

3

SPECIAL-PURPOSE DIODES

INTRODUCTION

Chapter 2 was devoted to general-purpose and rectifier diodes, which are the most widely used types. In this chapter, we will cover several other types of diodes that are designed for specific applications, including the zener, varactor (variable-capacitance), light-emitting, photodiode, current regulator, Schottky, tunnel, *pin*, step-recovery, and laser diodes.

CHAPTER OUTLINE

- 3-1 Zener Diodes
- 3-2 Zener Diode Applications
- 3-3 Varactor Diodes
- 3-4 Optical Diodes
- 3-5 Other Types of Diodes
- 3-6 Troubleshooting
- ▣▣▣ System Application



CHAPTER OBJECTIVES

- Describe the characteristics of a zener diode and analyze its operation
- Explain how a zener can be used in voltage regulation and limiting applications
- Describe the variable-capacitance characteristics of a varactor diode and analyze its operation in a typical circuit
- Discuss the operation and characteristics of LEDs and photodiodes
- Discuss the basic characteristics of current regulator, Schottky, *pin*, step-recovery, tunnel, and laser diodes
- Troubleshoot zener diode regulators

KEY TERMS

Zener diode
Zener breakdown
Varactor
Light-emitting diode (LED)
Electroluminescence
Photodiode
Laser

SYSTEM APPLICATION PREVIEW

Your assignment will be to analyze and test a new system for counting and controlling items for packaging and shipment. The first system is to be installed in a sporting goods manufacturing plant to control the packaging of baseballs for shipment. The first step in your assignment is to learn all you can about various special-purpose diodes. You will then apply your knowledge to the system application at the end of the chapter.

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Study aids for this chapter are available at
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3-1 ZENER DIODES

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
- Identify a zener diode by its symbol
- Discuss avalanche and zener breakdown
- Analyze the V - I characteristic curve of a zener diode
- Discuss the zener equivalent circuit
- Define temperature coefficient and apply it to zener analysis
- Discuss power dissipation in a zener and apply derating
- Interpret a zener diode data sheet



FIGURE 3-1
Zener diode symbol.



The symbol for a zener diode is shown in Figure 3-1. 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 1, that when a diode reaches reverse breakdown, its voltage remains almost constant even though the current changes drastically. This volt-ampere characteristic is shown again in Figure 3-2 with normal operating regions for rectifier diodes and for zener diodes shown as shaded areas. If a zener diode is forward-biased, it operates the same as a rectifier diode.

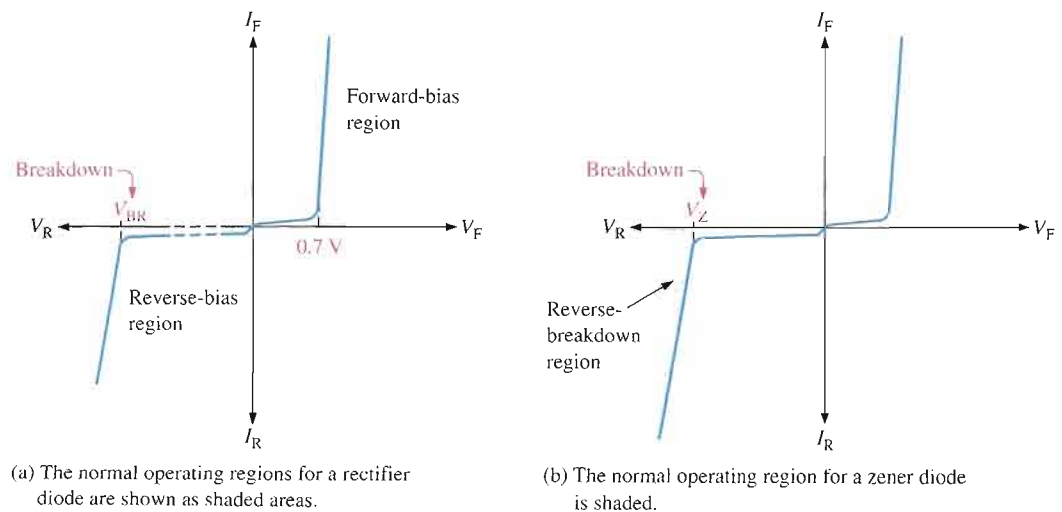


FIGURE 3-2

General diode V - I characteristic.

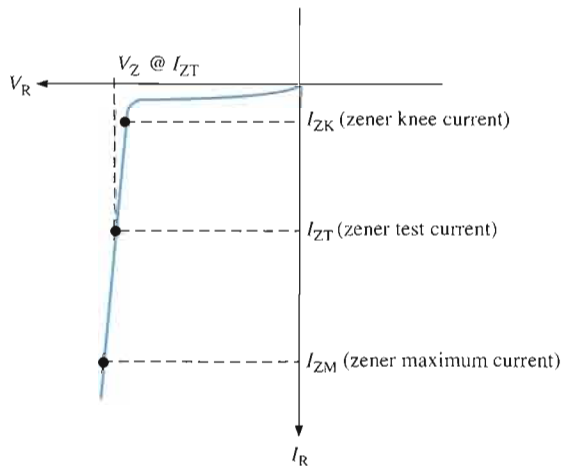
Zener Breakdown

Zener diodes are designed to operate in reverse breakdown. Two types of reverse breakdown in a zener diode are *avalanche* and *zener*. The avalanche breakdown, discussed in Chapter 1, occurs in both rectifier and zener diodes at a sufficiently high reverse voltage. **Zener breakdown** 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 predominantly in zener breakdown. Those with breakdown voltages greater than approximately 5 V operate predominantly in **avalanche breakdown**. Both types, however, are called *zener diodes*. Zeners are commercially available with breakdown voltages of 1.8 V to 200 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 the zener test current, I_{ZT} , and is designated V_{ZT} .

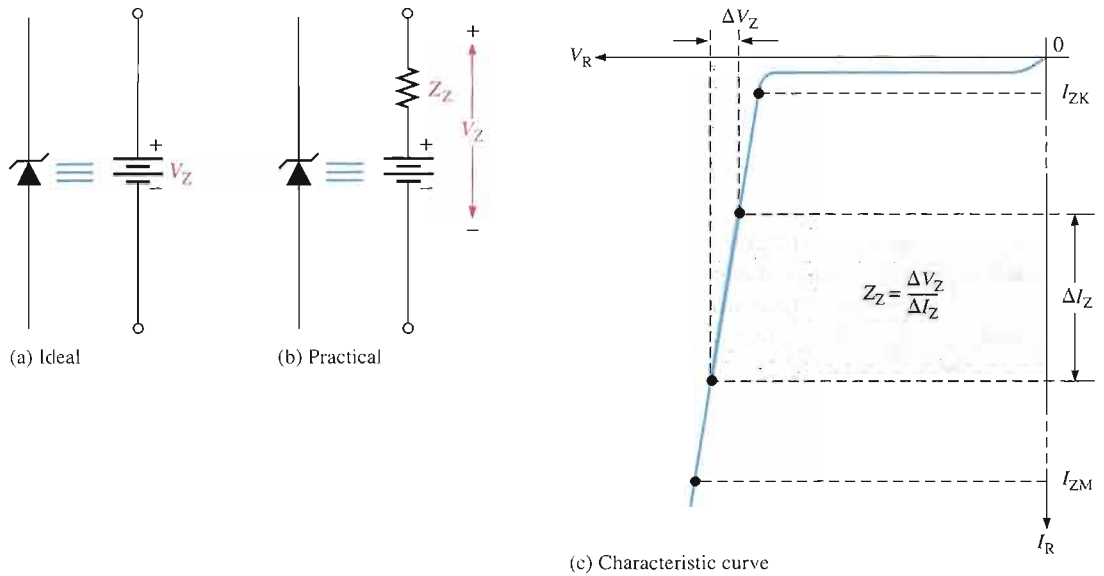
Zener Regulation The ability to keep the reverse voltage across its terminals essentially constant is the key feature of the zener diode. A zener diode operating in breakdown acts as a voltage regulator because it maintains a nearly constant voltage across its terminals over a specified range of reverse-current 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_{ZT} , is usually specified on a data sheet at a value of reverse current called the *zener test current*, I_{ZT} .

Zener Equivalent Circuit

Figure 3-4(a) shows the ideal model of a zener diode in reverse breakdown. It has a constant voltage drop equal to the nominal zener voltage. This constant voltage drop is represented by a dc voltage source even though the zener diode does not actually produce an emf voltage. The dc source simply indicates that the effect of reverse breakdown is a constant voltage across the zener terminals.



▲ FIGURE 3-4

Zener diode equivalent circuit models and the characteristic curve illustrating Z_Z .

Figure 3-4(b) represents the practical model of a zener diode, where the zener impedance (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 3-4(c). By Ohm’s law, the ratio of ΔV_Z to ΔI_Z is the impedance, as expressed in the following equation:

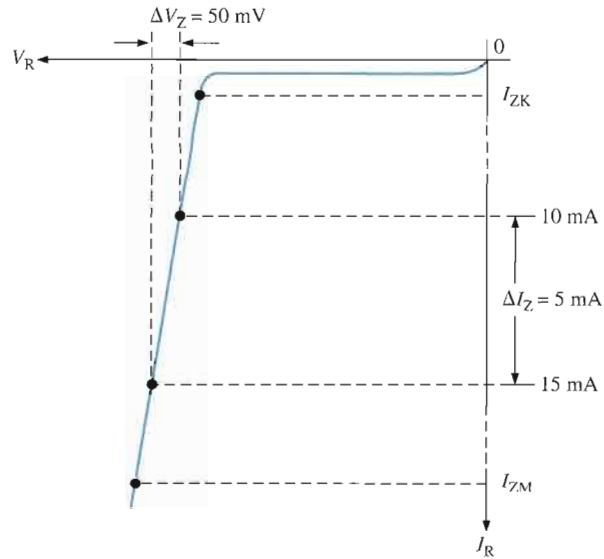
Equation 3-1
$$Z_Z = \frac{\Delta V_Z}{\Delta I_Z}$$

Normally, Z_Z is specified at I_{ZT} , the zener test current, and is designated Z_{ZT} . In most cases, you can assume that Z_Z is constant over the full linear range of zener current values and is purely resistive.

