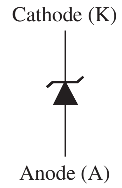
3–1 THE ZENER DIODE

A major application for zener diodes is as a type of voltage regulator for providing stable reference voltages for use in power supplies, voltmeters, and other instruments. In this section, you will see how the zener diode maintains a nearly constant dc voltage under the proper operating conditions. You will learn the conditions and limitations for properly using the zener diode and the factors that affect its performance.

After completing this section, you should be able to

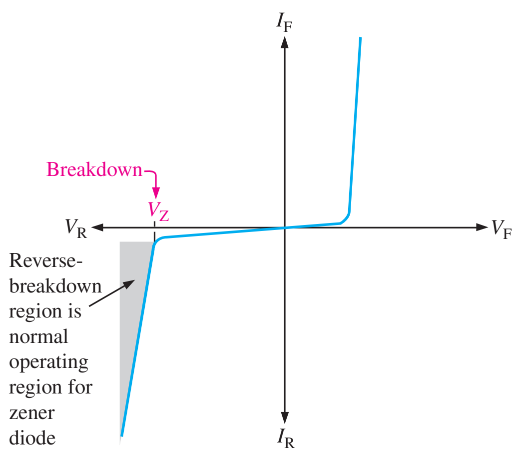
- **Describe the characteristics of a zener diode and analyze its operation**
- Recognize a zener diode by its schematic symbol
- Discuss zener breakdown
    - Define *avalanche breakdown*
- Explain zener breakdown characteristics
    - Describe zener regulation
- Discuss zener equivalent circuits
- Define *temperature coefficient*
    - Analyze zener voltage as a function of temperature
- Discuss zener power dissipation and derating
    - Apply power derating to a zener diode
- Interpret zener diode datasheets

The symbol for a zener diode is shown in Figure 3–1. Instead of a straight line representing the cathode, the zener diode has a bent line that reminds you of the letter Z (for zener). A **zener diode** is a silicon *pn* junction device that is designed for operation in the reverse-breakdown region. The breakdown voltage of a zener diode is set by carefully controlling the doping level during manufacture. Recall, from the discussion of the diode characteristic curve in Chapter 2, that when a diode reaches reverse breakdown, its voltage remains almost constant even though the current changes drastically, and this is the key to zener diode operation. This volt-ampere characteristic is shown again in Figure 3–2 with the normal operating region for zener diodes shown as a shaded area.



▲ **FIGURE 3–1**

Zener diode symbol.



◀ **FIGURE 3–2**

General zener diode *V-I* characteristic.

Zener Breakdown

Zener diodes are designed to operate in reverse breakdown. Two types of reverse breakdown in a zener diode are *avalanche* and *zener.* The avalanche effect, discussed in Chapter 2, occurs in both rectifier and zener diodes at a sufficiently high reverse voltage. **Zener breakdown**

HISTORY NOTE

Clarence Melvin Zener, an American physicist, was born in Indianapolis and earned his PhD from Harvard in 1930. He was the first to describe the properties of reverse breakdown that are exploited by the zener diode. As a result, Bell Labs, where the device was developed, named the diode after him. He was also involved in areas of superconductivity, metallurgy, and geometric programming.

occurs in a zener diode at low reverse voltages. A zener diode is heavily doped to reduce the breakdown voltage. This causes a very thin depletion region. As a result, an intense electric field exists within the depletion region. Near the zener breakdown voltage (V_Z), the field is intense enough to pull electrons from their valence bands and create current.

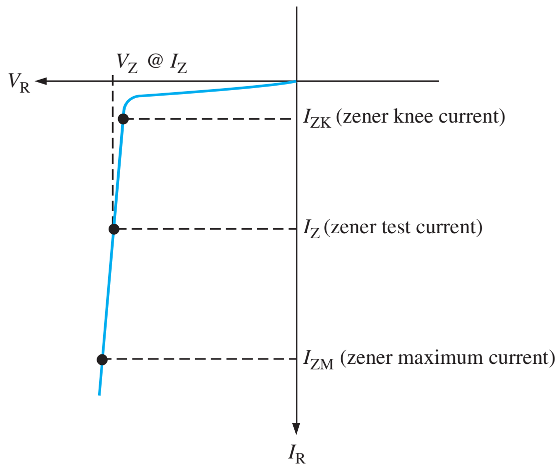
Zener diodes with breakdown voltages of less than approximately 5 V operate predominately in zener breakdown. Those with breakdown voltages greater than approximately 5 V operate predominately in **avalanche breakdown.** Both types, however, are called *zener diodes.* Zeners are commercially available with breakdown voltages from less than 1 V to more than 250 V with specified tolerances from 1% to 20%.

Breakdown Characteristics

Figure 3–3 shows the reverse portion of a zener diode's characteristic curve. Notice that as the reverse voltage (V_R) is increased, the reverse current (I_R) remains extremely small up to the "knee" of the curve. The reverse current is also called the zener current, I_Z. At this point, the breakdown effect begins; the internal zener resistance, also called zener impedance (Z_Z), begins to decrease as the reverse current increases rapidly. From the bottom of the knee, the zener breakdown voltage (V_Z) remains essentially constant although it increases slightly as the zener current, I_Z, increases.

▶ FIGURE 3–3

Reverse characteristic of a zener diode. V_Z is usually specified at a value of the zener current known as the test current.

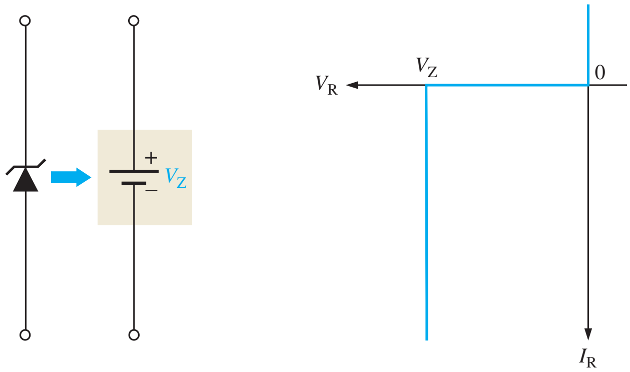


Zener Regulation The ability to keep the reverse voltage across its terminals essentially constant is the key feature of the zener diode. A zener diode operating in breakdown acts as a voltage regulator because it maintains a nearly constant voltage across its terminals over a specified range of reverse-current values.

A minimum value of reverse current, I_{ZK}, must be maintained in order to keep the diode in breakdown for voltage regulation. You can see on the curve in Figure 3–3 that when the reverse current is reduced below the knee of the curve, the voltage decreases drastically and regulation is lost. Also, there is a maximum current, I_{ZM}, above which the diode may be damaged due to excessive power dissipation. So, basically, the zener diode maintains a nearly constant voltage across its terminals for values of reverse current ranging from I_{ZK} to I_{ZM}. A nominal zener voltage, V_Z, is usually specified on a datasheet at a value of reverse current called the *zener test current.*

Zener Equivalent Circuits

Figure 3–4 shows the ideal model (first approximation) of a zener diode in reverse breakdown and its ideal characteristic curve. It has a constant voltage drop equal to the nominal zener voltage. This constant voltage drop across the zener diode produced by reverse breakdown is represented by a dc voltage symbol even though the zener diode does not produce a voltage.



(a) Ideal model (b) Ideal characteristic curve

◀ FIGURE 3–4

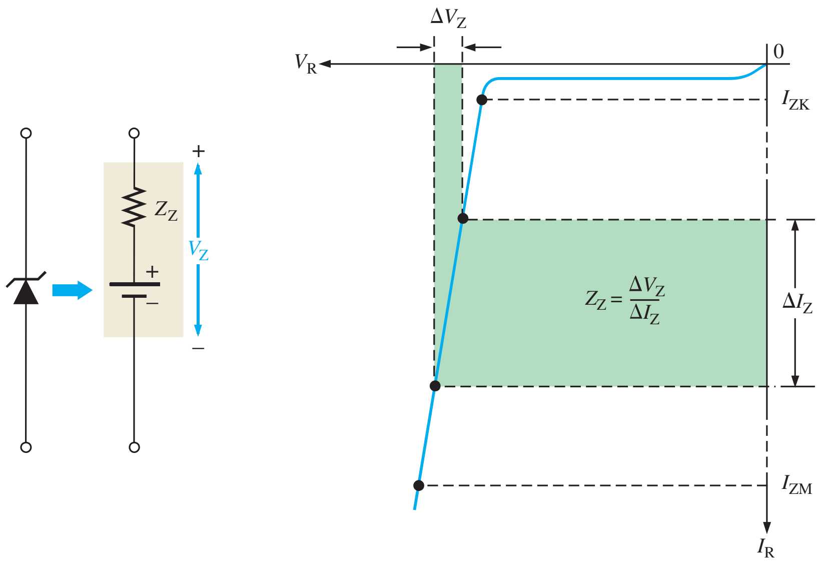
Ideal zener diode equivalent circuit model and the characteristic curve.

Figure 3–5(a) represents the practical model (second approximation) of a zener diode, where the zener impedance (resistance), Z_Z, is included. Since the actual voltage curve is not ideally vertical, a change in zener current (ΔI_Z) produces a small change in zener voltage (ΔV_Z), as illustrated in Figure 3–5(b). By Ohm's law, the ratio of ΔV_Z to ΔI_Z is the impedance, as expressed in the following equation:

$$\boldsymbol{Z_Z = \frac{\Delta V_Z}{\Delta I_Z}}$$

Equation 3–1

Normally, Z_Z is specified at the zener test current. In most cases, you can assume that Z_Z is a small constant over the full range of zener current values and is purely resistive. It is best to avoid operating a zener diode near the knee of the curve because the impedance changes dramatically in that area.



(a) Practical model (b) Characteristic curve. The slope is exaggerated for illustration.

◀ FIGURE 3–5

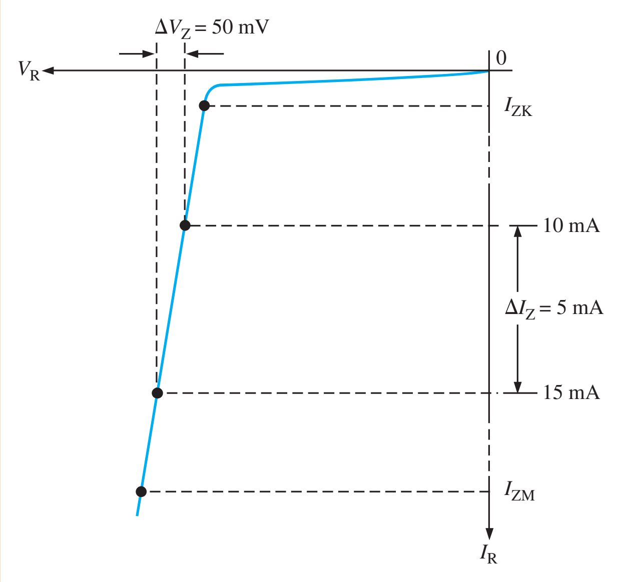
Practical zener diode equivalent circuit and the characteristic curve illustrating Z_Z.

For most circuit analysis and troubleshooting work, the ideal model will give very good results and is much easier to use than more complicated models. When a zener diode is operating normally, it will be in reverse breakdown and you should observe the nominal breakdown voltage across it. Most **schematics** will indicate on the drawing what this voltage should be.

EXAMPLE 3–1

A zener diode exhibits a certain change in V_Z for a certain change in I_Z on a portion of the linear characteristic curve between I_{ZK} and I_{ZM} as illustrated in Figure 3–6. What is the zener impedance?

▶ **FIGURE 3–6**



Solution

$$Z_Z = \frac{\Delta V_Z}{\Delta I_Z} = \frac{50\text{ mV}}{5\text{ mA}} = \mathbf{10\ \Omega}$$

*Related Problem**

Calculate the zener impedance if the change in zener voltage is 100 mV for a 20 mA change in zener current on the linear portion of the characteristic curve.

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

Temperature Coefficient

The temperature coefficient specifies the percent change in zener voltage for each degree Celsius change in temperature. For example, a 12 V zener diode with a positive temperature coefficient of 0.01%/°C will exhibit a 1.2 mV increase in V_Z when the junction temperature increases one degree Celsius. The formula for calculating the change in zener voltage for a given junction temperature change, for a specified temperature coefficient, is

Equation 3–2

$$\Delta V_Z = V_Z \times TC \times \Delta T$$

where V_Z is the nominal zener voltage at the reference temperature of 25°C, TC is the temperature coefficient, and ΔT is the change in temperature from the reference temperature. A positive TC means that the zener voltage increases with an increase in temperature or decreases with a decrease in temperature. A negative TC means that the zener voltage decreases with an increase in temperature or increases with a decrease in temperature.

