°\text{C}]$$
$$= 240 \text{ mW}$$

From Eq. 2-12,
$$I_{ZM} = \frac{P_2}{V_Z} = \frac{240 \text{ mW}}{7.5 \text{ V}}$$
$$= 32 \text{ mA}$$

Example 2-16

For the Zener diode circuit in Fig. 2-29, $E = 20$ V, and $R_1 = 620\ \Omega$. The Zener diode is a 1N755. Calculate the diode current and power dissipation.

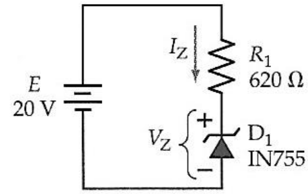


Figure 2-29 Circuit for Ex. 2-16.

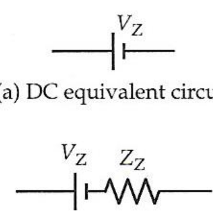
Solution

From the data sheet in Fig. 2-28, it is seen that for the 1N755 Zener diode, $V_Z = 7.5$ V

$$V_{R1} = E - V_Z = 20\text{ V} - 7.5\text{ V}$$
$$= 12.5\text{ V}$$
$$I_Z = I_{R1} = \frac{V_{R1}}{R_1} = \frac{12.5\text{ V}}{620\ \Omega}$$
$$= 20.16\text{ mA}$$
$$P_D = V_Z I_Z = 7.5\text{ V} \times 20.16\text{ mA}$$
$$= 151\text{ mW}$$

Equivalent Circuit

The dc equivalent circuit for a Zener diode is simply a voltage cell with a voltage V_Z, as in Fig. 2-30a. This is the complete equivalent circuit for the device for all dc calculations. For the ac equivalent circuit (Fig. 2-30b), the dynamic impedance is included in series with the voltages cell. The ac equivalent circuit is used in situations where the Zener current is varied by small amounts. It must be understood that these equivalent circuits apply only when the Zener diode is maintained in reverse breakdown. If the device becomes forward-biased, then the equivalent circuit for a forward-biased diode must be used.



(a) DC equivalent circuit

(b) AC equivalent circuit

Figure 2-30 DC and AC equivalent circuits for a Zener diode.

Example 2-17

A Zener diode with $V_Z = 4.3$ V has Z_Z equal to 22 Ω when $I_Z = 20$ mA. Calculate the upper and lower limits of V_Z when I_Z changes by ±5 mA.

Solution

$$\Delta V_Z = \pm(\Delta I_Z \times Z_Z) = \pm(5\text{ mA} \times 22\ \Omega)$$

$$= \pm 110 \text{ mV}$$

$$V_{Z(max)} = V_Z + \Delta V_Z = 4.3 \text{ V} + 110 \text{ mV}$$

$$= 4.41 \text{ V}$$

$$V_{Z(min)} = V_Z - \Delta V_Z = 4.3 \text{ V} - 110 \text{ mV}$$

$$= 4.19 \text{ V}$$

Practice Problems

2-9.1 Calculate the maximum current for a 1N753 Zener diode at device temperatures of 50°C and 100°C.

2-9.2 A 1N749 Zener diode is connected in series with an 820 Ω resistor and a 12 V supply. Calculate the diode current and power dissipation.

Review Questions

Section 2-1

2-1 Sketch the symbol for a semiconductor diode, labelling the anode and cathode and showing the polarity and current direction for forward bias. Show the direction of movement of charge carriers when the device is (a) forward-biased and (b) reverse-biased.

2-2 Draw sketches to show the appearance of low-current and medium-current diodes, and show how the cathode is identified in each case.

Section 2-2

2-3 Sketch typical forward and reverse characteristics for a germanium diode and for a silicon diode. Discuss the characteristics, and compare silicon and germanium diodes.

2-4 For diodes, define forward voltage drop, maximum forward current, dynamic resistance, reverse saturation current, and reverse breakdown voltage.

2-5 Show how the diode dynamic resistance can be determined from the forward characteristics. Write an equation for calculating the dynamic resistance from the dc forward current.

Section 2-3

2-6 Sketch the characteristics for an ideal diode and the approximate characteristics for practical diodes. Briefly explain each characteristic.

2-7 Draw the dc equivalent circuit for a diode and the piecewise linear equivalent circuit. Discuss the application of each.

Section 2-4

2-8 Explain the purpose of a dc load line. Write the equation for drawing a dc load line for a series circuit consisting of a supply voltage (E), a resistor (R_1), and a diode (D_1).

2-9 Define the Q-point in a diode circuit, and explain how it is related to the diode characteristics and the dc load line.

Section 2-5

2-10 Sketch and explain a power-versus-temperature graph for a diode. Define the power-derating factor for a diode.