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 3-5. What is the zener impedance?

► FIGURE 3-5



Solution

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

Related Problem*

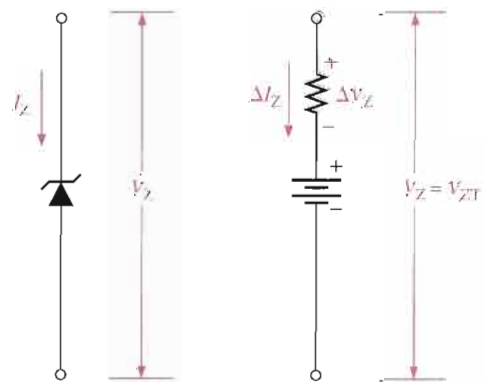
Calculate the zener impedance if the change in zener voltage is 100 mV for a 20 mA change in zener current on the linear portion of the characteristic curve.

*Answers are at the end of the chapter.

EXAMPLE 3-2

A 1N4736 zener diode has a Z_{ZT} of 3.5Ω . The data sheet gives $V_{ZT} = 6.8 \text{ V}$ at $I_{ZT} = 37 \text{ mA}$ and $I_{ZK} = 1 \text{ mA}$. What is the voltage across the zener terminals when the current is 50 mA? When the current is 25 mA? Figure 3-6 represents the zener diode.

► FIGURE 3-6



Solution For $I_Z = 50 \text{ mA}$: The 50 mA current is a 13 mA increase above $I_{ZT} = 37 \text{ mA}$.

$$\Delta I_Z = I_Z - I_{ZT} = +13 \text{ mA}$$

$$\Delta V_Z = \Delta I_Z Z_{ZT} = (13 \text{ mA})(3.5 \Omega) = +45.5 \text{ mV}$$

The change in voltage due to the increase in current above the I_{ZT} 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 $I_{ZT} = 37$ mA.

$$\Delta I_Z = -12 \text{ mA}$$

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

The change in voltage due to the decrease in current below I_{ZT} 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 1N4742 zener with $V_{ZT} = 12$ V at $I_{ZT} = 21$ mA and $Z_{ZT} = 9 \Omega$.

Temperature Coefficient

The temperature coefficient specifies the percent change in zener voltage for each degree centigrade 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 centigrade. The formula for calculating the change in zener voltage for a given junction temperature change, for a specified temperature coefficient, is

$$\text{Equation 3-2} \quad \Delta V_Z = V_Z \times TC \times \Delta T$$

where V_Z is the nominal zener voltage at 25°C, TC is the temperature coefficient, and ΔT is the change in 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

$$\text{Equation 3-3} \quad \Delta V_Z = TC \times \Delta T$$

EXAMPLE 3-3

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

$$\begin{aligned} \Delta V_Z &= V_Z \times TC \times \Delta T = (8.2 \text{ V})(0.05\%/^\circ\text{C})(60^\circ\text{C} - 25^\circ\text{C}) \\ &= (8.2 \text{ V})(0.0005/^\circ\text{C})(35^\circ\text{C}) = 144 \text{ mV} \end{aligned}$$

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

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

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 centigrade?

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:

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

Equation 3–4

EXAMPLE 3–4

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

$$\begin{aligned} P_{D(\text{derated})} &= P_{D(\max)} - (\text{mW}/^\circ\text{C})\Delta T \\ &= 400 \text{ mW} - (3.2 \text{ mW}/^\circ\text{C})(90^\circ\text{C} - 50^\circ\text{C}) \\ &= 400 \text{ mW} - 128 \text{ mW} = \mathbf{272 \text{ mW}} \end{aligned}$$

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 Data Sheet Information

The amount and type of information found on data sheets for zener diodes (or any category of electronic device) varies from one type of diode to the next. The data sheet for some zeners contains more information than for others. Figure 3–7 gives an example of the type of information that you have studied that can be found on a typical data sheet but does not represent the complete data sheet. This particular information is for a popular zener series, the 1N4728–1N4764.

Electrical Characteristics The electrical characteristics are listed in a tabular form in Figure 3–7(a) with the zener type numbers in the first column. This feature is common to most device data sheets.

Zener voltage For each zener type number, the nominal zener voltage, V_Z , for a specified value of zener test current, I_{ZT} , is listed in the second column. The nominal value of V_Z can vary depending on the tolerance. For example, the 1N4738 has a nominal V_Z of 8.2 V. For 10% tolerance, this value can range from 7.38 V to 9.02 V.

Zener test current The value of zener current, I_{ZT} , in mA at which the nominal zener voltage is specified is listed in the third column of the table in Figure 3–7(a).

Zener impedance Z_{ZT} is the value of dynamic impedance in ohms measured at the test current. The values of Z_{ZT} for each zener type are listed in the fourth column. The term *dynamic* means that it is measured as an ac quantity; that is, the change in voltage for a specified change in current ($Z_{ZT} = \Delta V_Z / \Delta I_Z$). You cannot get Z_{ZT} using V_Z and

Maximum Ratings

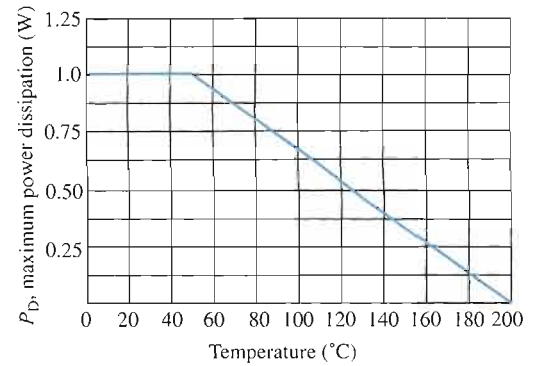
Rating	Symbol	Value	Unit
DC power dissipation @ $T_A = 50^\circ\text{C}$	P_D	1.0	Watt
Derate above 50°C		6.67	mW/ $^\circ\text{C}$
Operating and storage junction Temperature range	T_J, T_{stg}	-65 to +200	$^\circ\text{C}$

Electrical Characteristics ($T_A = 25^\circ\text{C}$ unless otherwise noted) $V_P = 1.2\text{ V max.}$
 $I_T = 200\text{ mA}$ for all types.

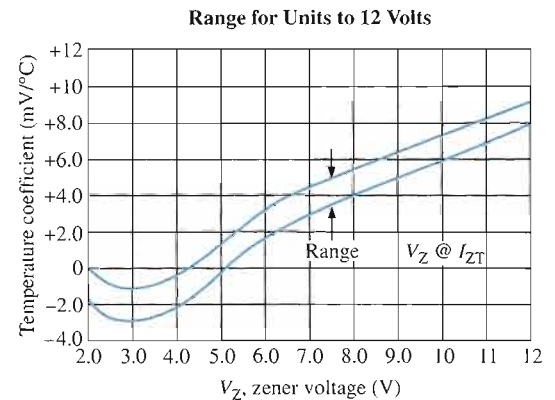
JEDEC Type No. (Note 1)	Nominal Zener Voltage $V_Z @ I_{ZT}$ Volts	Test Current I_{ZT} mA	Maximum Zener Impedance			Leakage Current	
			$Z_{ZT} @ I_{ZT}$ Ohms	$Z_{ZK} @ I_{ZK}$ Ohms	I_{ZK} mA	I_R $\mu\text{A Max}$	V_R Volts
1N4728	3.3	76	10	400	1.0	100	1.0
1N4729	3.6	69	10	400	1.0	100	1.0
1N4730	3.9	64	9.0	400	1.0	50	1.0
1N4731	4.3	58	9.0	400	1.0	10	1.0
1N4732	4.7	53	8.0	500	1.0	10	1.0
1N4733	5.1	49	7.0	550	1.0	10	1.0
1N4734	5.6	45	5.0	600	1.0	10	2.0
1N4735	6.2	41	2.0	700	1.0	10	3.0
1N4736	6.8	37	3.5	700	1.0	10	4.0
1N4737	7.5	34	4.0	700	0.5	10	5.0
1N4738	8.2	31	4.5	700	0.5	10	6.0
1N4739	9.1	28	5.0	700	0.5	10	7.0
1N4740	10	25	7.0	700	0.25	10	7.6
1N4741	11	23	8.0	700	0.25	5.0	8.4
1N4742	12	21	9.0	700	0.25	5.0	9.1
1N4743	13	19	10	700	0.25	5.0	9.9
1N4744	15	17	14	700	0.25	5.0	11.4
1N4745	16	15.5	16	700	0.25	5.0	12.2
1N4746	18	14	20	750	0.25	5.0	13.7
1N4747	20	12.5	22	750	0.25	5.0	15.2
1N4748	22	11.5	23	750	0.25	5.0	16.7
1N4749	24	10.5	25	750	0.25	5.0	18.2
1N4750	27	9.5	35	750	0.25	5.0	20.6
1N4751	30	8.5	40	1000	0.25	5.0	22.8
1N4752	33	7.5	45	1000	0.25	5.0	25.1
1N4753	36	7.0	50	1000	0.25	5.0	27.4
1N4754	39	6.5	60	1000	0.25	5.0	29.7
1N4755	43	6.0	70	1500	0.25	5.0	32.7
1N4756	47	5.5	80	1500	0.25	5.0	35.8
1N4757	51	5.0	95	1500	0.25	5.0	38.8
1N4758	56	4.5	110	2000	0.25	5.0	42.6
1N4759	62	4.0	125	2000	0.25	5.0	47.1
1N4760	68	3.7	150	2000	0.25	5.0	51.7
1N4761	75	3.3	175	2000	0.25	5.0	56.0
1N4762	82	3.0	200	3000	0.25	5.0	62.2
1N4763	91	2.8	250	3000	0.25	5.0	69.2
1N4764	100	2.5	350	3000	0.25	5.0	76.0

NOTE 1 — Tolerance and Type Number Designation. The JEDEC type numbers listed have a standard tolerance on the nominal zener voltage of $\pm 10\%$. A standard tolerance of $\pm 5\%$ on individual units is also available and is indicated by suffixing "A" to the standard type number. C for $\pm 2.0\%$, D for $\pm 1.0\%$.