In some cases, the temperature coefficient is expressed in mV/°C rather than as %/°C. For these cases, ΔV_Z is calculated as

Equation 3–3

$$\Delta V_Z = TC \times \Delta T$$

EXAMPLE 3–2 An 8.2 V zener diode (8.2 V at 25°C) has a positive temperature coefficient of 0.05%/°C. What is the zener voltage at 60°C?

Solution The change in zener voltage is

$$\Delta V_Z = V_Z \times TC \times \Delta T = (8.2\text{ V})(0.05\%/°\text{C})(60°\text{C} - 25°\text{C})$$
$$= (8.2\text{ V})(0.0005/°\text{C})(35°\text{C}) = 144\text{ mV}$$

Notice that 0.05%/°C was converted to 0.0005/°C. The zener voltage at 60°C is

$$V_Z + \Delta V_Z = 8.2\text{ V} + 144\text{ mV} = \mathbf{8.34\ V}$$

Related Problem A 12 V zener has a positive temperature coefficient of 0.075%/°C. How much will the zener voltage change when the junction temperature decreases 50 degrees Celsius?

Zener Power Dissipation and Derating

Zener diodes are specified to operate at a maximum power called the maximum dc power dissipation, $P_{D(max)}$. For example, the 1N746 zener is rated at a $P_{D(max)}$ of 500 mW and the 1N3305A is rated at a $P_{D(max)}$ of 50 W. The dc power dissipation is determined by the formula,

$$P_D = V_Z I_Z$$

Power Derating The maximum power dissipation of a zener diode is typically specified for temperatures at or below a certain value (50°C, for example). Above the specified temperature, the maximum power dissipation is reduced according to a derating factor. The derating factor is expressed in mW/°C. The maximum derated power can be determined with the following formula:

$$P_{D(derated)} = P_{D(max)} - (\text{mW}/°\text{C})\Delta T$$

EXAMPLE 3–3 A certain zener diode has a maximum power rating of 400 mW at 50°C and a derating factor of 3.2 mW/°C. Determine the maximum power the zener can dissipate at a temperature of 90°C.

Solution

$$P_{D(derated)} = P_{D(max)} - (\text{mW}/°\text{C})\Delta T$$
$$= 400\text{ mW} - (3.2\text{ mW}/°\text{C})(90°\text{C} - 50°\text{C})$$
$$= 400\text{ mW} - 128\text{ mW} = \mathbf{272\ mW}$$

Related Problem A certain 50 W zener diode must be derated with a derating factor of 0.5 W/°C above 75°C. Determine the maximum power it can dissipate at 160°C.

Zener Diode Datasheet Information

The amount and type of information found on datasheets for zener diodes (or any category of electronic device) varies from one type of diode to the next. The datasheet for some zeners contains more information than for others. Figure 3–7 gives an example of the type of information you have studied that can be found on a typical datasheet. This particular information is for a zener series, the 1N4728A–1N4764A.

FAIRCHILD
SEMICONDUCTOR®

1N4728A - 1N4764A

Zeners

DO-41 Glass case
COLOR BAND DENOTES CATHODE

Absolute Maximum Ratings * T_a = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
P_D	Power Dissipation @ TL ≤ 50°C, Lead Length = 3/8"	1.0	W
	Derate above 50°C	6.67	mW/°C
T_J, T_{STG}	Operating and Storage Temperature Range	-65 to +200	°C

* These ratings are limiting values above which the serviceability of the diode may be impaired.

Electrical Characteristics T_a = 25°C unless otherwise noted

Device	V_Z (V) @ I_Z (Note 1)			Test Current	Max. Zener Impedance			Leakage Current	
	Min.	Typ.	Max.	I_Z (mA)	Z_Z @ I_Z (Ω)	Z_{ZK} @ I_{ZK} (Ω)	I_{ZK} (mA)	I_R (μA)	V_R (V)
1N4728A	3.315	3.3	3.465	76	10	400	1	100	1
1N4729A	3.42	3.6	3.78	69	10	400	1	100	1
1N4730A	3.705	3.9	4.095	64	9	400	1	50	1
1N4731A	4.085	4.3	4.515	58	9	400	1	10	1
1N4732A	4.465	4.7	4.935	53	8	500	1	10	1
1N4733A	4.845	5.1	5.355	49	7	550	1	10	1
1N4734A	5.32	5.6	5.88	45	5	600	1	10	2
1N4735A	5.89	6.2	6.51	41	2	700	1	10	3
1N4736A	6.46	6.8	7.14	37	3.5	700	1	10	4
1N4737A	7.125	7.5	7.875	34	4	700	0.5	10	5
1N4738A	7.79	8.2	8.61	31	4.5	700	0.5	10	6
1N4739A	8.645	9.1	9.555	28	5	700	0.5	10	7
1N4740A	9.5	10	10.5	25	7	700	0.25	10	7.6
1N4741A	10.45	11	11.55	23	8	700	0.25	5	8.4
1N4742A	11.4	12	12.6	21	9	700	0.25	5	9.1
1N4743A	12.35	13	13.65	19	10	700	0.25	5	9.9
1N4744A	14.25	15	15.75	17	14	700	0.25	5	11.4
1N4745A	15.2	16	16.8	15.5	16	700	0.25	5	12.2
1N4746A	17.1	18	18.9	14	20	750	0.25	5	13.7
1N4747A	19	20	21	12.5	22	750	0.25	5	15.2
1N4748A	20.9	22	23.1	11.5	23	750	0.25	5	16.7
1N4749A	22.8	24	25.2	10.5	25	750	0.25	5	18.2
1N4750A	25.65	27	28.35	9.5	35	750	0.25	5	20.6
1N4751A	28.5	30	31.5	8.5	40	1000	0.25	5	22.8
1N4752A	31.35	33	34.65	7.5	45	1000	0.25	5	25.1
1N4753A	34.2	36	37.8	7	50	1000	0.25	5	27.4
1N4754A	37.05	39	40.95	6.5	60	1000	0.25	5	29.7
1N4755A	40.85	43	45.15	6	70	1500	0.25	5	32.7
1N4756A	44.65	47	49.35	5.5	80	1500	0.25	5	35.8
1N4757A	48.45	51	53.55	5	95	1500	0.25	5	38.8
1N4758A	53.2	56	58.8	4.5	110	2000	0.25	5	42.6
1N4759A	58.9	62	65.1	4	125	2000	0.25	5	47.1
1N4760A	64.6	68	71.4	3.7	150	2000	0.25	5	51.7
1N4761A	71.25	75	78.75	3.3	175	2000	0.25	5	56
1N4762A	77.9	82	86.1	3	200	3000	0.25	5	62.2
1N4763A	86.45	91	95.55	2.8	250	3000	0.25	5	69.2
1N4764A	95	100	105	2.5	350	3000	0.25	5	76

Notes:
1. Zener Voltage (V_Z)
The zener voltage is measured with the device junction in the thermal equilibrium at the lead temperature (T_L) at 30°C ± 1°C and 3/8" lead length.

▲ FIGURE 3–7

Partial datasheet for the 1N4728A–1N4764A series 1 W zener diodes. Copyright Fairchild Semiconductor Corporation. Used by permission. Datasheets are available at www.fairchildsemi.com.

Absolute Maximum Ratings The maximum power dissipation, P_D, is specified as 1.0 W up to 50°C. Generally, the zener diode should be operated at least 20% below this maximum to assure reliability and longer life. The power dissipation is derated as shown on the datasheet at 6.67 mW for each degree above 50°C. For example, using the procedure illustrated in Example 3–3, the maximum power dissipation at 60°C is

$$P_D = 1\text{ W} - 10°\text{C}(6.67\text{ mW/°C}) = 1\text{ W} - 66.7\text{ mW} = 0.9933\text{ W}$$

At 125°C, the maximum power dissipation is

$$P_D = 1\text{ W} - 75°\text{C}(6.67\text{ mW/°C}) = 1\text{ W} - 500.25\text{ mW} = 0.4998\text{ W}$$

Notice that a maximum reverse current is not specified but can be determined from the maximum power dissipation for a given value of V_Z. For example, at 50°C, the maximum zener current for a zener voltage of 3.3 V is

$$I_{ZM} = \frac{P_D}{V_Z} = \frac{1\text{ W}}{3.3\text{ V}} = 303\text{ mA}$$

The operating junction temperature, T_J, and the storage temperature, T_{STG}, have a range of from −65°C to 200°C.

Electrical Characteristics The first column in the datasheet lists the zener type numbers, 1N4728A through 1N4764A.

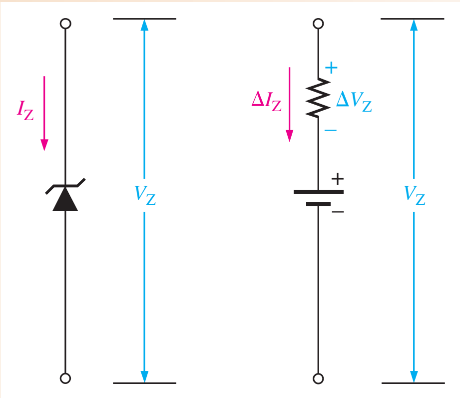
Zener voltage, V_Z, and zener test current, I_Z For each device type, the minimum, typical, and maximum zener voltages are listed. V_Z is measured at the specified zener test current, I_Z. For example, the zener voltage for a 1N4728A can range from 3.315 V to 3.465 V with a typical value of 3.3 V at a test current of 76 mA.

Maximum zener impedance Z_Z is the maximum zener impedance at the specified test current, I_Z. For example, for a 1N4728A, Z_Z is 10 Ω at 76 mA. The maximum zener impedance, Z_{ZK}, at the knee of the characteristic curve is specified at I_{ZK}, which is the current at the knee of the curve. For example, Z_{ZK} is 400 Ω at 1 mA for a 1N4728A.

Leakage current Reverse leakage current is specified for a reverse voltage that is less than the knee voltage. This means that the zener is not in reverse breakdown for these measurements. For example I_R is 100 μA for a reverse voltage of 1 V in a 1N4728A.

EXAMPLE 3–4

From the datasheet in Figure 3–7, a 1N4736A zener diode has a Z_Z of 3.5 Ω. The datasheet gives $V_Z = 6.8$ V at a test current, I_Z, of 37 mA. What is the voltage across the zener terminals when the current is 50 mA? When the current is 25 mA? Figure 3–8 represents the zener diode.



▲ FIGURE 3–8

Solution For $I_Z = 50$ mA: The 50 mA current is a 13 mA increase above the test current, I_Z, of 37 mA.

$$\Delta I_Z = I_Z - 37\text{ mA} = 50\text{ mA} - 37\text{ mA} = +13\text{ mA}$$
$$\Delta V_Z = \Delta I_Z Z_Z = (13\text{ mA})(3.5\ \Omega) = +45.5\text{ mV}$$

The change in voltage due to the increase in current above the I_Z value causes the zener terminal voltage to increase. The zener voltage for $I_Z = 50$ mA is

$$V_Z = 6.8\text{ V} + \Delta V_Z = 6.8\text{ V} + 45.5\text{ mV} = \mathbf{6.85\text{ V}}$$

For $I_Z = 25$ mA: The 25 mA current is a 12 mA decrease below the test current, I_Z, of 37 mA.

$$\Delta I_Z = -12\text{ mA}$$
$$\Delta V_Z = \Delta I_Z Z_Z = (-12\text{ mA})(3.5\ \Omega) = -42\text{ mV}$$

The change in voltage due to the decrease in current below the test current causes the zener terminal voltage to decrease. The zener voltage for $I_Z = 25$ mA is

$$V_Z = 6.8\text{ V} - \Delta V_Z = 6.8\text{ V} - 42\text{ mV} = \mathbf{6.76\text{ V}}$$

Related Problem Repeat the analysis for $I_Z = 10$ mA and for $I_Z = 30$ mA using a 1N4742A zener with $V_Z = 12$ V at $I_Z = 21$ mA and $Z_Z = 9\ \Omega$.

SECTION 3–1 CHECKUP
Answers can be found at www.pearsonhighered.com/floyd.

1. In what region of their characteristic curve are zener diodes operated?
2. At what value of zener current is the zener voltage normally specified?
3. How does the zener impedance affect the voltage across the terminals of the device?
4. What does a positive temperature coefficient of **0.05%/°C** mean?
5. Explain power derating.

3–2 ZENER DIODE APPLICATIONS

The zener diode can be used as a type of voltage regulator for providing stable reference voltages. In this section, you will see how zeners can be used as voltage references, regulators, and as simple limiters or clippers.