2-11 Discuss how temperature change affects diode forward voltage drop.

Section 2-6

2-12 Explain the origins of depletion layer capacitance and diffusion capacitance, and discuss the importance of each.

2-13 Sketch the complete equivalent circuits for forward-biased and reverse-biased diodes. Sketch the ac equivalent circuit for a forward-biased diode. Briefly explain each circuit.

2-14 Define reverse recovery time. Sketch waveforms to show the effect of reverse recovery time on a diode switched rapidly from *on* to *off*. Explain each waveform.

Section 2-7

2-15 Discuss the major differences between switching diodes and rectifier diodes.

2-16 Define the following diode quantities: peak reverse voltage, repetitive peak surge current, and steady-state forward current.

Section 2-8

2-17 Describe how an ohmmeter and a digital multimeter may be used for testing diodes.

2-18 Sketch circuits for obtaining diode forward and reverse characteristics by measuring corresponding current and voltage levels. Explain.

2-19 Draw a sketch to show how the forward characteristics of a diode may be plotted on an XY recorder.

Section 2-9

2-20 Discuss the different types of junction breakdown that can occur in a reverse-biased diode. Sketch the circuit symbol for a Zener diode, and briefly explain Zener diode operation.

2-21 Sketch typical characteristics for a Zener diode. Explain the shape of the characteristics, and identify the important points.

2-22 Sketch the equivalent circuit for a Zener diode. Briefly explain.

Problems

Section 2-2

2-1 Calculate the static forward resistance for the characteristics in Fig. 2-31 at a 200 mA forward current. Determine the reverse resistance at a 75 V reverse voltage.

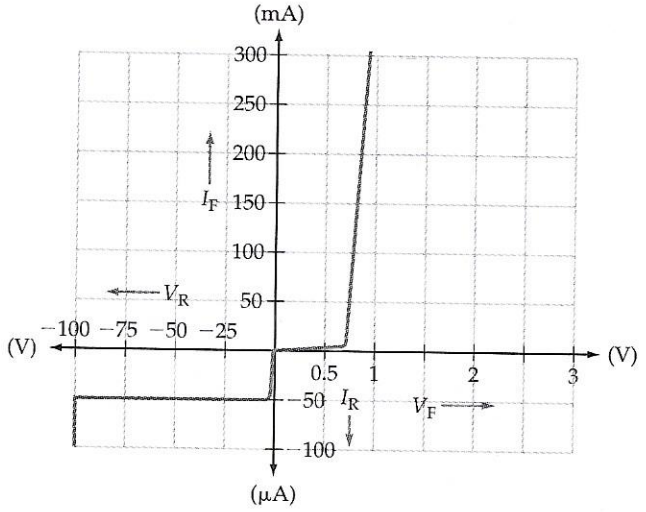


Figure 2-31 Diode characteristics for Problems 2-1, 2-2, and 2-9.

2-2 Determine the dynamic resistance at a 150 mA forward current for a diode with the characteristics shown in Fig. 2-31.

2-3 Calculate the static forward resistance for the diode characteristics shown in Fig. 2-32 at a 25 mA forward current. Also, determine the dynamic resistance for the device at $I_F = 25$ mA, using the characteristic and using Eq. 2-2.

Section 2-3

2-4 Calculate the forward current in a circuit consisting of a germanium diode connected in series with a 9 V battery and a 3.3 kΩ resistor.

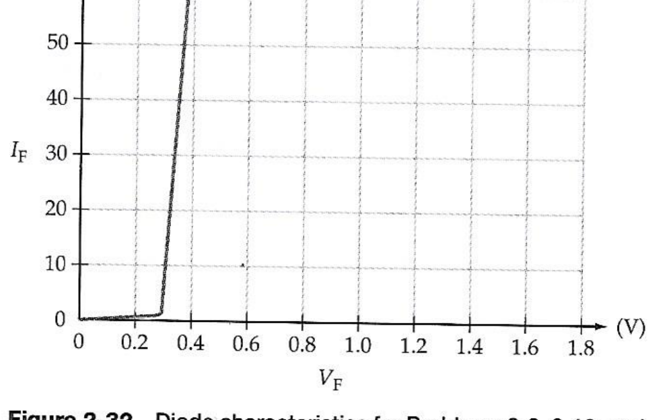


Figure 2-32 Diode characteristics for Problems 2-3, 2-10, and 2-11.

2-5 A silicon diode in series with a 2.7 kΩ resistor and a battery is to have an I_F of 1.96 mA. Calculate the battery voltage.

2-6 Draw the piecewise linear characteristics for a silicon diode with a 0.6 Ω dynamic resistance and a 75 mA maximum forward current.