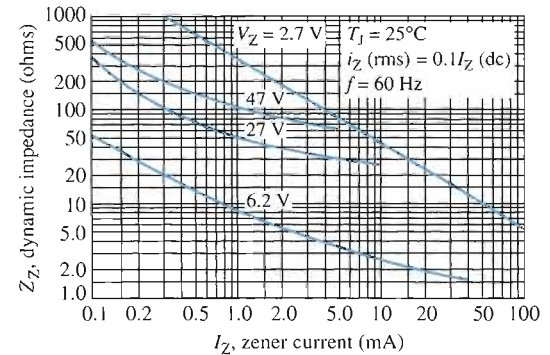
(a) Electrical characteristics



(b) Power derating



(c) Temperature coefficient



(d) Effect of zener current on zener impedance

▲ FIGURE 3-7

Partial data sheet for the 1N4728–1N4764 series 1 W zener diodes.

I_{ZT} , which are dc values. The table also includes Z_{ZK} , which is the impedance measured at the zener knee current, I_{ZK} .

Reverse leakage current The values of leakage current are listed in the fifth column of the table. The leakage current is the current through the reverse-biased zener diode for values of reverse voltage less than the value at the knee of the characteristic curve. Notice that the values are extremely small as was the case for rectifier diodes.

Maximum zener current The maximum dc current, I_{ZM} , is not specified on this particular data sheet. However, it is worth mentioning because you will find it on some data sheets. The value of I_{ZM} is specified based on the power rating, the zener voltage

at I_{ZM} , and the zener voltage tolerance. An approximate value for I_{ZM} can be calculated using the maximum power dissipation, $P_{D(max)}$ and V_Z at I_{ZT} as follows:

$$I_{ZM} = \frac{P_{D(max)}}{V_Z}$$

Equation 3–5

Graphical Data Some data sheets provide various types of data in the form of graphs while others do not. Figure 3–7 includes graphs for data related to concepts covered in this section.

Power derating Figure 3–7(b) shows a power derating curve for this particular series of zener diodes. Notice that the zeners are rated for a maximum power dissipation of 1 W for temperatures of 50°C and below. Above 50°C the power rating decreases linearly as shown. For example, at 140°C the power rating is approximately 400 mW.

Temperature coefficients Figure 3–7(c) shows the temperature coefficient in mV/°C versus zener voltage for zener voltages up to 12 V. The two curves define a range for the temperature coefficient. For example, a 6 V zener diode exhibits a temperature coefficient that can range from about 1.5 mV/°C to about 3 mV/°C.

Effect of zener current on zener impedance Figure 3–7(d) shows how the zener impedance, Z_Z , varies with current for selected values of nominal zener voltage: 2.7 V, 6.2 V, 27 V, and 47 V. Notice that Z_Z decreases with increasing current.

SECTION 3–1 REVIEW

Answers are at the end of the chapter.

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. For a certain zener diode, $V_Z = 10$ V at $I_{ZT} = 30$ mA. If $Z_Z = 8$ Ω , what is the terminal voltage at $I_Z = 50$ mA?
5. What does a positive temperature coefficient of 0.05%/°C mean?
6. 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 regulators and as simple limiters or clippers.

After completing this section, you should be able to

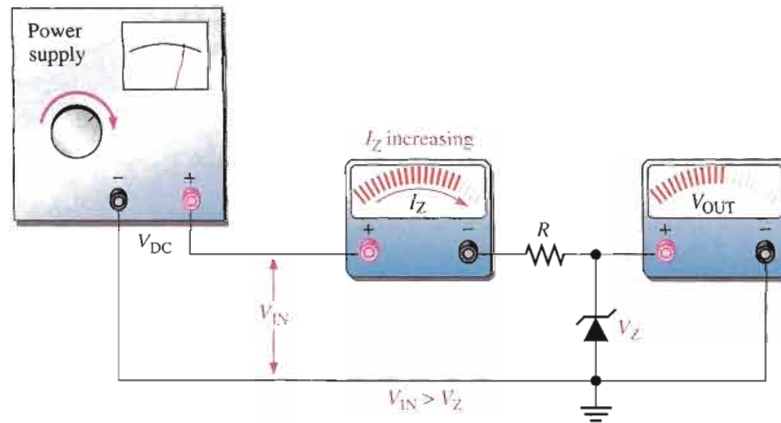
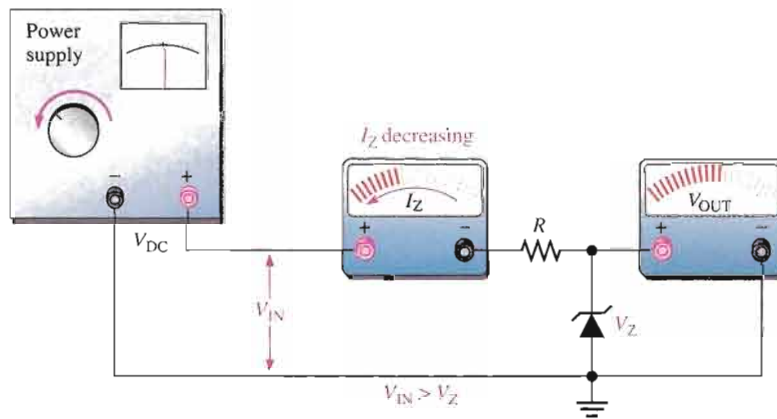
- Explain how a zener can be used in voltage regulation and limiting applications
- Analyze zener diode regulators under varying input and varying load conditions
- Analyze zener waveform-limiting circuits

Zener Regulation with a Varying Input Voltage

Figure 3–8 illustrates how a zener diode can be used to regulate a varying dc 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

► FIGURE 3-8

Zener regulation of a varying input voltage.


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

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

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, suppose that the 1N4740 10 V zener diode in Figure 3-9 can maintain regulation over a range of zener current values from $I_{ZK} = 0.25$ mA to $I_{ZM} = 100$ mA. From the data sheet in Figure 3-7, $P_{D(max)} = 1$ W and $V_Z = 10$ V.

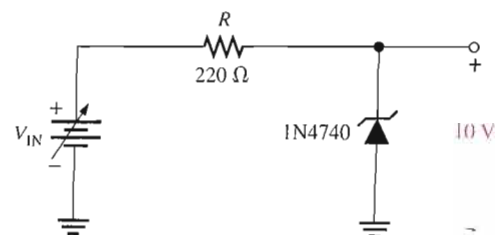
$$I_{ZM} = \frac{P_{D(max)}}{V_Z} = \frac{1 \text{ W}}{10 \text{ V}} = 100 \text{ mA}$$

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

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

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

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

► FIGURE 3-9


For the maximum zener current, the voltage across the $220\ \Omega$ resistor is

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

Therefore,

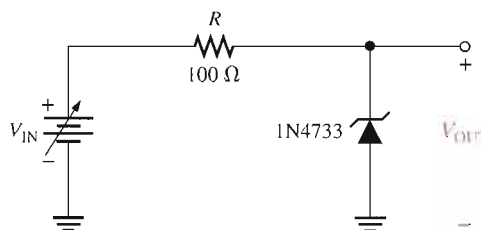
$$V_{IN(\text{max})} \cong 22\ \text{V} + 10\ \text{V} = 32\ \text{V}$$

This shows that this zener diode can 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 3-10.

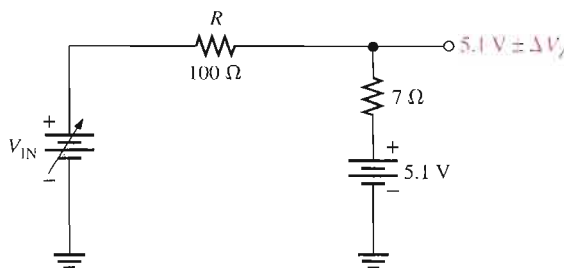
► FIGURE 3-10



Solution From the data sheet in Figure 3-7, obtain the following information for the 1N4733: $V_Z = 5.1\ \text{V}$ at $I_{ZT} = 49\ \text{mA}$, $I_{ZK} = 1\ \text{mA}$, and $Z_Z = 7\ \Omega$ at I_{ZT} . For simplicity, assume this value of Z_Z over the range of current values. The equivalent circuit is shown in Figure 3-11.

► FIGURE 3-11

Equivalent of circuit in Figure 3-10.



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

$$\begin{aligned} V_{OUT} &\cong 5.1\ \text{V} - \Delta V_Z = 5.1\ \text{V} - (I_{ZT} - I_{ZK})Z_Z \\ &= 5.1\ \text{V} - (48\ \text{mA})(7\ \Omega) = 5.1\ \text{V} - 0.336\ \text{V} = 4.76\ \text{V} \end{aligned}$$

Therefore,

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

To find the maximum input voltage, first calculate the maximum zener current. Assume the temperature is 50°C or below, so from the graph in Figure 3-7(b), the power dissipation is 1 W.

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

At I_{ZM} , the output voltage is

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

Therefore,

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

Related Problem Determine the minimum and maximum input voltages that can be regulated if a 1N4736 zener diode is used in Figure 3–10.



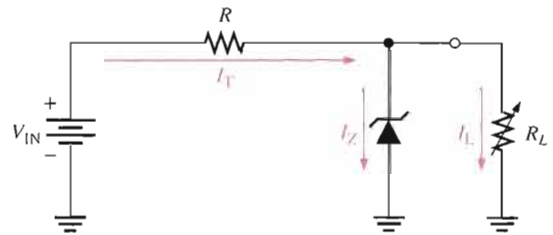
Open the Multisim file E03-05 in the Examples folder on your CD-ROM. For the calculated minimum and maximum dc input voltages, measure the resulting output voltages. Compare with the calculated values.