After completing this section, you should be able to

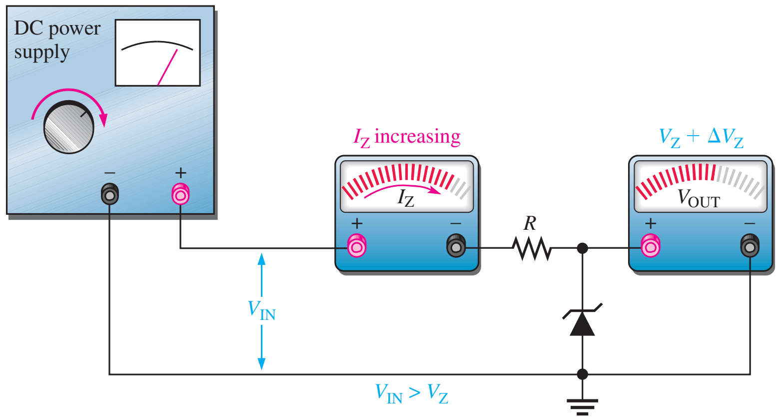
- **Apply a zener diode in voltage regulation**
- Analyze zener regulation with a variable input voltage
- Discuss zener regulation with a variable load
- Describe zener regulation from no load to full load
- Discuss zener limiting

Zener Regulation with a Variable Input Voltage

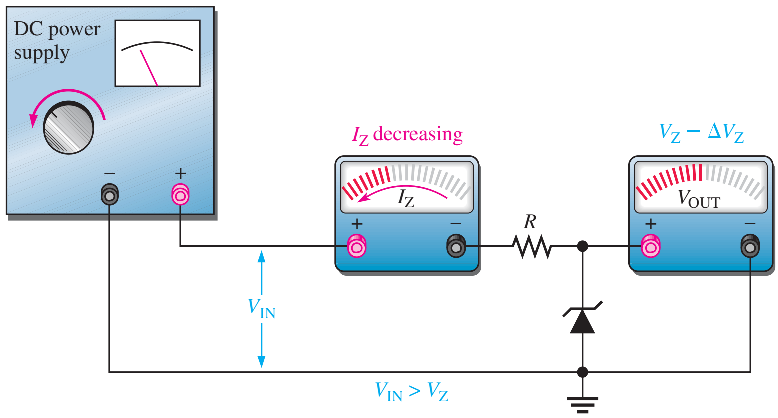
Zener diode regulators can provide a reasonably constant dc level at the output, but they are not particularly efficient. For this reason, they are limited to applications that require only low current to the load. Figure 3–9 illustrates how a zener diode can be used to regulate a dc

FIGURE 3–9

Zener regulation of a varying input voltage.



(a) As the input voltage increases, the output voltage remains nearly constant ($I_{ZK} < I_Z < I_{ZM}$).



(b) As the input voltage decreases, the output voltage remains nearly constant ($I_{ZK} < I_Z < I_{ZM}$).

voltage. As the input voltage varies (within limits), the zener diode maintains a nearly constant output voltage across its terminals. However, as V_{IN} changes, I_Z will change proportionally so that the limitations on the input voltage variation are set by the minimum and maximum current values (I_{ZK} and I_{ZM}) with which the zener can operate. Resistor R is the series current-limiting resistor. The meters indicate the relative values and trends.

To illustrate regulation, let's use the ideal model of the 1N4740A zener diode (ignoring the zener resistance) in the circuit of Figure 3–10. The absolute lowest current that will maintain regulation is specified at I_{ZK}, which for the 1N4740A is 0.25 mA and represents the no-load current. The maximum current is not given on the datasheet but can be calculated from the power specification of 1 W, which is given on the datasheet. Keep in mind that both the minimum and maximum values are at the operating extremes and represent worst-case operation.

$$I_{ZM} = \frac{P_{D(max)}}{V_Z} = \frac{1\text{ W}}{10\text{ V}} = 100\text{ mA}$$

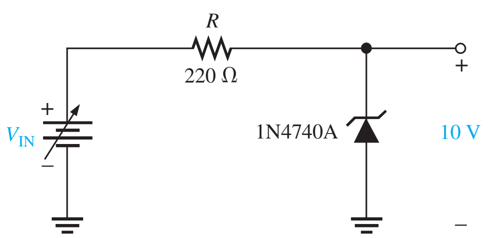


FIGURE 3–10

For the minimum zener current, the voltage across the 220 Ω resistor is

$$V_R = I_{ZK}R = (0.25\text{ mA})(220\ \Omega) = 55\text{ mV}$$

Since $V_R = V_{IN} - V_Z$,

$$V_{IN(min)} = V_R + V_Z = 55\text{ mV} + 10\text{ V} = 10.055\text{ V}$$

For the maximum zener current, the voltage across the 220 Ω resistor is

$$V_R = I_{ZM}R = (100\text{ mA})(220\ \Omega) = 22\text{ V}$$

Therefore,

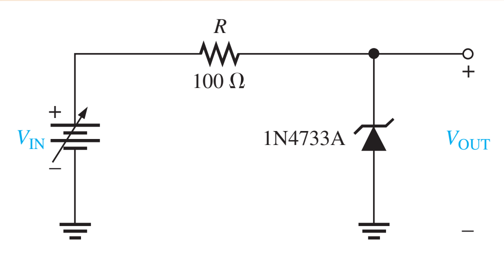
$$V_{IN(max)} = 22\text{ V} + 10\text{ V} = 32\text{ V}$$

This shows that this zener diode can ideally regulate an input voltage from 10.055 V to 32 V and maintain an approximate 10 V output. The output will vary slightly because of the zener impedance, which has been neglected in these calculations.

EXAMPLE 3–5

Determine the minimum and the maximum input voltages that can be regulated by the zener diode in Figure 3–11.

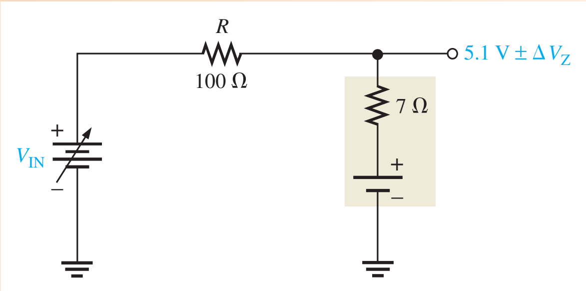
▶ FIGURE 3–11



Solution From the datasheet in Figure 3–7 for the 1N4733A: $V_Z = 5.1$ V at $I_Z = 49$ mA, $I_{ZK} = 1$ mA, and $Z_Z = 7\ \Omega$ at I_Z. For simplicity, assume this value of Z_Z over the range of current values. The equivalent circuit is shown in Figure 3–12.

▶ FIGURE 3–12

Equivalent of circuit in Figure 3–11.



At $I_{ZK} = 1$ mA, the output voltage is

$$V_{OUT} \cong 5.1\text{ V} - \Delta V_Z = 5.1\text{ V} - (I_Z - I_{ZK})Z_Z = 5.1\text{ V} - (49\text{ mA} - 1\text{ mA})(7\ \Omega)$$
$$= 5.1\text{ V} - (48\text{ mA})(7\ \Omega) = 5.1\text{ V} - 0.336\text{ V} = 4.76\text{ V}$$

Therefore,

$$V_{IN(min)} = I_{ZK}R + V_{OUT} = (1\text{ mA})(100\ \Omega) + 4.76\text{ V} = \mathbf{4.86\text{ V}}$$

To find the maximum input voltage, first calculate the maximum zener current. Assume the temperature is 50°C or below; so from Figure 3–7, the power dissipation is 1 W.

$$I_{ZM} = \frac{P_{D(max)}}{V_Z} = \frac{1\text{ W}}{5.1\text{ V}} = 196\text{ mA}$$

At I_{ZM}, the output voltage is

$$V_{OUT} \cong 5.1\text{ V} + \Delta V_Z = 5.1\text{ V} + (I_{ZM} - I_Z)Z_Z$$
$$= 5.1\text{ V} + (147\text{ mA})(7\ \Omega) = 5.1\text{ V} + 1.03\text{ V} = 6.13\text{ V}$$

Therefore,

$$V_{IN(max)} = I_{ZM}R + V_{OUT} = (196\text{ mA})(100\ \Omega) + 6.13\text{ V} = \mathbf{25.7\ V}$$

Related Problem Determine the minimum and maximum input voltages that can be regulated if a 1N4736A zener diode is used in Figure 3–11.

Open the Multisim file E03-05 in the Examples folder on the companion website. For the calculated minimum and maximum dc input voltages, measure the resulting output voltages. Compare with the calculated values.

Zener Regulation with a Variable Load

Figure 3–13 shows a zener voltage regulator with a variable load resistor across the terminals. The zener diode maintains a nearly constant voltage across R_L as long as the zener current is greater than I_{ZK} and less than I_{ZM}.

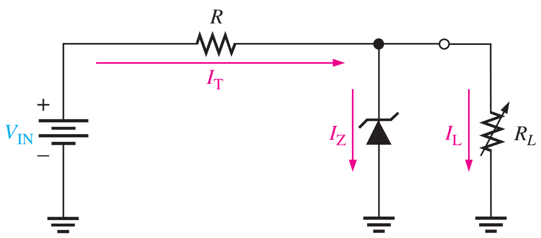


FIGURE 3–13

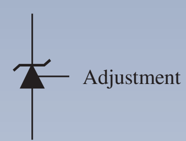
Zener regulation with a variable load.

From No Load to Full Load

When the output terminals of the zener regulator are open ($R_L = \infty$), the load current is zero and *all* of the current is through the zener; this is a no-load condition. When a load resistor (R_L) is connected, part of the total current is through the zener and part through R_L. The total current through R remains essentially constant as long as the zener is regulating. As R_L is decreased, the load current, I_L, increases and I_Z decreases. The zener diode continues to regulate the voltage until I_Z reaches its minimum value, I_{ZK}. At this point the load current is maximum, and a full-load condition exists. The following example will illustrate this.

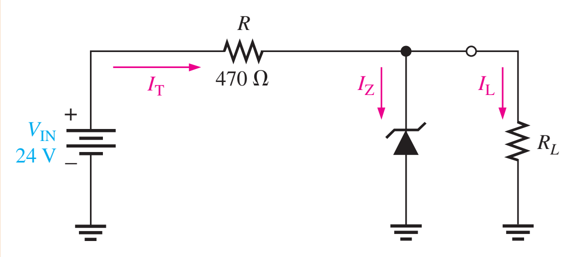
FYI

One type of temperature sensor uses the zener diode breakdown voltage as a temperature indicator. The breakdown voltage of a zener is directly proportional to the Kelvin temperature. This type of sensor is small, accurate, and linear. The LM125/LM235/LM335 is an integrated circuit that is more complex than a simple zener diode. However, it displays a very precise zener characteristic. In addition to the anode and cathode terminals, this device has an adjustment for calibration purposes. The symbol is shown below.



EXAMPLE 3–6 Determine the minimum and the maximum load currents for which the zener diode in Figure 3–14 will maintain regulation. What is the minimum value of R_L that can be used? $V_Z = 12$ V, $I_{ZK} = 1$ mA, and $I_{ZM} = 50$ mA. Assume an ideal zener diode where $Z_Z = 0\ \Omega$ and V_Z remains a constant 12 V over the range of current values, for simplicity.

▶ FIGURE 3–14



Solution When $I_L = 0$ A ($R_L = \infty$), I_Z is maximum and equal to the total circuit current I_T.

$$I_{Z(max)} = I_T = \frac{V_{IN} - V_Z}{R} = \frac{24\text{ V} - 12\text{ V}}{470\ \Omega} = 25.5\text{ mA}$$

If R_L is removed from the circuit, the load current is 0 A. Since $I_{Z(max)}$ is less than I_{ZM}, 0 A is an acceptable minimum value for I_L because the zener can handle all of the 25.5 mA.

$$I_{L(min)} = \mathbf{0\ A}$$

The maximum value of I_L occurs when I_Z is minimum ($I_Z = I_{ZK}$), so

$$I_{L(max)} = I_T - I_{ZK} = 25.5\text{ mA} - 1\text{ mA} = \mathbf{24.5\ mA}$$

The minimum value of R_L is

$$R_{L(min)} = \frac{V_Z}{I_{L(max)}} = \frac{12\text{ V}}{24.5\text{ mA}} = \mathbf{490\ \Omega}$$

Therefore, if R_L is less than 490 Ω, R_L will draw more of the total current away from the zener and I_Z will be reduced below I_{ZK}. This will cause the zener to lose regulation. Regulation is maintained for any value of R_L between 490 Ω and infinity.