2-7 Draw a straight-line approximation of the forward characteristic for a silicon diode that has a 0.5 Ω dynamic resistance and a maximum forward current of 300 mA.

Section 2-4

2-8 A diode with the characteristics in Fig. 2-13b is to pass a 35 mA current from a 5.5 V supply. Draw the dc load line and calculate the required series resistance value. Determine the new current level when the supply is reduced to 3.5 V.

2-9 A diode with the forward characteristic in Fig. 2-31 is connected in series with a 30 Ω resistance and a 6 V supply. Determine the diode current, and find the new current when the resistance is changed to 20 Ω.

2-10 A diode which has the characteristics shown in Fig. 2-32 is to pass a 20 mA forward current when the supply is 12 V. Determine the value of resistance that must be connected in series with the diode.

2-11 Calculate the new supply voltage for the circuit in Problem 2-10 to give a 15 mA current level.

Section 2-5

2-12 A diode with a maximum power dissipation of 1000 mW at 25°C is to pass an average forward current of 500 mA. The forward voltage drop for the device is 0.8 V, and the power derating factor is 10 mW/°C. Calculate the maximum temperature at which the diode may be safely operated.

2-13 The diode specified in Problem 2-12 is to be operated at a temperature of 75°C. Calculate the maximum level of average forward current that the diode can safely pass.

2-14 Draw the power dissipation-versus-temperature graph for the diode specified in Problem 2-12.

2-15 A diode with a 0.9 V forward drop has a 1.5 W maximum power dissipation at 25°C. If the device derating factor is 7.5 mW/°C, calculate the maximum forward current level at 25°C and at 75°C. Assume that V_F remains constant.

2-16 Estimate the forward voltage drop at 75°C of the silicon diode in Problem 2-15. Determine the junction dynamic resistances at the temperature extremes if I_F is 20 mA.

2-17 A 5 V supply is applied via a 150 Ω resistor to a silicon diode and a germanium diode that are connected in series. Determine the diode current at 25°C and at 100°C.

Section 2-6

2-18 Calculate the minimum fall time for a voltage pulse applied to a diode with a reverse recovery time of (a) 6 ns and (b) 50 ns.

2-19 A diode has an applied voltage with a 200 ns fall time. Determine the diode maximum reverse recovery time for satisfactory operation.

2-20 Calculate a suitable minimum fall time for a switching waveform applied to a diode that has a 12 ns reverse recovery time.

2-21 Calculate the minimum fall time for a voltage pulse applied to a circuit with a 1N914 diode.

Section 2-7

2-22 A diode connected in series with a 560 Ω resistor has a supply voltage that alternates between peak levels of +150 V and −150 V. Select a suitable device from the data sheets A-1 and A-2 in Appendix A.

2-23 Referring to data sheet A-3 in Appendix A, determine the peak reverse voltage and average rectified forward current for a 1N5398 diode.

2-24 A rectifier diode has to pass an average current of 55 mA and survive a 40 V peak reverse voltage. Select a suitable device from data sheets A-1 to A-3 in Appendix A.

Section 2-8

2-25 The arrangement shown in Fig. 2-24 is to be used to plot the forward characteristics of a 1N917 diode. Determine a resistance value for R_1, and select appropriate V/cm scales for the horizontal and vertical inputs of the XY recorder. The graph should be approximately 20 cm × 20 cm.

2-26 Plot the forward characteristics of a diode from the following experimental data:

V_F (V)	0.24	0.26	0.28	0.29	0.30	0.31	0.32	0.33	0.34
I_F (mA)	0.05	0.07	0.09	0.5	0.9	20	40	60	80

Section 2-9

2-27 Determine the maximum current that may be used with a 1N757 Zener diode at temperatures of 25°C and 80°C.

2-28 A 1N750 Zener diode is connected in series with an 470 Ω resistor and a 10 V supply voltage. Calculate the diode current and power dissipation.

Practice Problem Answers

2-2.1 5.5 Ω, 30 MΩ
2-2.2 0.5 Ω, 0.5 Ω
2-3.1 2.89 mA
2-3.2 (Point A: 0 mA, 0.3 V), (Point B: 100 mA, 0.35 V)
2-3.3 174 mA
2-4.1 20 mA
2-4.2 50 Ω
2-4.3 3.45 V
2-5.1 154 mA, 61.5 mA
2-5.2 267 mV, 421 mV, 1.23 Ω, 1.54 Ω

2-5.3 780 mV
2-6.1 50 ns
2-6.2 150 ns
2-6.3 154 ns
2-7.1 600 V, 1.5 A, 50 A
2-7.2 1N5392
2-8.2 Vertical 1 V/cm, Horizontal 0.1 V/cm, 100 Ω
2-9.1 64.5 mA, 38.7 mA
2-9.2 40.4 mW