Zener Regulation with a Variable Load

Figure 3–12 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 3-12**

Zener regulation with a variable load.



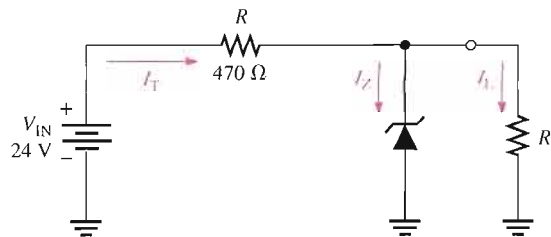
From No Load to Full Load

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.

EXAMPLE 3-6

Determine the minimum and the maximum load currents for which the zener diode in Figure 3–13 will maintain regulation. What is the minimum value of R_L that can be used? $V_Z = 12 \text{ V}$, $I_{ZK} = 1 \text{ mA}$, and $I_{ZM} = 50 \text{ mA}$. Assume $Z_Z = 0 \Omega$ and V_Z remains a constant 12 V over the range of current values, for simplicity.

▶ FIGURE 3-13



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

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

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. If R_L is removed from the circuit, the load current is 0 A.

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

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

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

The minimum value of R_L is

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

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 3-13 will maintain regulation. Determine the minimum value of R_L that can be used. $V_Z = 3.3$ V (constant), $I_{ZK} = 1$ mA, $I_{ZM} = 150$ mA. Assume $Z_Z = 0$ Ω for simplicity.



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

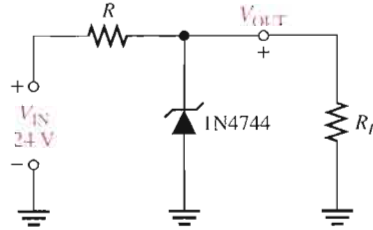
In the last example, we assumed that Z_Z was zero and, therefore, the zener voltage remained constant over the range of currents. We made this assumption to demonstrate the concept of how the regulator works with a varying load. Such an assumption is often acceptable and in many cases produces results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

EXAMPLE 3-7

For the circuit in Figure 3-14:

- Determine V_{OUT} at I_{ZK} and at I_{ZM} .
- Calculate the value of R that should be used.
- Determine the minimum value of R_L that can be used.

► **FIGURE 3-14**



Solution First, review Example 3-6. The 1N4744 zener used in the regulator circuit of Figure 3-14 is a 15 V diode. The data sheet in Figure 3-7(a) gives the following information: $V_Z = 15\text{ V}$ @ I_{ZT} , $I_{ZK} = 0.25\text{ mA}$, $I_{ZT} = 17\text{ mA}$, and $Z_{ZT} = 14\ \Omega$.

- (a) For I_{ZK} :

$$\begin{aligned} V_{OUT} &= V_Z = 15\text{ V} - \Delta I_Z Z_{ZT} = 15\text{ V} - (I_{ZT} - I_{ZK}) Z_{ZT} \\ &= 15\text{ V} - (16.75\text{ mA})(14\ \Omega) = 15\text{ V} - 0.235\text{ V} = \mathbf{14.76\text{ V}} \end{aligned}$$

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

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

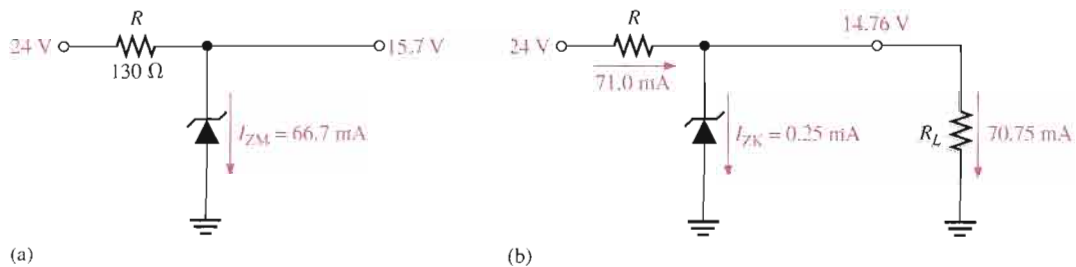
For I_{ZM} :

$$\begin{aligned} V_{OUT} &= V_Z = 15\text{ V} + \Delta I_Z Z_{ZT} \\ &= 15\text{ V} + (I_{ZM} - I_{ZT}) Z_{ZT} = 15\text{ V} + (49.7\text{ mA})(14\ \Omega) = \mathbf{15.7\text{ V}} \end{aligned}$$

- (b) Calculate the value of R for the maximum zener current that occurs when there is no load as shown in Figure 3-15(a).

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

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



► **FIGURE 3-15**

(c) For the minimum load resistance (maximum load current), the zener current is minimum ($I_{ZK} = 0.25 \text{ mA}$) as shown in Figure 3–15(b).

$$I_T = \frac{V_{IN} - V_{OUT}}{R} = \frac{24 \text{ V} - 14.76 \text{ V}}{130 \Omega} = 71.0 \text{ mA}$$

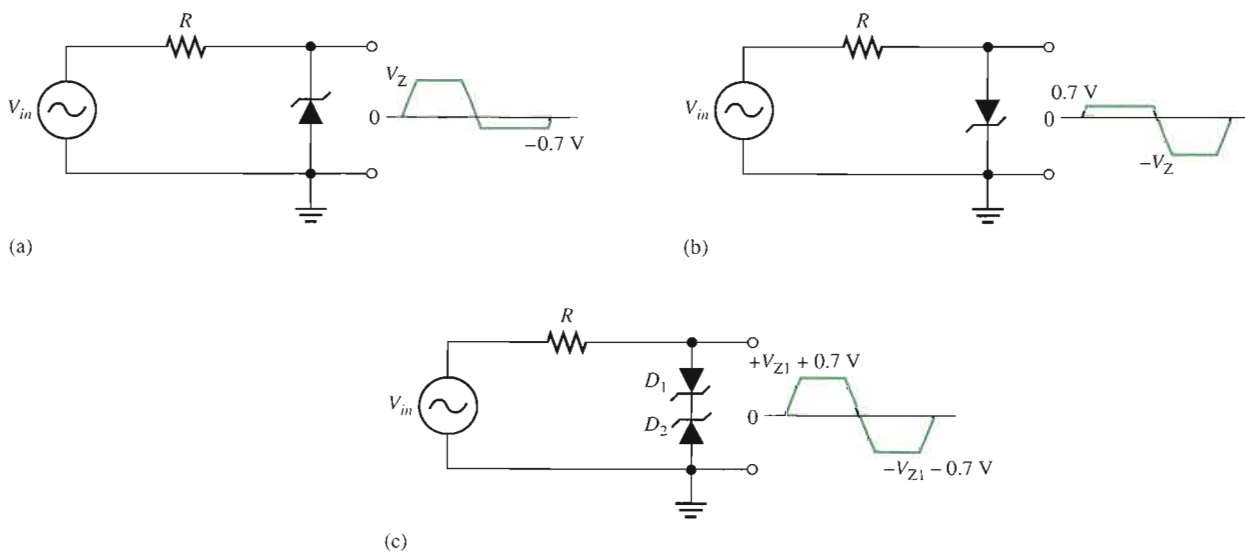
$$I_L = I_T - I_{ZK} = 71.0 \text{ mA} - 0.25 \text{ mA} = 70.75 \text{ mA}$$

$$R_{L(\min)} = \frac{V_{OUT}}{I_L} = \frac{14.76 \text{ V}}{70.75 \text{ mA}} = \mathbf{209 \Omega}$$

Related Problem Repeat each part of the preceding analysis if the zener is changed to a 12 V device (1N4742).

Zener Limiting

In addition to voltage regulation applications, zener diodes can be used in ac applications to limit voltage swings to desired levels. Figure 3–16 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 is turned around, as in part (b), the negative peak is limited by zener action and the positive voltage is limited to $+0.7 \text{ V}$. Two back-to-back zeners limit both peaks to the zener voltage $\pm 0.7 \text{ V}$, 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.



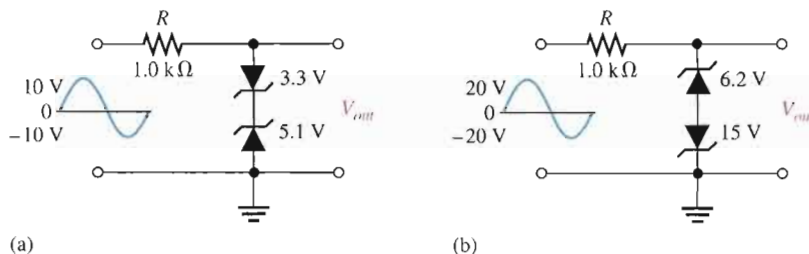
▲ **FIGURE 3–16**

Basic zener limiting action with a sinusoidal input voltage.

EXAMPLE 3-8

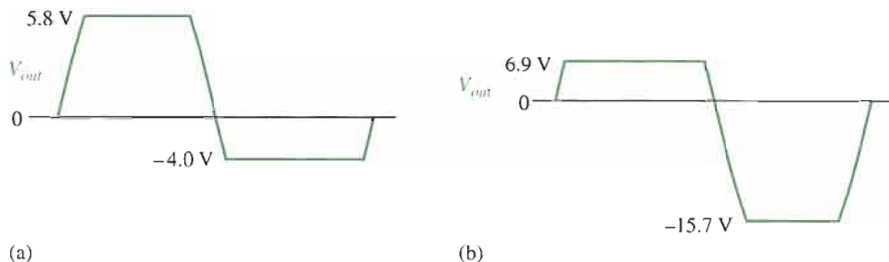
Determine the output voltage for each zener limiting circuit in Figure 3-17.

► **FIGURE 3-17**



Solution See Figure 3-18 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 3-18**



- Related Problem**
- What is the output in Figure 3-17(a) if the input voltage is increased to a peak value of 20 V?
 - What is the output in Figure 3-17(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 your CD-ROM. For the specified input voltages, measure the resulting output waveforms. Compare with the waveforms shown in the example.