Related Problem Find the minimum and maximum load currents for which the circuit in Figure 3–14 will maintain regulation. Determine the minimum value of R_L that can be used. $V_Z = 3.3$ V (constant), $I_{ZK} = 1$ mA, and $I_{ZM} = 150$ mA. Assume an ideal zener.

Open the Multisim file E03-06 in the Examples folder on the companion website. For the calculated minimum value of load resistance, verify that regulation occurs.

In the last example, we assumed that Z_Z was zero and, therefore, the zener voltage remained constant over the range of currents. We made this assumption to demonstrate the concept of how the regulator works with a varying load. Such an assumption is often acceptable and in many cases produces results that are reasonably accurate. In Example 3–7, we will take the zener impedance into account.

EXAMPLE 3–7

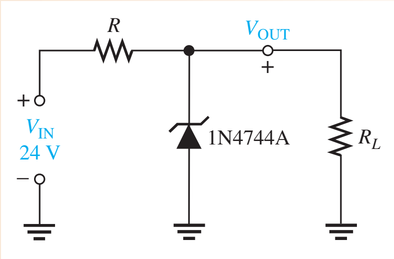
For the circuit in Figure 3–15:

(a) Determine V_{OUT} at I_{ZK} and at I_{ZM}.

(b) Calculate the value of R that should be used.

(c) Determine the minimum value of R_L that can be used.

▶ FIGURE 3–15



Solution The 1N4744A zener used in the regulator circuit of Figure 3–15 is a 15 V diode. The datasheet in Figure 3–7 gives the following information:
$V_Z = 15\text{ V} @ I_Z = 17\text{ mA}, I_{ZK} = 0.25\text{ mA}$, and $Z_Z = 14\ \Omega$.

(a) For I_{ZK}:

$$V_{OUT} = V_Z - \Delta I_Z Z_Z = 15\text{ V} - \Delta I_Z Z_Z = 15\text{ V} - (I_Z - I_{ZK})Z_Z$$
$$= 15\text{ V} - (16.75\text{ mA})(14\ \Omega) = 15\text{ V} - 0.235\text{ V} = \mathbf{14.76\ V}$$

Calculate the zener maximum current. The maximum power dissipation is 1 W.

$$I_{ZM} = \frac{P_{D(max)}}{V_Z} = \frac{1\text{ W}}{15\text{ V}} = 66.7\text{ mA}$$

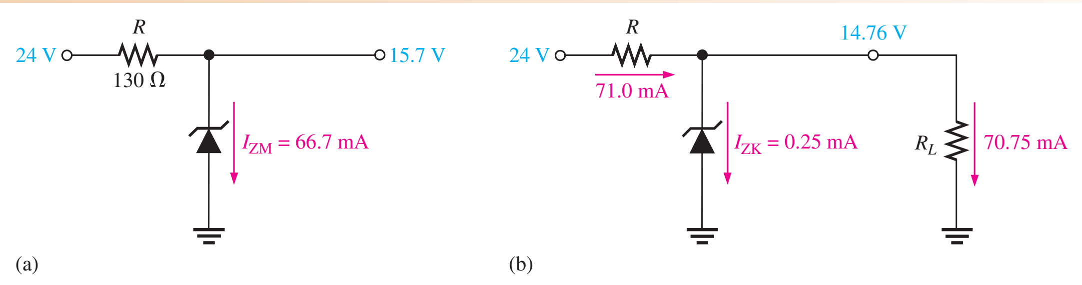
For I_{ZM}:

$$V_{OUT} = V_Z + \Delta I_Z Z_Z = 15\text{ V} + \Delta I_Z Z_Z$$
$$= 15\text{ V} + (I_{ZM} - I_Z)Z_Z = 15\text{ V} + (49.7\text{ mA})(14\ \Omega) = \mathbf{15.7\ V}$$

(b) Calculate the value of R for the maximum zener current that occurs when there is no load as shown in Figure 3–16(a).

$$R = \frac{V_{IN} - V_{OUT}}{I_{ZK}} = \frac{24\text{ V} - 15.7\text{ V}}{66.7\text{ mA}} = 124\ \Omega$$

$R = \mathbf{130\ \Omega}$ (nearest larger standard value).



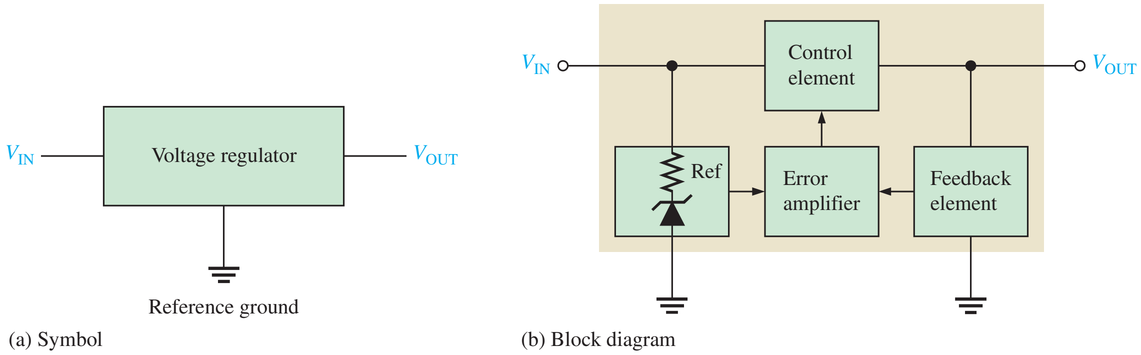
▲ FIGURE 3–16

(c) For the minimum load resistance (maximum load current), the zener current is minimum ($I_{ZK} = 0.25$ mA) as shown in Figure 3–16(b).

$$I_T = \frac{V_{IN} - V_{OUT}}{R} = \frac{24\text{ V} - 14.76\text{ V}}{130\ \Omega} = 71.0\text{ mA}$$
$$I_L = I_T - I_{ZK} = 71.0\text{ mA} - 0.25\text{ mA} = 70.75\text{ mA}$$
$$R_{L(min)} = \frac{V_{OUT}}{I_L} = \frac{14.76\text{ V}}{70.75\text{ mA}} = \mathbf{209\ \Omega}$$

Related Problem Repeat each part of the preceding analysis if the zener is changed to a 1N4742A 12 V device.

You have seen how the zener diode regulates voltage. Its regulating ability is somewhat limited by the change in zener voltage over a range of current values, which restricts the load current that it can handle. To achieve better regulation and provide for greater variations in load current, the zener diode is combined as a key element with other circuit components to create a 3-terminal linear voltage regulator. Three-terminal voltage regulators that were introduced in Chapter 2 are IC devices that use the zener to provide a reference voltage for an internal amplifier. For a given dc input voltage, the 3-terminal regulator maintains an essentially constant dc voltage over a range of input voltages and load currents. The dc output voltage is always less than the input voltage. The details of this type of regulator are covered in Chapter 17. Figure 3–17 illustrates a basic 3-terminal regulator showing where the zener diode is used.

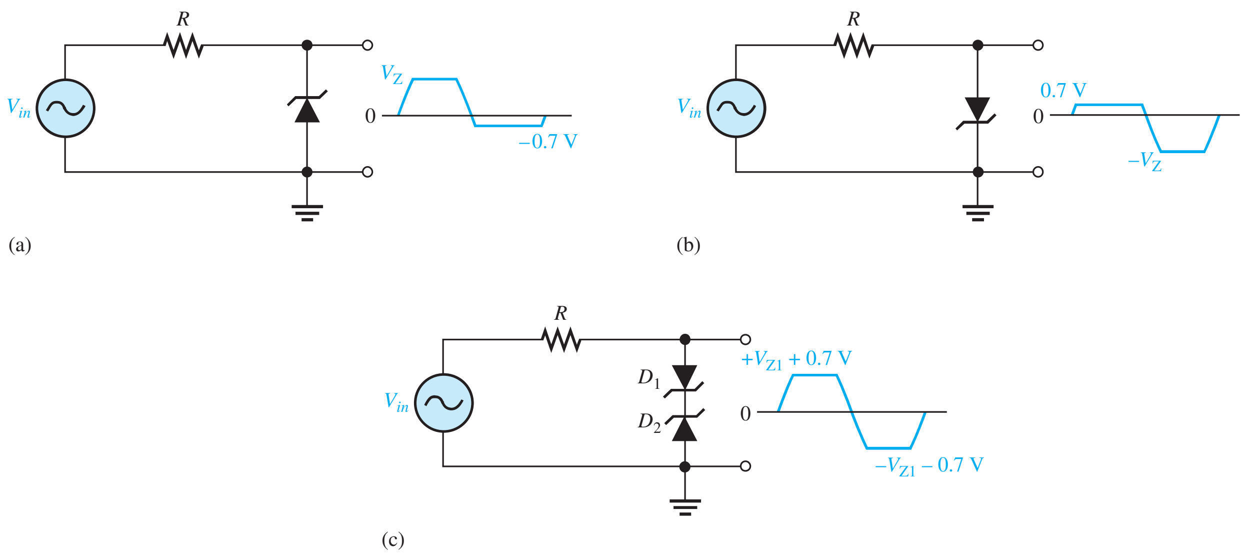


▲ **FIGURE 3–17**

Three-terminal voltage regulators.

Zener Limiter

In addition to voltage regulation applications, zener diodes can be used in ac applications to limit voltage swings to desired levels. Figure 3–18 shows three basic ways the limiting action of a zener diode can be used. Part (a) shows a zener used to limit the positive peak of a signal voltage to the selected zener voltage. During the negative alternation, the zener acts as a forward-biased diode and limits the negative voltage to −0.7 V. When the zener



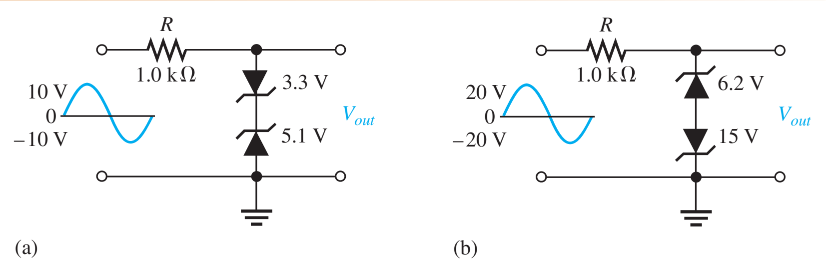
▲ **FIGURE 3–18**

Basic zener limiting action with a sinusoidal input voltage.

is turned around, as in part (b), the negative peak is limited by zener action and the positive voltage is limited to +0.7 V. Two back-to-back zeners limit both peaks to the zener voltage ±0.7 V, as shown in part (c). During the positive alternation, D_2 is functioning as the zener limiter and D_1 is functioning as a forward-biased diode. During the negative alternation, the roles are reversed.

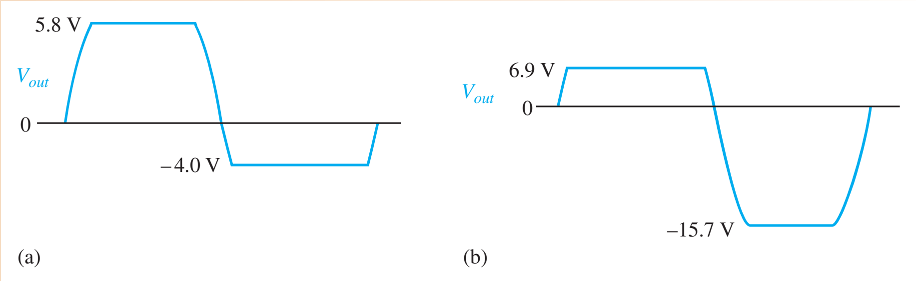
EXAMPLE 3–8

Determine the output voltage for each zener limiting circuit in Figure 3–19.



▲ FIGURE 3–19

Solution See Figure 3–20 for the resulting output voltages. Remember, when one zener is operating in breakdown, the other one is forward-biased with approximately 0.7 V across it.



▲ FIGURE 3–20

Related Problem

(a) What is the output in Figure 3–19(a) if the input voltage is increased to a peak value of 20 V?

(b) What is the output in Figure 3–19(b) if the input voltage is decreased to a peak value of 5 V?

Open the Multisim file E03-08 in the Examples folder on the companion website. For the specified input voltages, measure the resulting output waveforms. Compare with the waveforms shown in the example.

SECTION 3–2 CHECKUP

1. In a zener diode regulator, what value of load resistance results in the maximum zener current?
2. Explain the terms *no load* and *full load*.
3. How much voltage appears across a zener diode when it is forward-biased?

3–6 TROUBLESHOOTING

In this section, you will see how a faulty zener diode can affect the output of a regulated dc power supply. Although IC regulators are generally used for power supply outputs, the zener is occasionally used when less precise regulation and low current is acceptable. Like other diodes, the zener can fail open, it can exhibit degraded performance, or it can short out.

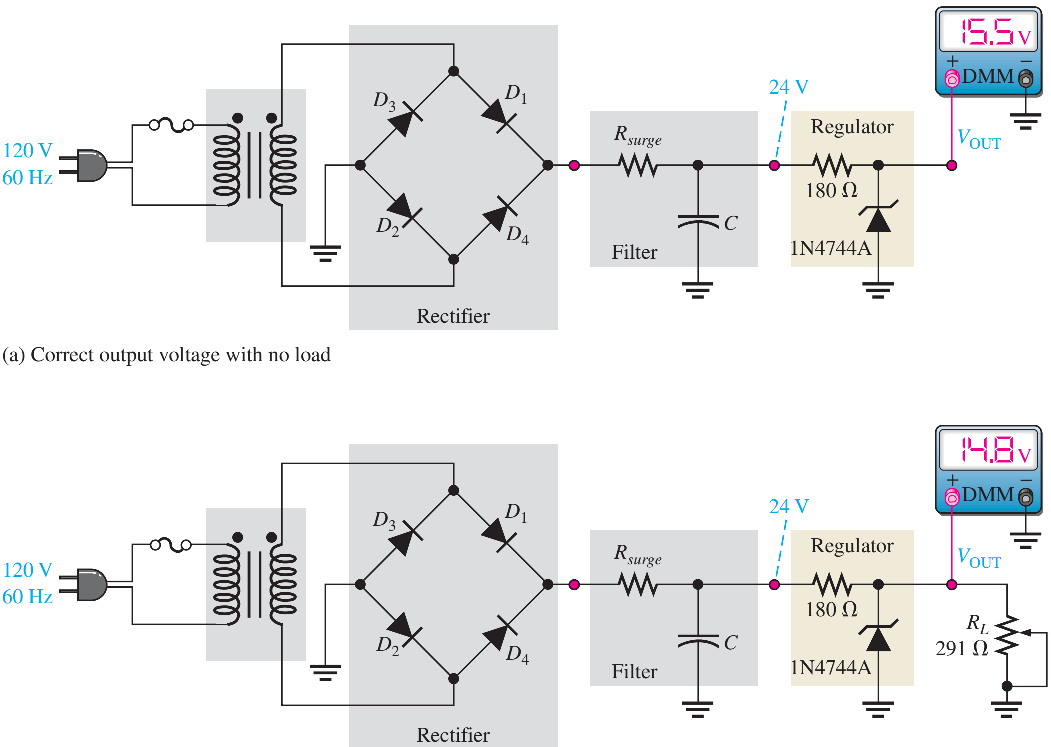
After completing this section, you should be able to

- **Troubleshoot zener diode regulators**
  - Recognize the effects of an open zener
  - Recognize the effects of a zener with degraded performance or shorted

Chapter 18: Basic Programming Concepts for Automated Testing
Selected sections from Chapter 18 may be introduced as part of this troubleshooting coverage or, optionally, the entire Chapter 18 may be covered later or not at all.

A Zener-Regulated DC Power Supply

Figure 3–59 shows a filtered dc power supply that produces a constant 24 V before it is regulated down to 15 V by the zener regulator. The 1N4744A zener diode is the same as the one in Example 3–7. A no-load check of the regulated output voltage shows 15.5 V as indicated in part (a). The typical voltage expected at the zener test current for this particular



(a) Correct output voltage with no load

(b) Correct output voltage with full load

▲ FIGURE 3–59

Zener-regulated power supply test.

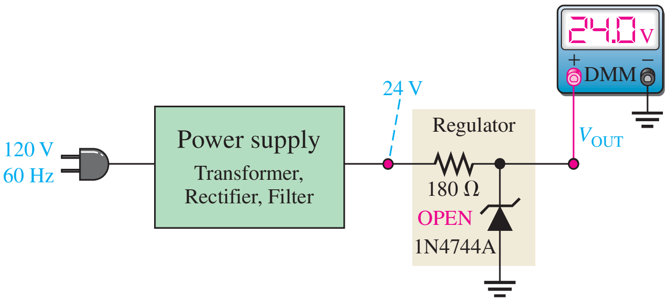
diode is 15 V. In part (b), a potentiometer is connected to provide a variable load resistance. It is adjusted to a minimum value for a full-load test as determined by the following calculations. The full-load test is at minimum zener current (I_{ZK}). The meter reading of 14.8 V indicates approximately the expected output voltage of 15.0 V.

$$I_T = \frac{24\text{ V} - 14.8\text{ V}}{180\ \Omega} = 51.1\text{ mA}$$

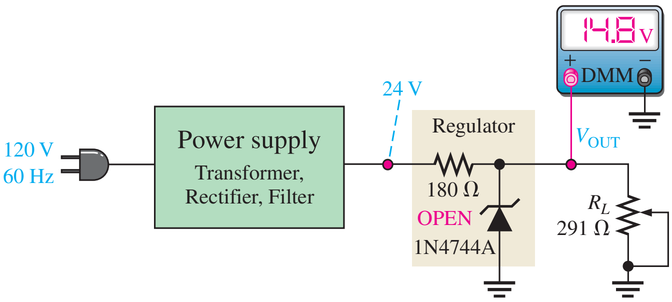
$$I_L = I_T - I_Z = 51.1\text{ mA} - 0.25\text{ mA} = 50.9\text{ mA}$$

$$R_{L(\min)} = \frac{14.8\text{ V}}{50.9\text{ mA}} = 291\ \Omega$$

Case 1: Zener Diode Open If the zener diode fails open, the power supply test gives the approximate results indicated in Figure 3–60. In the no-load check shown in part (a), the output voltage is 24 V because there is no voltage dropped between the filtered output of the power supply and the output terminal. This definitely indicates an open between the output terminal and ground. In the full-load check, the voltage of 14.8 V results from the voltage-divider action of the 180 Ω series resistor and the 291 Ω load. In this case, the result is too close to the normal reading to be a reliable fault indication but the no-load check will verify the problem. Also, if R_L is varied, V_{OUT} will vary if the zener diode is open.



(a) Open zener diode with no load

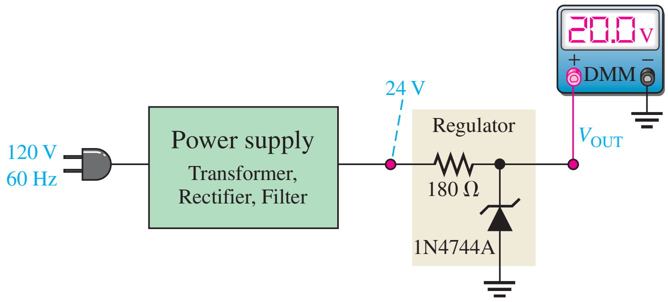


(b) Open zener diode cannot be detected by full-load measurement in this case.

▲ **FIGURE 3–60**

Indications of an open zener.

Case 2: Incorrect Zener Voltage As indicated in Figure 3–61, a no-load check that results in an output voltage greater than the maximum zener voltage but less than the power supply output voltage indicates that the zener has failed such that its internal impedance is more than it should be. The 20 V output in this case is 4.5 V higher than the expected value of 15.5 V. That additional voltage indicates the zener is faulty or the wrong type has been installed. A 0 V output, of course, indicates that there is a short.



▲ **FIGURE 3–61**

Indication of faulty or wrong zener.

Multisim Troubleshooting Exercises

These file circuits are in the Troubleshooting Exercises folder on the companion website. Open each file and determine if the circuit is working properly. If it is not working properly, determine the fault.

1. Multisim file TSE03-01
2. Multisim file TSE03-02
3. Multisim file TSE03-03
4. Multisim file TSE03-04
5. Multisim file TSE03-05

SECTION 3–6 CHECKUP

1. In a zener regulator, what are the symptoms of an open zener diode?
2. If a zener regulator fails so that the zener impedance is greater than the specified value, is the output voltage more or less than it should be?
3. If you measure 0 V at the output of a zener-regulated power supply, what is the most likely fault(s)?
4. The zener diode regulator in a power supply is open. What will you observe on the output with a voltmeter if the load resistance is varied within its specified range?

Application Activity: *Regulated DC Power Supply*

The unregulated 16 V dc power supply developed in Chapter 2 is to be upgraded to a regulated power supply with a fixed output voltage of 12 V. An integrated circuit 3–terminal voltage regulator is to be used and a red LED incorporated to indicate when the power is on. The printed circuit board for the unregulated power supply was designed to accommodate these additions.

The Circuit

Practical considerations for the circuit are the type of regulator, the selection of the LED power-on indicator and limiting resistor, and the value and placement of the fuse.

3–4 Optical Diodes

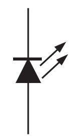
In this section, three types of optoelectronic devices are introduced: the light-emitting diode, quantum dots, and the photodiode. As the name implies, the light-emitting diode is a light emitter. Quantum dots are very tiny light emitters made from silicon with great promise for various devices, including light-emitting diodes. On the other hand, the photodiode is a light detector.

After completing this section, you should be able to

- **Discuss the basic characteristics, operation, and applications of LEDs, quantum dots, and photodiodes**
- Describe the light-emitting diode (LED)
  - ◆ Identify the LED schematic symbol ◆ Discuss the process of electroluminescence ◆ List some LED semiconductor materials ◆ Discuss LED biasing ◆ Discuss light emission
- Interpret an LED datasheet
  - ◆ Define and discuss radiant intensity and irradiance
- Describe some LED applications
- Discuss high-intensity LEDs and applications
  - ◆ Explain how high-intensity LEDs are used in traffic lights ◆ Explain how high-intensity LEDs are used in displays
- Describe the organic LED (OLED)
- Discuss quantum dots and their application
- Describe the photodiode and interpret a typical datasheet
  - ◆ Discuss photodiode sensitivity

The Light-Emitting Diode (LED)

The symbol for an LED is shown in Figure 3–28.



▲ FIGURE 3–28

Symbol for an LED. When forward-biased, it emits light.

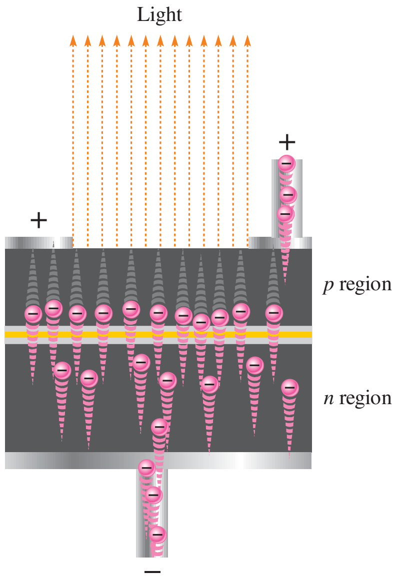
The basic operation of the **light-emitting diode (LED)** is as follows. When the device is forward-biased, electrons cross the *pn* junction from the *n*-type material and recombine with holes in the *p*-type material. Recall from Chapter 1 that these free electrons are in the conduction band and at a higher energy than the holes in the valence band. The difference in energy between the electrons and the holes corresponds to the energy of visible light. When recombination takes place, the recombining electrons release energy in the form of **photons.** The emitted light tends to be monochromatic (one color) that depends on the band gap (and other factors). A large exposed surface area on one layer of the semiconductive material permits the photons to be emitted as visible light. This process, called **electroluminescence**, is illustrated in Figure 3–29. Various impurities are added during the doping process to establish the **wavelength** of the emitted light. The wavelength determines the color of visible light. Some LEDs emit photons that are not part of the visible spectrum but have longer wavelengths and are in the **infrared** (IR) portion of the spectrum.

LED Semiconductor Materials The semiconductor gallium arsenide (GaAs) was used in early LEDs and emits IR radiation, which is invisible. The first visible red LEDs were produced using gallium arsenide phosphide (GaAsP) on a GaAs substrate. The efficiency was increased using a gallium phosphide (GaP) substrate, resulting in brighter red LEDs and also allowing orange LEDs.

Later, GaP was used as the light-emitter to achieve pale green light. By using a red and a green chip, LEDs were able to produce yellow light. The first super-bright red, yellow, and green LEDs were produced using gallium aluminum arsenide phosphide (GaAlAsP). By the early 1990s ultrabright LEDs using indium gallium aluminum phosphide (InGaAlP) were available in red, orange, yellow, and green.

▶ FIGURE 3–29

Electroluminescence in a forward-biased LED.