SECTION 3-2
REVIEW

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

3-3 VARACTOR DIODES

Varactor diodes are also known as variable-capacitance diodes because the junction capacitance varies with the amount of reverse-bias voltage. Varactor diodes are specifically designed to take advantage of this variable-capacitance characteristic. These devices are commonly used in electronic tuning circuits used in communications systems.

After completing this section, you should be able to

- Describe the variable-capacitance characteristics of a varactor diode and analyze its operation in a typical circuit
- Identify a varactor diode symbol
- Explain why a reverse-biased varactor exhibits capacitance
- Discuss how the capacitance varies with reverse-bias voltage
- Interpret a varactor data sheet
- Define *tuning ratio*
- Define *quality factor, Q*
- Discuss varactor temperature coefficients
- Analyze a varactor-tuned band-pass filter

A **varactor** is a diode that always operates in reverse-bias and is doped to maximize the inherent capacitance of the depletion region. The depletion region, widened by the reverse bias, acts as a capacitor dielectric because of its nonconductive characteristic. The p and n regions are conductive and act as the capacitor plates, as illustrated in Figure 3-19.

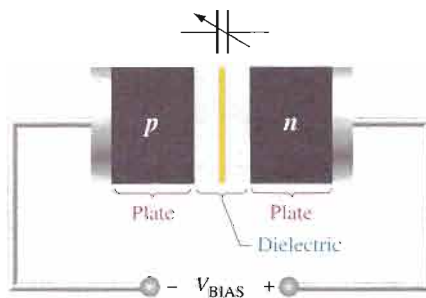
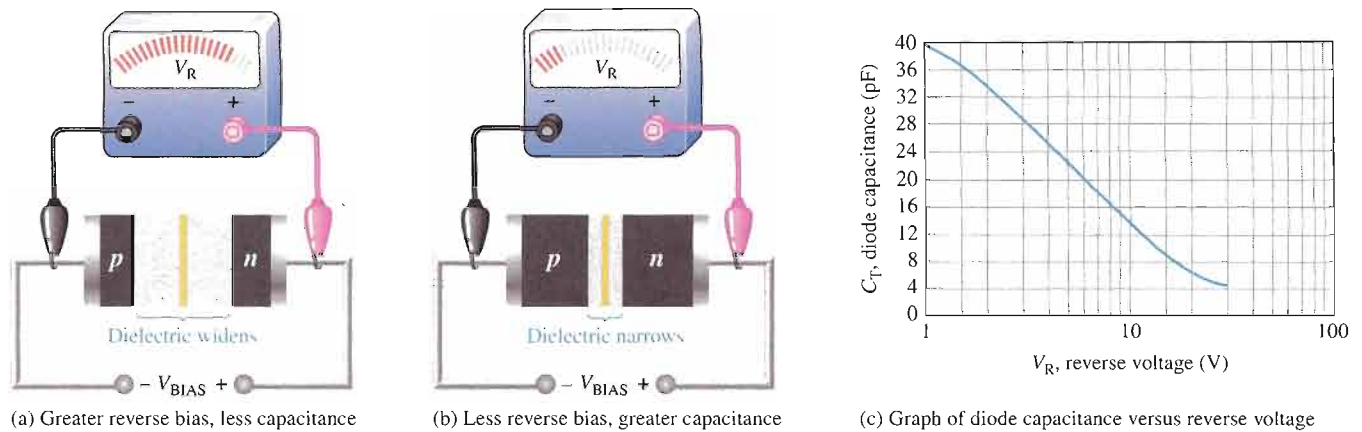


FIGURE 3-19

The reverse-biased varactor diode acts as a variable capacitor.

Basic Operation

As the reverse-bias voltage increases, the depletion region widens, effectively increasing the plate separation and the dielectric thickness and thus decreasing the capacitance. When the reverse-bias voltage decreases, the depletion region narrows, thus increasing the capacitance. This action is shown in Figure 3-20(a) and (b). A graph of diode capacitance (C_T) versus reverse voltage for a certain varactor is shown in Figure 3-20(c). For this particular device, C_T varies from 40 pF to slightly greater than 4 pF as V_R varies from 1 V to 40 V.



▲ FIGURE 3-20

Varactor diode capacitance varies with reverse voltage.

Recall that capacitance is determined by the parameters of plate area (A), dielectric constant (ϵ), and dielectric thickness (d), as expressed in the following formula:

$$C = \frac{A\epsilon}{d}$$

In a varactor diode, these capacitance parameters are controlled by the method of doping near the pn junction and the size and geometry of the diode's construction. Nominal varactor capacitances are typically available from a few picofarads to several hundred picofarads. Figure 3-21 shows a common symbol for a varactor.



▲ FIGURE 3-21

Varactor diode symbol.

Varactor Data Sheet Information

A partial data sheet for a specific series of varactor diodes (1N5139–1N5148) is shown in Figure 3-22. The values of nominal diode capacitance, C_T , are measured at a reverse voltage of 4 V dc and range from 6.8 pF to 47 pF for this particular series.

Capacitance Tolerance Range The minimum and maximum values of C_T are based on 10% tolerance. For example, this means that when reverse-biased at 4 V, the 1N5139 can exhibit a capacitance anywhere between 6.1 pF and 7.5 pF. This tolerance range should not be confused with the range of capacitance values that result from varying the reverse bias as determined by the tuning ratio, which we will discuss next.

Tuning Ratio The varactor **tuning ratio** is also called the *capacitance ratio*. It is the ratio of the diode capacitance at a minimum reverse voltage to the diode capacitance at a maximum reverse voltage. For the varactor diodes represented in Figure 3-22, the tuning ratio is the ratio of C_T measured at a V_R of 4 V divided by C_T measured at a V_R of 60 V. The tuning ratio is designated as C_4/C_{60} in this case.

For the 1N5139, the typical tuning ratio is 2.9. This means that the capacitance value decreases by a factor of 2.9 as V_R is increased from 4 V to 60 V. The following calculation illustrates how to use the tuning ratio (TR) to find the capacitance range for the 1N5139. From the data table in Figure 3-22(a), $C_4 = 6.8$ pF, and the typical $TR = C_4/C_{60} = 2.9$. Therefore,

$$C_{60} = \frac{C_4}{TR} = \frac{6.8 \text{ pF}}{2.9} = 2.3 \text{ pF}$$

The diode capacitance varies from 6.8 pF to 2.3 pF when V_R is increased from 4 V to 60 V.

The capacitance range can also be determined from the graph in Figure 3-22(b), which shows how the varactor capacitance varies for reverse voltages from 1 V to 60 V. On the

Maximum Ratings ($T_C = 25^\circ\text{C}$ unless otherwise noted)

Rating	Symbol	Value	Unit
Reverse voltage	V_R	60	Volts
Forward current	I_F	250	mA
RF power input*	P_{in}	5.0	Watts
Device dissipation @ $T_A = 25^\circ\text{C}$	P_D	400	mW
Derate above 25°C		2.67	mW/ $^\circ\text{C}$
Device dissipation @ $T_C = 25^\circ\text{C}$	P_C	2.0	Watts
Derate above 25°C		13.3	mW/ $^\circ\text{C}$
Junction temperature	T_J	+175	$^\circ\text{C}$
Storage temperature range	T_{stg}	-65 to +200	$^\circ\text{C}$

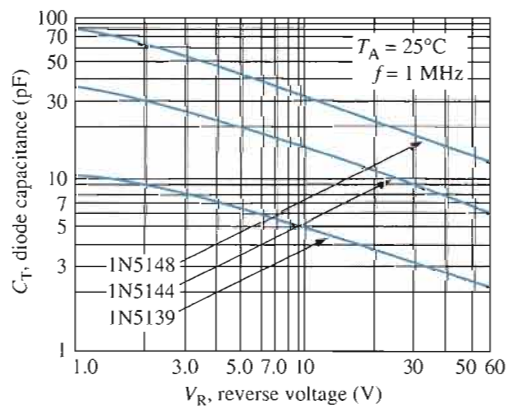
*The RF power input rating assumes that an adequate heat sink is provided.

Electrical Characteristics ($T_A = 25^\circ\text{C}$ unless otherwise noted)

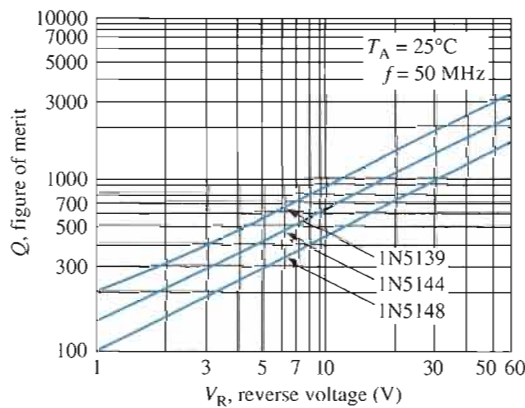
Characteristic	Symbol	Min	Typ	Max	Unit
Reverse breakdown voltage ($I_R = 10 \mu\text{A}$ dc)	$V_{(BR)R}$	60	70	-	V dc
Reverse voltage leakage current ($V_R = 55 \text{ V dc}$, $T_A = 25^\circ\text{C}$)	I_R	-	-	0.02	μA dc
($V_R = 55 \text{ V dc}$, $T_A = 150^\circ\text{C}$)		-	-	20	
Series inductance ($f = 250 \text{ MHz}$, $L \approx 1/16''$)	L_S	-	5.0	-	nH
Case capacitance ($f = 1.0 \text{ MHz}$, $L \approx 1/16''$)	C_C	-	0.25	-	pF
Diode capacitance temperature coefficient ($V_R = 4.0 \text{ V dc}$, $f = 1.0 \text{ MHz}$)	TC_C	-	200	300	ppm/ $^\circ\text{C}$

Device	C_T , Diode Capacitance $V_R = 4.0 \text{ V dc}$, $f = 1.0 \text{ MHz}$ pF			Q , Figure of Merit $V_R = 4.0 \text{ V dc}$ $f = 50 \text{ MHz}$	TR , Tuning Ratio C_4/C_{60} $f = 1.0 \text{ MHz}$	
	Min	Typ	Max		Min	Typ
1N5139	6.1	6.8	7.5	350	2.7	2.9
1N5140	9.0	10	11	300	2.8	3.0
1N5141	10.8	12	13.2	300	2.8	3.0
1N5142	13.5	15	16.5	250	2.8	3.0
1N5143	16.2	18	19.8	250	2.8	3.0
1N5144	19.8	22	24.2	200	3.2	3.4
1N5145	24.3	27	29.7	200	3.2	3.4
1N5146	29.7	33	36.3	200	3.2	3.4
1N5147	36.1	39	42.9	200	3.2	3.4
1N5148	42.3	47	51.7	200	3.2	3.4

(a) Electrical characteristics



(b) Diode capacitance



(c) Figure of merit

▲ FIGURE 3-22

Partial data sheet for the 1N5139–1N5148 varactor diodes.

graph, you can see that the capacitance for the 1N5139 is approximately 10.5 pF at $V_R = 1 \text{ V}$ and approximately 2.3 pF at $V_R = 60 \text{ V}$.