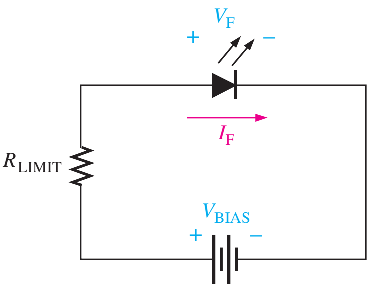
FYI

Efficiency is a term used in many fields to show how well a particular process works. It is the ratio of the output to the input and is a dimensionless number, often expressed as a percentage. An efficiency of 100% is the theoretical maximum that can never be achieved in real systems. For lighting, the term *efficacy* is used with units of lumens per watt and is related to the efficiency of converting input power (in watts) to light that can be seen by the human eye (lumens). The theoretical maximum efficacy is 683 lumens/watt.

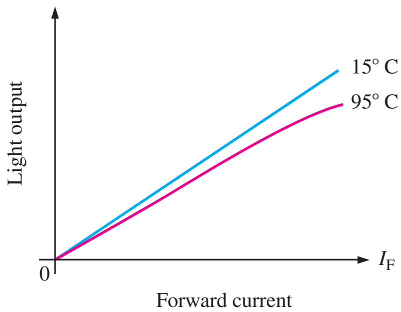
Blue LEDs using silicon carbide (SiC) and ultrabright blue LEDs made of gallium nitride (GaN) became available. High intensity LEDs that produce green and blue are also made using indium gallium nitride (InGaN). High-intensity white LEDs are formed using ultrabright blue GaN coated with fluorescent phosphors that absorb the blue light and reemit it as white light.

LED Biasing The forward voltage across an LED is considerably greater than for a silicon diode. Typically, the maximum V_F for LEDs is between 1.2 V and 3.2 V, depending on the material. Reverse breakdown for an LED is much less than for a silicon rectifier diode (3 V to 10 V is typical).

The LED emits light in response to a sufficient forward current, as shown in Figure 3–30(a). The amount of power output translated into light is directly proportional to the forward current, as indicated in Figure 3–30(b). An increase in I_F corresponds proportionally to an increase in light output. The light output (both intensity and color) is also dependent on temperature. Light intensity goes down with higher temperature as indicated in the figure.



(a) Forward-biased operation

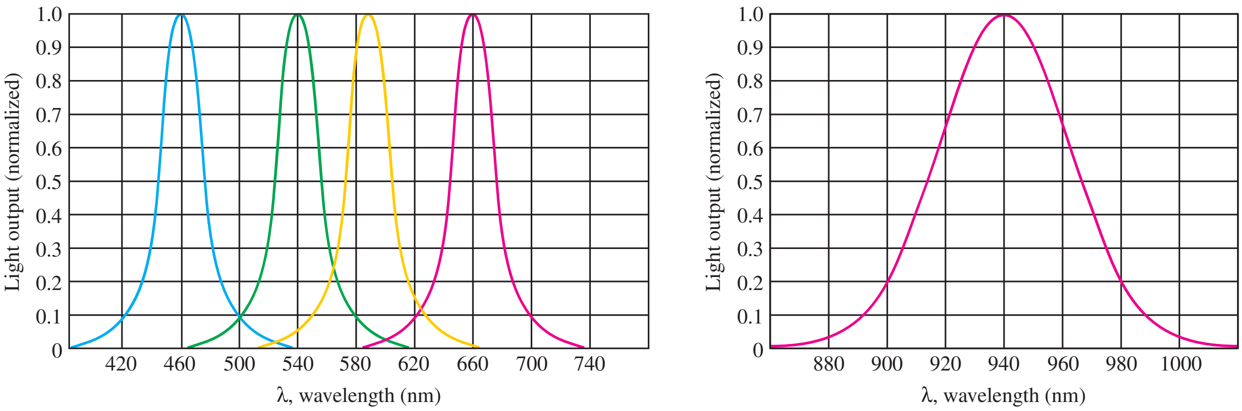


(b) General light output versus forward current for two temperatures

▲ FIGURE 3–30

Basic operation of an LED.

Light Emission An LED emits light over a specified range of wavelengths as indicated by the **spectral** output curves in Figure 3–31. The curves in part (a) represent the light output versus wavelength for typical visible LEDs, and the curve in part (b) is for a typical infrared LED. The wavelength (λ) is expressed in nanometers (nm). The normalized output of the visible red LED peaks at 660 nm, the yellow at 590 nm, green at 540 nm, and blue at 460 nm. The output for the infrared LED peaks at 940 nm.



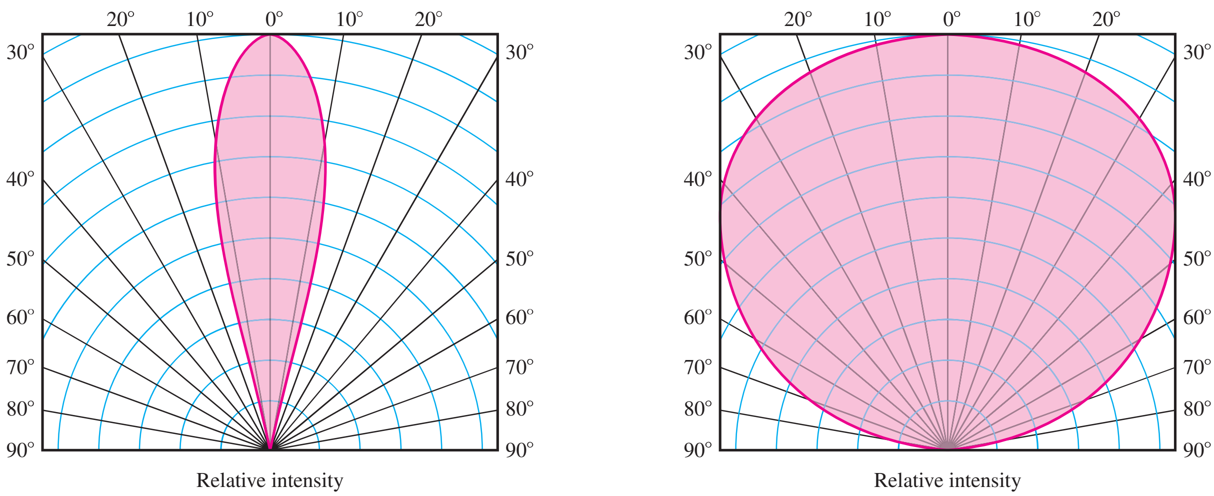
(a) Visible light

(b) Infrared (IR)

▲ FIGURE 3–31

Examples of typical spectral output curves for LEDs.

The graphs in Figure 3–32 show typical **radiation** patterns for small LEDs. LEDs are directional light sources (unlike filament or fluorescent bulbs). The radiation pattern is generally perpendicular to the emitting surface; however, it can be altered by the shape of the emitter surface and by lenses and diffusion films to favor a specific direction. Directional patterns can be an advantage for certain applications, such as traffic lights, where the light is intended to be seen only by certain drivers. Figure 3–32(a) shows the pattern for a forward-directed LED such as used in small panel indicators. Figure 3–32(b) shows the pattern for a wider viewing angle such as found in many super-bright LEDs. A wide variety of patterns are available from manufacturers; one variation is to design the LED to emit nearly all the light to the side in two lobes.



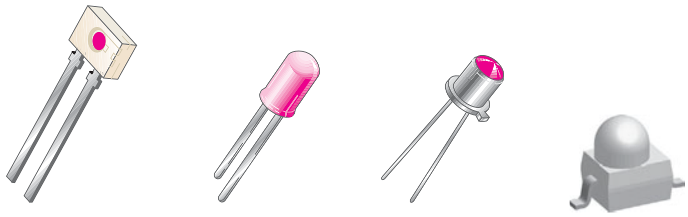
(a) A narrow viewing angle LED

(b) A wide viewing angle LED

▲ FIGURE 3–32

Radiation patterns for two different LEDs.

Typical small LEDs for indicators are shown in Figure 3–33(a). In addition to small LEDs for indicators, bright LEDs are becoming popular for lighting because of their superior efficiency and long life. A typical LED for lighting can deliver 50–60 lumens per watt, which is approximately five times greater efficiency than a standard incandescent bulb. LEDs for lighting are available in a variety of configurations, including even flexible tubes for decorative lighting and low-wattage bulbs for outdoor walkways and gardens. Many



(a) Typical small LEDs for indicators

LED lamps are designed to work in 120 V standard fixtures. A few representative configurations are shown in Figure 3–33(b).

LED Datasheet Information

A partial datasheet for an TSMF1000 infrared (IR) light-emitting diode is shown in Figure 3–34. Notice that the maximum reverse voltage is only 5 V, the maximum forward current is 100 mA, and the forward voltage drop is approximately 1.3 V for $I_F = 20$ mA.

From the graph in part (c), you can see that the peak power output for this device occurs at a wavelength of 870 nm; its radiation pattern is shown in part (d).

Radiant Intensity and Irradiance In Figure 3–34(a), the **radiant intensity,** I_e (symbol not to be confused with current), is the output power per steradian and is specified as 5 mW/sr at $I_F = 20$ mA. The steradian (sr) is the unit of solid angular measurement. **Irradiance,** E, is the power per unit area at a given distance from an LED source expressed in mW/cm^2. Irradiance is important because the response of a detector (photodiode) used in conjunction with an LED depends on the irradiance of the light it receives.

Absolute Maximum Ratings

T_{amb} = 25°C, unless otherwise specified

Parameter	Test condition	Symbol	Value	Unit
Reverse Voltage		V_R	5	V
Forward current		I_F	100	mA
Peak Forward Current	t_p/T = 0.5, t_p = 100 µs	I_{FM}	200	mA
Surge Forward Current	t_p = 100 µs	I_{FSM}	0.8	A
Power Dissipation		P_V	190	mW
Junction Temperature		T_j	100	°C
Operating Temperature Range		T_{amb}	- 40 to + 85	°C

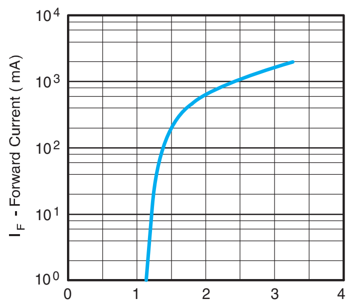
Basic Characteristics

T_{amb} = 25°C, unless otherwise specified

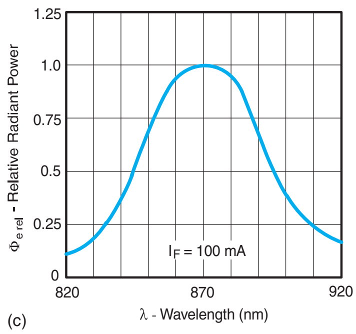
T_{amb} = 25°C, unless otherwise specified

Parameter	Test condition	Symbol	Min	Typ.	Max	Unit
Forward Voltage	I_F = 20 mA	V_F		1.3	1.5	V
	I_F = 1 A, t_p = 100 µs	V_F		2.4		V
Temp. Coefficient of V_F	I_F = 1.0 mA	TK_{VF}		- 1.7		mV/K
Reverse Current	V_R = 5 V	I_R			10	µA
Junction capacitance	V_R = 0 V, f = 1 MHz, E = 0	C_j		160		pF
Radiant Intensity	I_F = 20 mA	I_e	2.5	5	13	mW/sr
	I_F = 100 mA, t_p = 100 µs	I_e		25		mW/sr
Radiant Power	I_F = 100 mA, t_p = 20 ms	ϕ_e		35		mW
Temp. Coefficient of ϕ_e	I_F = 20 mA	$TK\phi_e$		- 0.6		%/K
Angle of Half Intensity		ϕ		± 17		deg
Peak Wavelength	I_F = 20 mA	λ_p		870		nm
Spectral Bandwidth	I_F = 20 mA	$\Delta\lambda$		40		nm
Temp. Coefficient of λ_p	I_F = 20 mA	$TK\lambda_p$		0.2		nm/K
Rise Time	I_F = 20 mA	t_r		30		ns
Fall Time	I_F = 20 mA	t_f		30		ns
Virtual Source Diameter		∅		1.2		mm

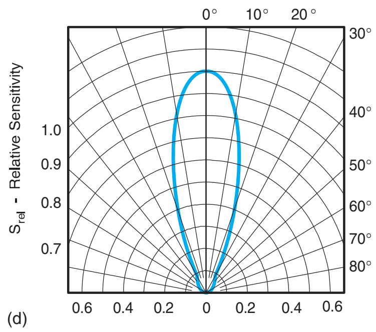
(a)



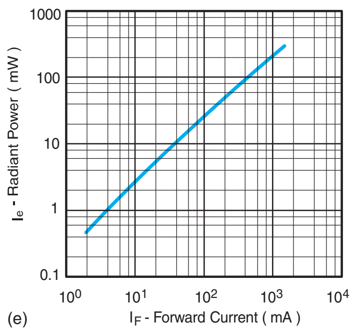
(b)



(c)



(d)



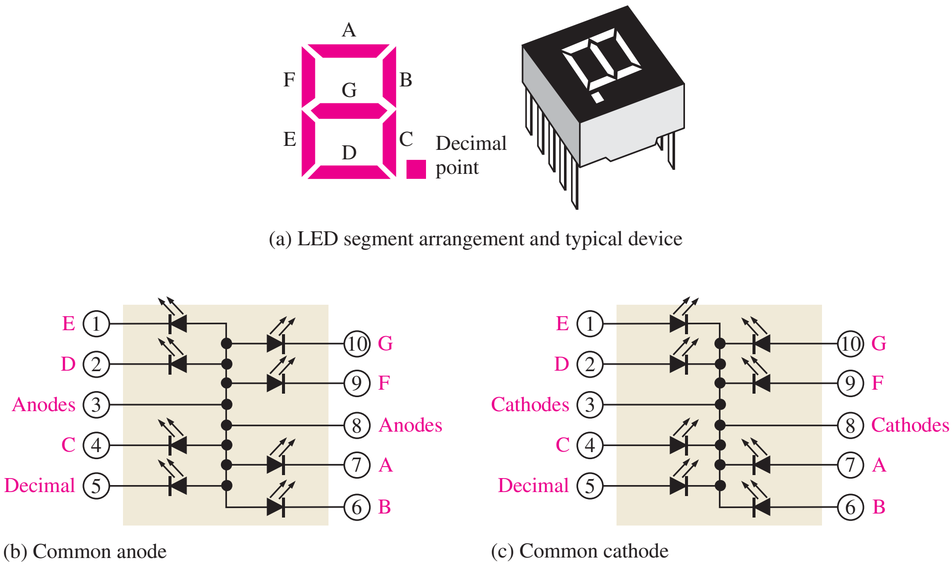
(e)

▲ FIGURE 3–34

Partial datasheet for an TSMF1000 IR light-emitting diode. Datasheet courtesy of Vishay Intertechnology, Inc. Datasheets are available at www.vishay.com.

Applications

Standard LEDs are used for indicator lamps and readout displays on a wide variety of instruments, ranging from consumer appliances to scientific apparatus. A common type of display device using LEDs is the seven-segment display. Combinations of the segments form the ten decimal digits as illustrated in Figure 3–35. Each segment in the display is an LED. By forward-biasing selected combinations of segments, any decimal digit and a decimal point can be formed. Two types of LED circuit arrangements are the common anode and common cathode as shown.



▲ FIGURE 3–35

The 7-segment LED display.

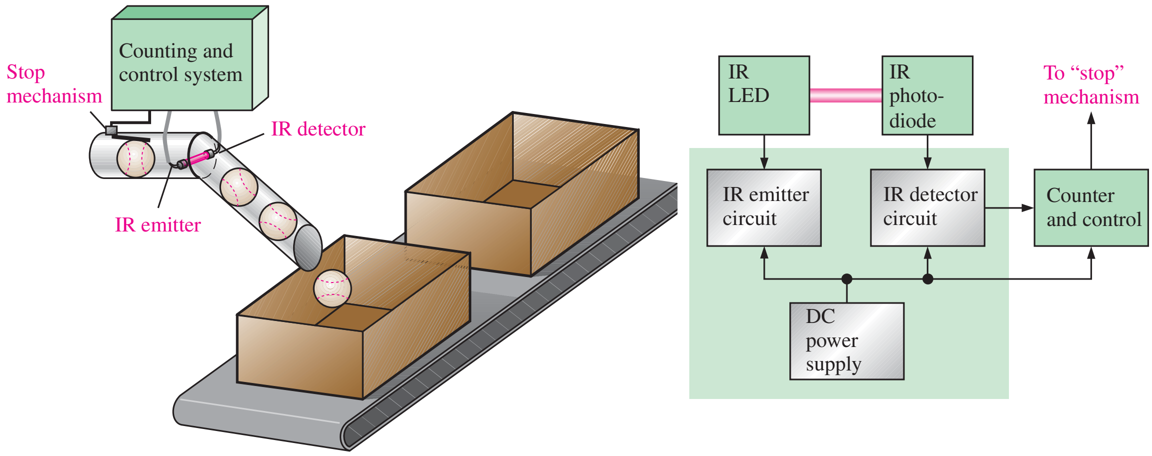
One common application of an infrared LED is in remote control units for TV, DVD, gate openers, etc. The IR LED sends out a beam of invisible light that is sensed by the receiver in your TV, for example. For each button on the remote control unit, there is a unique code. When a specific button is pressed, a coded electrical signal is generated that goes to the LED, which converts the electrical signal to a coded infrared light signal. The TV receiver recognizes the code and takes appropriate action, such as changing the channel or increasing the volume.

Also, IR light-emitting diodes are used in optical coupling applications, often in conjunction with fiber optics. Areas of application include industrial processing and control, position encoders, bar graph readers, and optical switching.

An example of how an IR LED could be used in an industrial application is illustrated in Figure 3–36. This particular system is used to count baseballs as they are fed down a chute into a box for shipping. As each ball passes through the chute, the IR beam emitted by the LED is interrupted. This is detected by the photodiode (discussed later) and the resulting change in current is sensed by a detector circuit. An electronic circuit counts each time that the beam is interrupted; and when a preset number of balls pass through the chute, the "stop" mechanism is activated to stop the flow of balls until the next empty box is automatically moved into place on the conveyor. When the next box is in place, the "stop" mechanism is deactivated and the balls begin to roll again. This idea can also be applied to inventory and packing control for many other types of products.

High-Intensity LEDs

LEDs that produce much greater light outputs than standard LEDs are found in many applications including traffic lights, automotive lighting, indoor and outdoor advertising and informational signs, and home lighting.



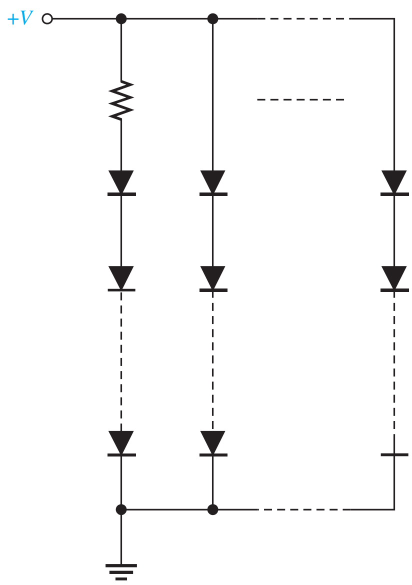
▲ **FIGURE 3–36**

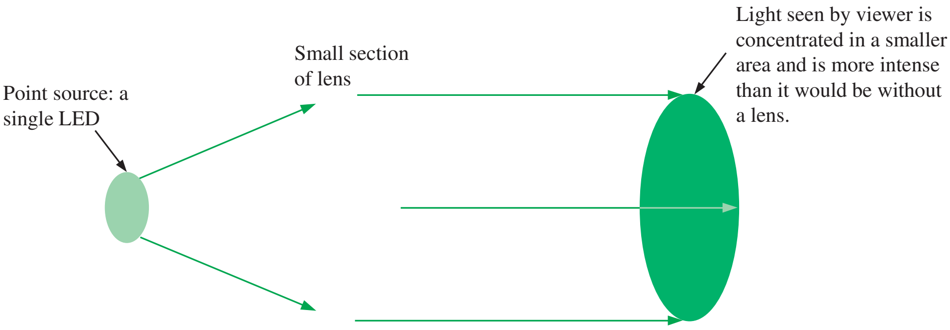
Basic concept and block diagram of a counting and control system.

Traffic Lights LEDs are quickly replacing the traditional incandescent bulbs in traffic signal applications. Arrays of tiny LEDs form the red, yellow, and green lights in a traffic light unit. An LED array has three major advantages over the incandescent bulb: brighter light, longer lifetime (years vs. months), and less energy consumption (about 90% less).

LED traffic lights are constructed in arrays with lenses that optimize and direct the light output. Figure 3–37(a) illustrates the concept of a traffic light array using red LEDs. A relatively low density of LEDs is shown for illustration. The actual number and spacing of the LEDs in a traffic light unit depends on the diameter of the unit, the type of lens, the color, and the required light intensity. With an appropriate LED density and a lens, an 8- or 12-inch traffic light will appear essentially as a solid-color circle.

LEDs in an array are usually connected either in a series-parallel or a parallel arrangement. A series connection is not practical because if one LED fails open, then all the LEDs are disabled. For a parallel connection, each LED requires a limiting resistor. To reduce the number of limiting resistors, a series-parallel connection can be used, as shown in Figure 3–37(b).





Some LED traffic arrays use small reflectors for each LED to help maximize the effect of the light output. Also, an optical lens covers the front of the array to direct the light from each individual diode to prevent improper dispersion of light and to optimize the visibility. Figure 3–38 illustrates how a lens is used to direct the light toward the viewer.

The particular LED circuit configuration depends on the voltage and the color of the LED. Different color LEDs require different forward voltages to operate. Red LEDs take the least; and as the color moves up the color spectrum toward blue, the voltage requirement increases. Typically, a red LED requires about 2 V, while blue LEDs require between 3 V and 4 V. Generally, LEDs, however, need 20 mA to 30 mA of current, regardless of their voltage requirements. Typical *V-I* curves for red, yellow, green, and blue LEDs are shown in Figure 3–39.

The voltage drop across the series-limiting resistor is

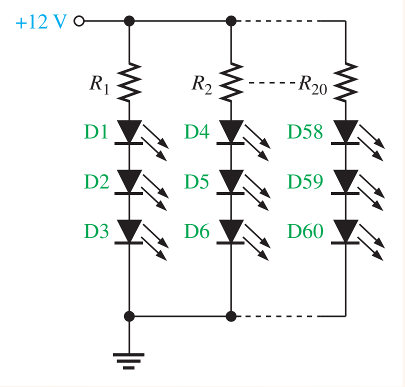
$$V = 12\text{ V} - 7.5\text{ V} = 4.5\text{ V}$$

The value of the limiting resistor is

$$R_{\text{LIMIT}} = \frac{4.5\text{ V}}{20\text{ mA}} = 225\ \Omega$$

The LED array has 20 parallel branches each with a limiting resistor and three LEDs, as shown in Figure 3–40.

▶ FIGURE 3–40



Related Problem Design a 12 V red LED array with minimum limiting resistors, a forward current of 30 mA, and containing 64 diodes.

LED Displays LEDs are widely used in large and small signs and message boards for both indoor and outdoor uses, including large-screen television. Signs can be single-color, multicolor, or full-color. Full-color screens use a tiny grouping of high-intensity red, green, and blue LEDs to form a **pixel**. A typical screen is made of thousands of RGB pixels with the exact number determined by the sizes of the screen and the pixel.

Red, green, and blue (RGB) are primary colors and when mixed together in varying amounts, can be used to produce any color in the visible spectrum. A basic pixel formed by three LEDs is shown in Figure 3–41. The light emission from each of the three diodes can be varied independently by varying the amount of forward current. Yellow is added to the three primary colors (RGBY) in some TV screen applications.

Other Applications High-intensity LEDs are becoming more widely used in automotive lighting for taillights, brakelights, turn signals, back-up lights, and interior applications. LED arrays are expected to replace most incandescent bulbs in automotive lighting. Eventually, headlights may also be replaced by white LED arrays. LEDs can be seen better in poor weather and can last 100 times longer than an incandescent bulb.

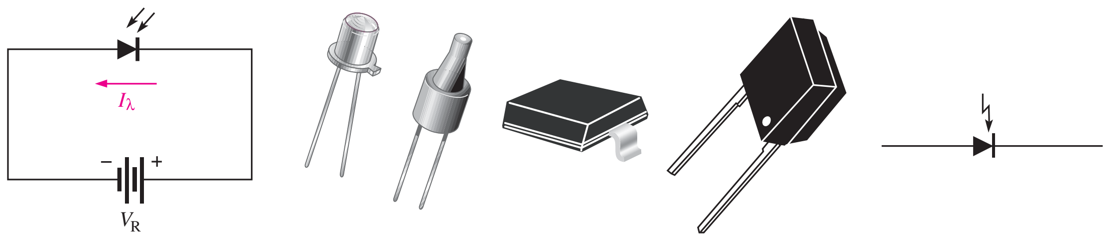
LEDs are also finding their way into interior home and business lighting applications. Arrays of white LEDs may eventually replace incandescent light bulbs and flourescent lighting in interior living and work areas. As previously mentioned, most white LEDs use a blue GaN (gallium nitride) LED covered by a yellowish phosphor coating made of a certain type of crystals that have been powdered and bound in a type of viscous adhesive. Since yellow light stimulates the red and green receptors of the eye, the resulting mix of blue and yellow light gives the appearance of white.

an incandescent bulb. Quantum dot filters can be designed to contain combinations of colors, giving designers control of the spectrum. The important advantage of quantum dot technology is that it does not lose the incoming light; it merely absorbs the light and reradiates it at a different frequency. This enables control of color without giving up efficiency. By placing a quantum dot filter in front of a white LED, the spectrum can be made to look like that of an incandescent bulb. The resulting light is more satisfactory for general illumination, while retaining the advantages of LEDs.