The 1N51XX series of varactor diodes are abrupt junction devices. The doping in the n and p regions is made uniform so that at the pn junction there is a relatively abrupt change from n to p instead of the more gradual change found in the rectifier diodes. The abruptness of the pn junction determines the tuning ratio. Other types of varactor diodes such as the MV1401 are hyper-abrupt devices in which the doping pattern results in an

even more abrupt junction. Many hyper-abrupt varactor diodes exhibit tuning ratios from 10 to 15.

Figure of Merit The figure of merit or **quality factor (Q)** of a reactive component is the ratio of energy stored and then returned by a capacitor (or inductor) to the energy dissipated in the resistance. The IN5139 has a minimum Q of 350 at $V_R = 4$ V, which indicates that the energy stored and returned by the diode capacitance is 350 times greater than the energy lost in the resistance of the device. High values of Q are desirable. Figure 3–22(c) is a graph showing how the typical figure of merit increases with increasing reverse voltage for three varactors in the series.

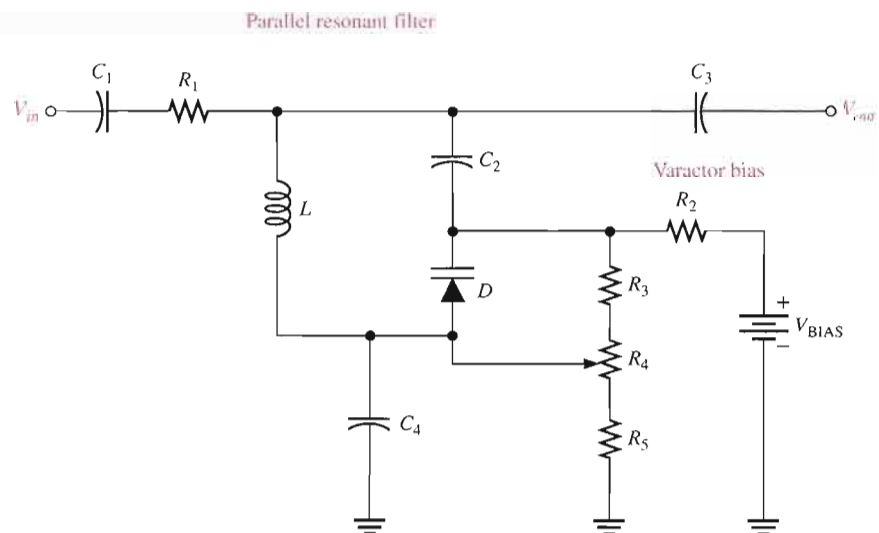
Temperature Coefficients The diode capacitance has a positive temperature coefficient so C_T increases a small amount as the temperature increases. The figure of merit has a negative temperature coefficient, so Q decreases as the temperature increases.

An Application

A major application of varactors is in tuning circuits. For example, electronic tuners in TV and other commercial receivers utilize varactors. When used in a resonant circuit, as illustrated in Figure 3–23, the varactor acts as a variable capacitor, thus allowing the resonant frequency to be adjusted by a variable voltage level. The varactor diode provides the total variable capacitance in the parallel resonant band-pass filter. The varactor diode and the inductor form a parallel resonant circuit from the output to ac ground. Capacitors C_1 , C_2 , C_3 , and C_4 are coupling capacitors to prevent the dc bias circuit from being loaded by the filter circuit. These capacitors have no effect on the filter's frequency response because their reactances are negligible at the resonant frequencies. C_1 prevents a dc path from the potentiometer wiper back to the ac source through the inductor and R_1 . C_2 prevents a dc path from the cathode of the varactor through the inductor to the anode of the varactor through the inductor. C_3 prevents a dc path from the wiper to a load on the output through the inductor. C_4 prevents a dc path from the wiper to ground.

► FIGURE 3–23

A resonant band-pass filter using a varactor diode for adjusting the resonant frequency over a specified range.



Resistors R_2 , R_3 , R_5 , and potentiometer R_4 form a variable dc voltage divider for biasing the varactor. The reverse-bias voltage across the varactor can be varied with the potentiometer.

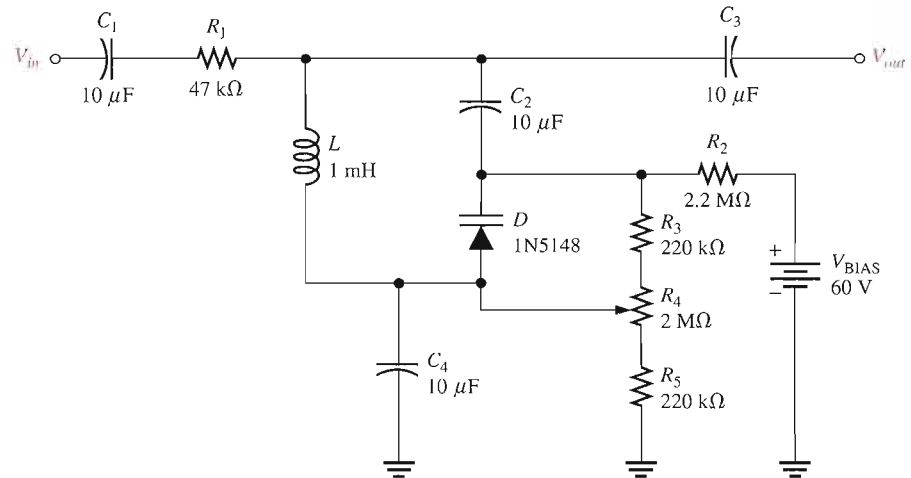
Recall that the parallel resonant frequency is

$$f_r \cong \frac{1}{2\pi\sqrt{LC}}$$

EXAMPLE 3-9

For the varactor-tuned band-pass filter in Figure 3-24, determine the range of resonant frequencies over which it can be adjusted. The values of the bias resistors are selected to prevent significant ac loading on the filter.

▶ FIGURE 3-24



Solution From the data sheet information in Figure 3-22(a), the 1N5148 varactor has a nominal capacitance of 47 pF at a reverse bias of 4 V.

First, determine the range of reverse-bias voltages for the filter circuit. The dc voltage at the cathode (V_K) of the varactor is fixed at

$$V_K = \left(\frac{R_3 + R_4 + R_5}{R_2 + R_3 + R_4 + R_5} \right) V_{\text{BIAS}} = \left(\frac{2.44 \text{ M}\Omega}{4.64 \text{ M}\Omega} \right) 60 \text{ V} = 31.6 \text{ V}$$

The dc voltage at the anode (V_A) of the varactor can be varied from a minimum to a maximum with the potentiometer R_4 .

$$V_{A(\text{min})} = \left(\frac{R_5}{R_2 + R_3 + R_4 + R_5} \right) V_{\text{BIAS}} = \left(\frac{220 \text{ k}\Omega}{4.64 \text{ M}\Omega} \right) 60 \text{ V} = 2.85 \text{ V}$$

$$V_{A(\text{max})} = \left(\frac{R_4 + R_5}{R_2 + R_3 + R_4 + R_5} \right) V_{\text{BIAS}} = \left(\frac{2.22 \text{ M}\Omega}{4.64 \text{ M}\Omega} \right) 60 \text{ V} = 28.7 \text{ V}$$

The minimum and maximum values for the reverse voltage, V_R , are determined as follows:

$$V_{R(\text{min})} = V_K - V_{A(\text{max})} = 31.6 \text{ V} - 28.7 \text{ V} = 2.9 \text{ V}$$

$$V_{R(\text{max})} = V_K - V_{A(\text{min})} = 31.6 \text{ V} - 2.85 \text{ V} = 28.7 \text{ V}$$

Although it is difficult to get exact figures from the graph in Figure 3-22(b), the approximate capacitance values of the varactor at 2.9 V and 29 V are $C_{2.9} \cong 55 \text{ pF}$ and $C_{29} \cong 17 \text{ pF}$. The minimum resonant frequency for the filter is

$$f_{r(\text{min})} \cong \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(1 \text{ mH})(55 \text{ pF})}} = \mathbf{679 \text{ kHz}}$$

The maximum resonant frequency for the filter is

$$f_{r(\text{max})} \cong \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(1 \text{ mH})(17 \text{ pF})}} = \mathbf{1.22 \text{ MHz}}$$

Related Problem If the bias voltage source in Figure 3–24 is reduced to 30 V, determine the range of the reverse voltage across the varactor.

SECTION 3-3 REVIEW

1. What is the key feature of a varactor diode?
2. Under what bias condition is a varactor operated?
3. What part of the varactor produces the capacitance?
4. Based on the graph in Figure 3–22(b), what happens to the diode capacitance when the reverse voltage is increased?
5. Define *tuning ratio*.