There are other promising applications, particularly in medical applications. Water-soluble quantum dots are used as a biochemical luminescent marker for cellular imaging and medical research. Research is also being done on quantum dots as the basic device units for information processing by manipulating two energy levels within the quantum dot.

The Photodiode

The **photodiode** is a device that operates in reverse bias, as shown in Figure 3–44(a), where I_λ is the reverse light current. The photodiode has a small transparent window that allows light to strike the *pn* junction. Some typical photodiodes are shown in Figure 3–44(b). An alternate photodiode symbol is shown in Figure 3–44(c).



(a) Reverse-bias operation using standard symbol (b) Typical devices (c) Alternate symbol

▲ FIGURE 3–44

Photodiode.

Recall that when reverse-biased, a rectifier diode has a very small reverse leakage current. The same is true for a photodiode. The reverse-biased current is produced by thermally generated electron-hole pairs in the depletion region, which are swept across the *pn* junction by the electric field created by the reverse voltage. In a rectifier diode, the reverse leakage current increases with temperature due to an increase in the number of electron-hole pairs.

A photodiode differs from a rectifier diode in that when its *pn* junction is exposed to light, the reverse current increases with the light intensity. When there is no incident light, the reverse current, I_λ, is almost negligible and is called the **dark current.** An increase in the amount of light intensity, expressed as irradiance (mW/cm^2), produces an increase in the reverse current, as shown by the graph in Figure 3–45(a).

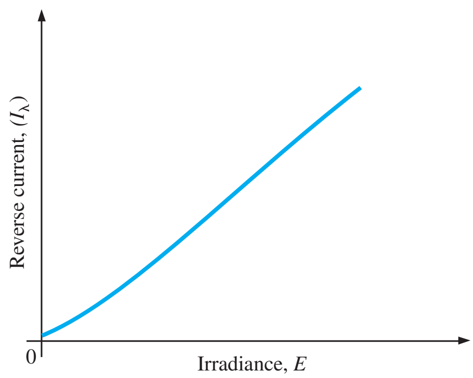
From the graph in Figure 3–45(b), you can see that the reverse current for this particular device is approximately 1.4 μA at a reverse-bias voltage of 10 V with an irradiance of 0.5 mW/cm^2. Therefore, the resistance of the device is

$$R_R = \frac{V_R}{I_\lambda} = \frac{10\text{ V}}{1.4\ \mu\text{A}} = 7.14\text{ M}\Omega$$

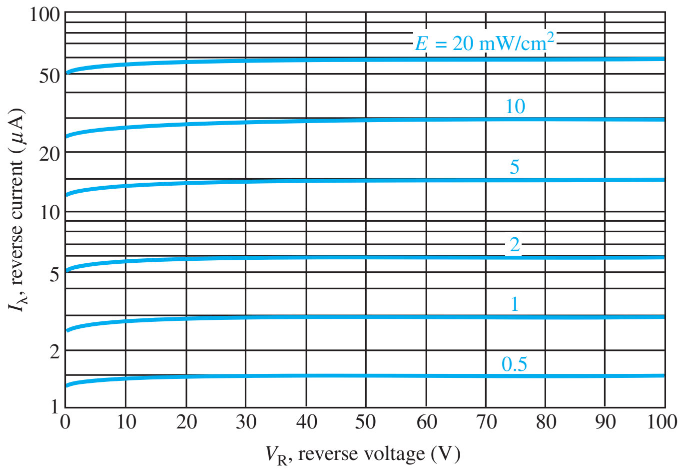
At 20 mW/cm^2, the current is approximately 55 μA at $V_R = 10$ V. The resistance under this condition is

$$R_R = \frac{V_R}{I_\lambda} = \frac{10\text{ V}}{55\ \mu\text{A}} = 182\text{ k}\Omega$$

These calculations show that the photodiode can be used as a variable-resistance device controlled by light intensity.



(a) General graph of reverse current versus irradiance

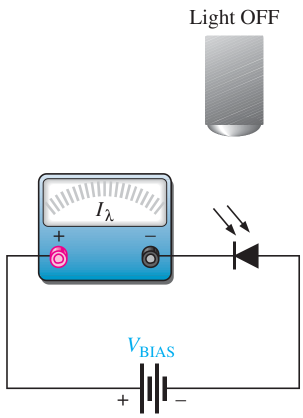


(b) Example of a graph of reverse current versus reverse voltage for several values of irradiance

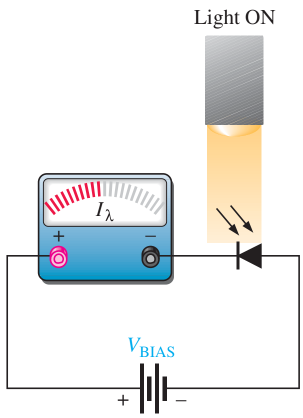
▲ **FIGURE 3–45**

Typical photodiode characteristics.

Figure 3–46 illustrates that the photodiode allows essentially no reverse current (except for a very small dark current) when there is no incident light. When a light beam strikes the photodiode, it conducts an amount of reverse current that is proportional to the light intensity (irradiance).



(a) No light, no current except negligible dark current



(b) Where there is incident light, resistance decreases and there is reverse current.

▲ **FIGURE 3–46**

Operation of a photodiode.

Photodiode Datasheet Information

A partial datasheet for an TEMD1000 photodiode is shown in Figure 3–47. Notice that the maximum reverse voltage is 60 V and the dark current (reverse current with no light) is typically 1 nA for a reverse voltage of 10 V. The dark current increases with an increase in reverse voltage and also with an increase in temperature.

Sensitivity From the graph in part (b), you can see that the maximum sensitivity for this device occurs at a wavelength of 950 nm. The angular response graph in part (c) shows an area of response measured as relative sensitivity. At 10° on either side of the maximum orientation, the sensitivity drops to approximately 82% of maximum.

Absolute Maximum Ratings

T_{amb} = 25°C, unless otherwise specified

Parameter	Test condition	Symbol	Value	Unit
Reverse Voltage		V_R	60	V
Power Dissipation	$T_{amb} \leq 25$°C	P_V	75	mW
Junction Temperature		T_j	100	°C
Storage Temperature Range		T_{stg}	- 40 to + 100	°C
Operating Temperature Range		T_{stg}	- 40 to + 85	°C
Soldering Temperature	$t \leq 5$ s	T_{sd}	< 260	°C

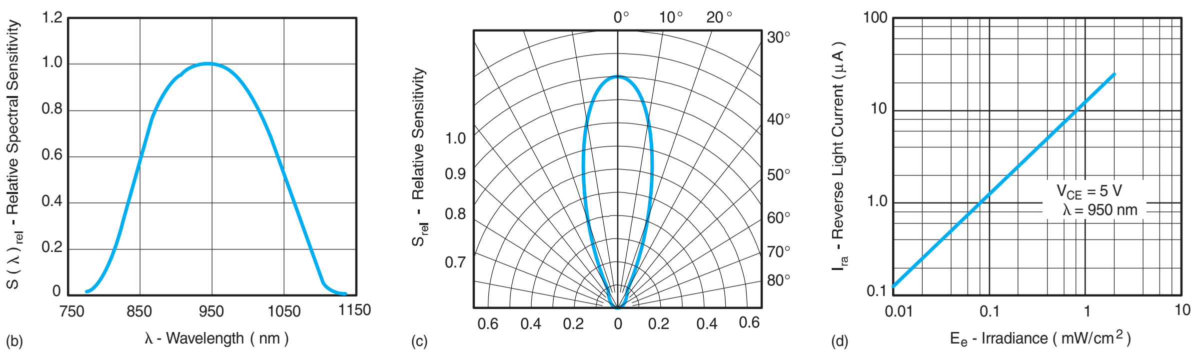
Basic Characteristics

T_{amb} = 25 °C, unless otherwise specified
T_{amb} = 25 °C, unless otherwise specified

Parameter	Test condition	Symbol	Min	Typ.	Max	Unit
Forward Voltage	I_F = 50 mA	V_F		1.0	1.3	V
Breakdown Voltage	I_R = 100 μA, E = 0	$V_{(BR)}$	60			V
Reverse Dark Current	V_R = 10 V, E = 0	I_{ro}		1	10	nA
Diode capacitance	V_R = 5 V, f = 1 MHz, E = 0	C_D		1.8		pF
Reverse Light Current	E_e = 1 mW/cm^2, λ = 870 nm, V_R = 5 V	I_{ra}		10		μA
	E_e = 1 mW/cm^2, λ = 950 nm, V_R = 5 V	I_{ra}	5	12		μA

Parameter	Test condition	Symbol	Min	Typ.	Max	Unit
Temp. Coefficient of I_{ra}	V_R = 5 V, = 870 nm	TK_{Ira}		0.2		%/K
Absolute Spectral Sensitivity	V_R = 5 V, = 870 nm	s(λ)		0.60		A/W
	V_R = 5 V, = 950 nm	s(λ)		0.55		A/W
Angle of Half Sensitivity		ϕ		±15		deg
Wavelength of Peak Sensitivity		$λ_p$		900		nm
Range of Spectral Bandwidth		$λ_{0.5}$		840 to 1050		nm
Rise Time	V_R = 10 V, R_L = 50, Ω λ = 820 nm	t_r		4		ns
Fall Time	V_R = 10 V, R_L = 50, Ω λ = 820 nm	t_f		4		ns

(a)



▲ **FIGURE 3–47**

Partial datasheet for the TEMD1000 photodiode. Datasheet courtesy of Vishay Intertechnology, Inc.

EXAMPLE 3–12

For a TEMD1000 photodiode,

(a) Determine the maximum dark current for V_R = 10 V.

(b) Determine the reverse light current for an irradiance of 1 mW/cm^2 at a wavelength of 850 nm if the device angle is oriented at 10° with respect to the maximum irradiance and the reverse voltage is 5 V.

Solution **(a)** From Figure 3–47(a), the maximum dark current I_{ro} = **10 nA.**

(b) From the graph in Figure 3–47(d), the reverse light current is 12 μ A at 950 nm. From Figure 3–47(b), the relative sensitivity is 0.6 at 850 nm. Therefore, the reverse light current is

$$I_\lambda = I_{ra} = 0.6(12\ \mu\text{A}) = 72\ \mu\text{A}$$

For an angle of 10°, the relative sensitivity is reduced to 0.92 of its value at 0°.

$$I_\lambda = I_{ra} = 0.92\,(7.2\ \mu\text{A}) = \mathbf{6.62\ \mu A}$$

Related Problem What is the reverse current if the wavelength is 1050 nm and the angle is 0°?

SECTION 3–4 CHECKUP

1. Name two types of LEDs in terms of their light-emission spectrum.
2. Which has the greater wavelength, visible light or infrared?
3. In what bias condition is an LED normally operated?
4. What happens to the light emission of an LED as the forward current increases?
5. The forward voltage drop of an LED is 0.7 V. (true or false)
6. What is a pixel?
7. In what bias condition is a photodiode normally operated?
8. When the intensity of the incident light (irradiance) on a photodiode increases, what happens to its internal reverse resistance?
9. What is *dark current*?

3–5 OTHER TYPES OF DIODES

In this section, several types of diodes that you are less likely to encounter as a technician but are nevertheless important are introduced. Among these are the laser diode, the Schottky diode, the *pin* diode, the step-recovery diode, the tunnel diode, and the current regulator diode.

After completing this section, you should be able to

- **Discuss the basic characteristics of several types of diodes**
- Discuss the laser diode and an application
  - Identify the schematic symbol
- Discuss the Schottky diode
  - Identify the schematic symbol
- Discuss the *pin* diode
- Discuss the step-recovery diode
  - Identify the schematic symbol
- Discuss the tunnel diode
  - Identify the schematic symbol
  - Describe a tunnel diode application
- Discuss the current regulation diode
  - Identify the schematic symbol