3-4 OPTICAL DIODES

In this section, two types of optoelectronic devices—the light-emitting diode (LED) and the photodiode—are introduced. As the name implies, the LED is a light emitter. The photodiode, on the other hand, is a light detector. We will examine the characteristics of both devices, and you will see an example of their use in a system application at the end of the chapter.

After completing this section, you should be able to

- **Discuss the operation and characteristics of LEDs and photodiodes**
- Identify LED and photodiode symbols
- Explain basically how an LED emits light
- Analyze the spectral output curves and radiation patterns of LEDs
- Interpret an LED data sheet
- Define *radiant intensity* and *irradiance*
- Use an LED seven-segment display
- Explain how a photodiode detects light
- Analyze the response curve of a photodiode
- Interpret a photodiode data sheet
- Discuss photodiode sensitivity



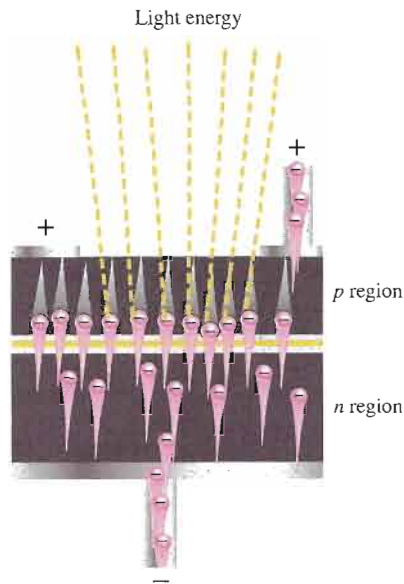
▲ **FIGURE 3-25**

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

The Light-Emitting Diode (LED)

The symbol for an LED is shown in Figure 3–25.

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. When recombination takes place, the recombining electrons release energy in the form of heat and light. 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 3–26. Various impurities are added during the doping process to establish



◀ **FIGURE 3-26**

Electroluminescence in a forward-biased LED.

the wavelength of the emitted light. The wavelength determines the color of the light and if it is visible or **infrared** (IR).

LED Semiconductor Materials The semiconductor gallium arsenide (GaAs) was used in early LEDs. 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. GaAs LEDs emit infrared (IR) radiation, which is invisible.

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.

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 re-emit it as white light.

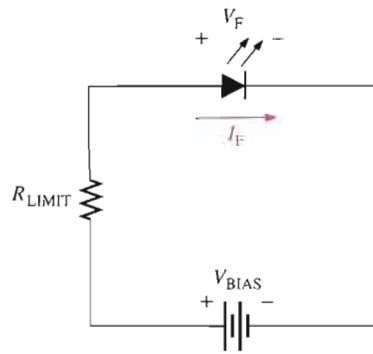
LED Biasing The forward voltage across an LED is considerably greater than for a silicon diode. Typically the maximum V_F for LEDs is between 1.2 V and 3.2 V, depending on the device. Reverse breakdown for an LED is much less than for a silicon rectifier diode (3 V to 10 V is typical).

The LED emits light in response to a sufficient forward current, as shown in Figure 3-27(a). The amount of power output translated into light is directly proportional to the forward current, as indicated in Figure 3-27(b). An increase in I_F corresponds proportionally to an increase in light output.

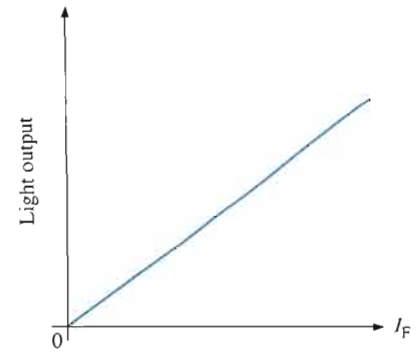
Light Emission The **wavelength** of light determines whether it is visible or infrared. An LED emits light over a specified range of wavelengths as indicated by the **spectral** output curves in Figure 3-28. The curves in part (a) represent the light output versus wavelength for typical visible LEDs, 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.

► **FIGURE 3-27**

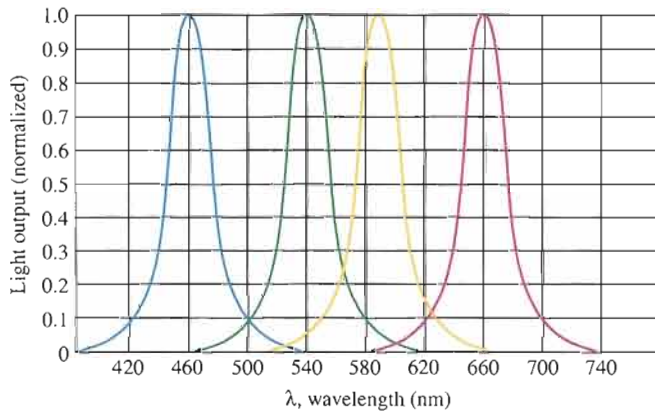
Basic operation of an LED.



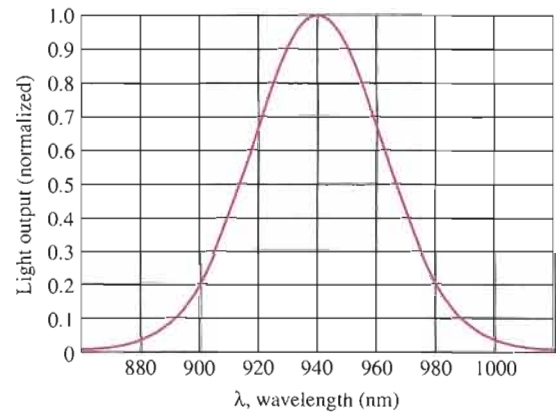
(a) Forward-biased operation



(b) General light output versus forward current



(a) Visible light



(b) Infrared (IR)

▲ **FIGURE 3-28**

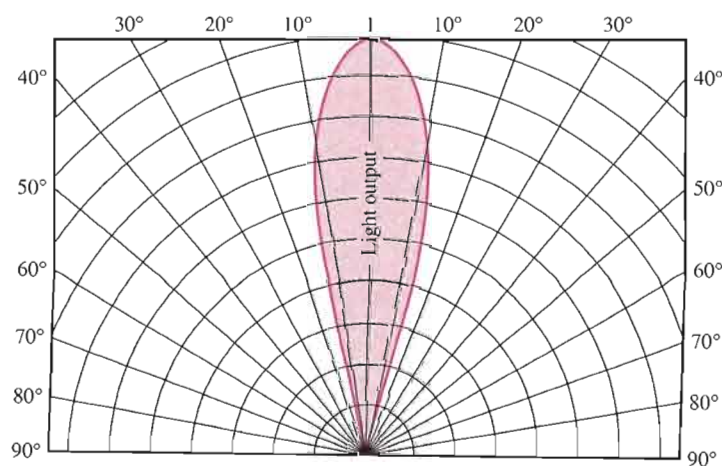
Examples of typical spectral output curves for LEDs.

The graph in Figure 3-29 is the **radiation pattern** for a typical LED. It shows how directional the emitted light is. The radiation pattern depends on the type of lens structure of the LED. The narrower the radiation pattern, the more the light is concentrated in a particular direction. Also, colored lenses are used to enhance the color.

Typical LEDs are shown in Figure 3-30. Photodiodes, to be studied next, generally have a similar appearance.

► **FIGURE 3-29**

General radiation pattern of a typical LED.



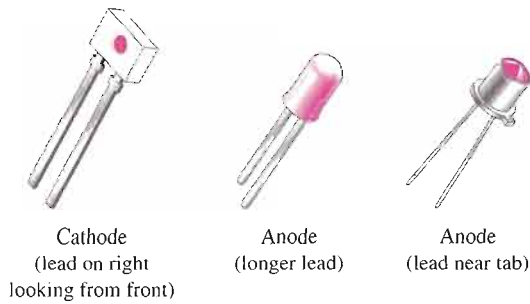


FIGURE 3-30

Typical LEDs.

LED Data Sheet Information

A partial data sheet for an MLED81 infrared (IR) light-emitting diode is shown in Figure 3-31. Notice that the maximum reverse voltage is only 5 V, the maximum continuous forward current is 100 mA, and the forward voltage drop is 1.35 V for $I_F = 100$ mA.

From the graph in part (c), you can see that the peak power output for this device occurs at a wavelength of 940 nm; its radiation pattern is shown in part (d). At 30° on either side of the maximum orientation, the output power drops to approximately 60% of maximum.

Radiant Intensity and Irradiance In Figure 3-31(a), the axial **radiant intensity**, I_e (symbol not to be confused with current), is the output power per steradian and is specified as 15 mW/sr. The steradian (sr) is the unit of solid angular measurement. **Irradiance**, H , is the power per unit area at a given distance from an LED source expressed in mW/cm^2 and can be calculated using radiant intensity and the distance in centimeters (cm) using the following formula:

$$H = \frac{I_e}{d^2}$$

Equation 3-6

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. We will discuss this further in relation to photodiodes.

EXAMPLE 3-10

From the LED data sheet in Figure 3-31 determine the following:

- The radiant intensity at 900 nm if the maximum output is 15 mW/sr.
- The forward voltage drop for $I_F = 20$ mA.
- The radiant intensity for $I_F = 30$ mA.
- The maximum irradiance at a distance of 10 cm from the LED source.

Solution (a) From the relative spectral emission graph in Figure 3-31(c), the relative radiant intensity at 900 nm is approximately 0.75. The radiant intensity is, therefore,

$$I_e = 0.75(15 \text{ mW/sr}) = \mathbf{11.3 \text{ mW/sr}}$$

- From the graph in part (b), $V_F = \mathbf{1.23 \text{ V}}$ for $I_F = 20$ mA.
- From the graph in part (e), $I_e = \mathbf{5 \text{ mW/sr}}$ for $I_F = 30$ mA.

$$(d) H = \frac{I_e}{d^2} = \frac{15 \text{ mW/sr}}{(10 \text{ cm})^2} = \mathbf{0.15 \text{ mW}/\text{cm}^2}$$

Related Problem If $I_e = 12$ mW/sr, at a wavelength of 940 nm, determine the radiant intensity at 1000 nm.

Maximum Ratings

Rating	Symbol	Value	Unit
Reverse voltage	V_R	5	Volts
Forward current — continuous	I_F	100	mA
Forward current — peak pulse	I_F	1	A
Total power dissipation @ $T_A = 25^\circ\text{C}$ Derate above 25°C	P_D	100 2.2	mW mW/°C
Ambient operating temperature range	T_A	-30 to +70	°C
Storage temperature	T_{stg}	-30 to +80	°C
Lead soldering temperature. 5 seconds max. 1/16 inch from case	—	260	°C

Electrical Characteristics ($T_A = 25^\circ\text{C}$ unless otherwise noted)

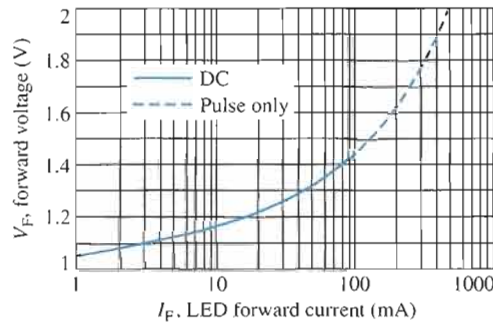
Characteristic	Symbol	Min	Typ	Max	Unit
Reverse leakage current ($V_R = 3\text{ V}$)	I_R	—	10	—	nA
Reverse leakage current ($V_R = 5\text{ V}$)	I_R	—	1	10	μA
Forward voltage ($I_F = 100\text{ mA}$)	V_F	—	1.35	1.7	V
Temperature coefficient of forward voltage	ΔV_F	—	-1.6	—	mV/K
Capacitance ($f = 1\text{ MHz}$)	C	—	25	—	pF

Optical Characteristics ($T_A = 25^\circ\text{C}$ unless otherwise noted)

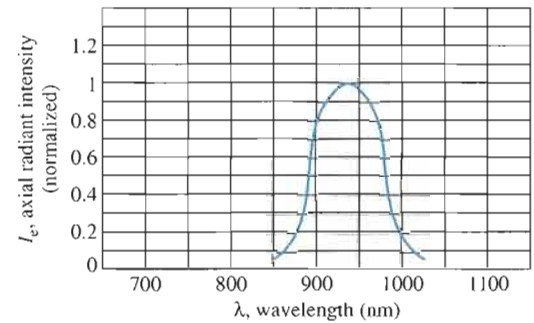
Characteristic	Symbol	Min	Typ	Max	Unit
Peak wavelength ($I_F = 100\text{ mA}$)	λ_p	—	940	—	nm
Spectral half-power bandwidth	$\Delta\lambda$	—	50	—	nm
Total power output ($I_F = 100\text{ mA}$)	ϕ_e	—	16	—	mW
Temperature coefficient of total power output	$\Delta\phi_e$	—	-0.25	—	%/K
Axial radiant intensity ($I_F = 100\text{ mA}$)	I_e	10	15	—	mW/sr
Temperature coefficient of axial radiant intensity	ΔI_e	—	-0.25	—	%/K
Power half-angle	ϕ	—	± 30	—	°



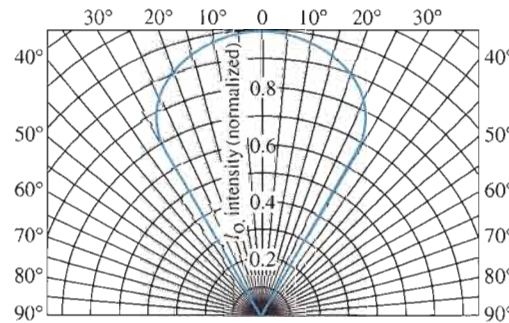
(a) Ratings and characteristics



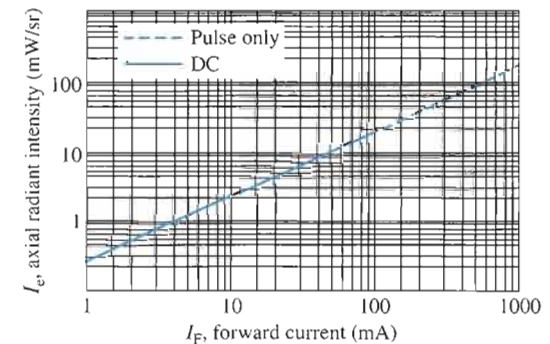
(b) LED forward voltage versus forward current



(c) Relative spectral emission



(d) Spatial radiation pattern



(e) Intensity versus forward current

▲ FIGURE 3-31

Partial data sheet for an MLED81 IR light-emitting diode.

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 3–32. 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.

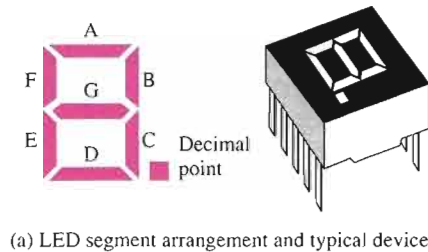
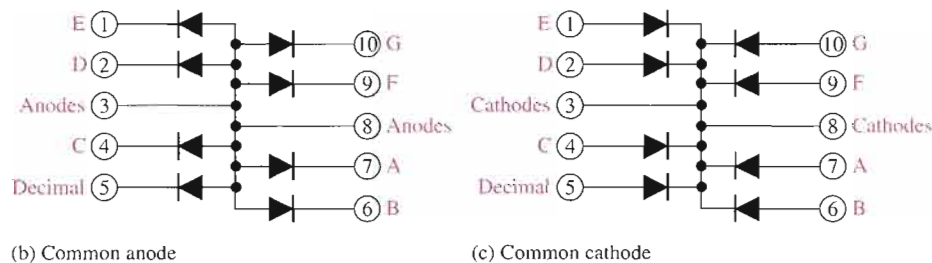


FIGURE 3–32

The 7-segment LED display.



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.

High-Intensity LEDs

LEDs come in a variety of colors, and they are available in different light intensities. High-intensity LEDs produce many times more light than do the standard LEDs and are found in a variety of applications. Many traffic signals in the United States use high-intensity LED arrays and, in the near future, all traffic lights will be LEDs. The large video screens that are seen everywhere from sports stadiums to banks and other commercial buildings are mostly constructed with high-intensity LEDs. The automotive industry plans to replace all incandescent bulbs, even headlights, with LEDs. Also, LEDs will play a significant role in home and office lighting in the future.

The Photodiode

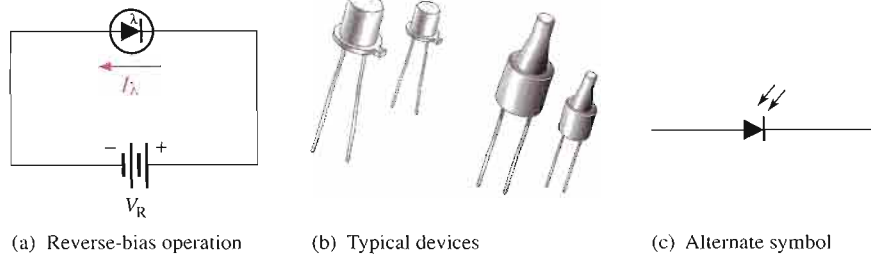
The **photodiode** is a device that operates in reverse bias, as shown in Figure 3–33(a), where I_A is the reverse current. The photodiode has a small transparent window that allows light to strike the *pn* junction. Some typical photodiodes are shown in Figure 3–33(b). An alternate photodiode symbol is shown in Figure 3–33(c).

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.



▶ FIGURE 3-33

Photodiode.

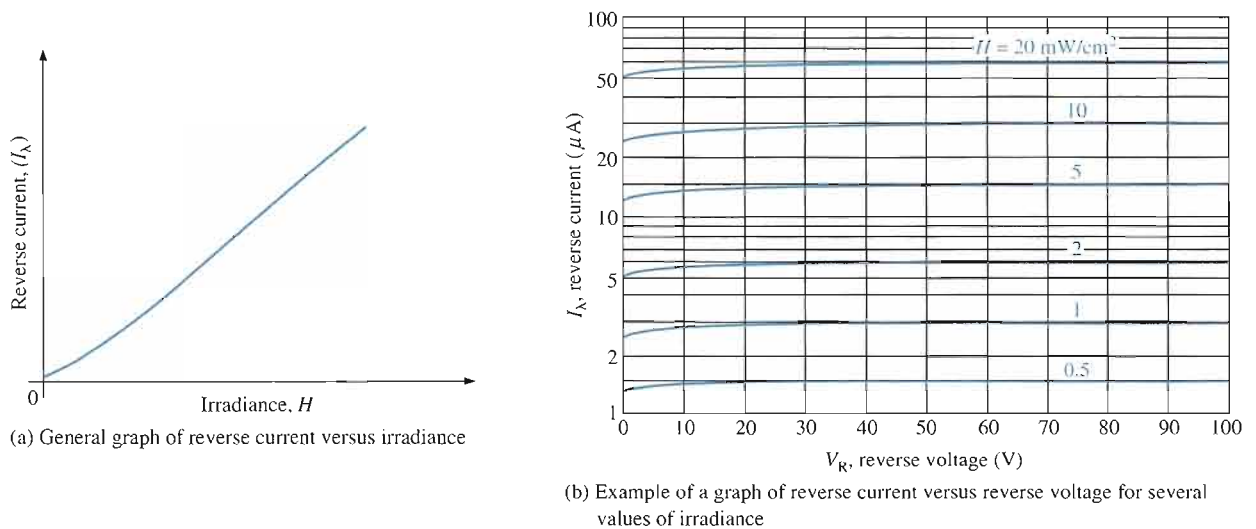


(a) Reverse-bias operation

(b) Typical devices

(c) Alternate symbol

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 3-34(a).



(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 3-34

Typical photodiode characteristics.

From the graph in Figure 3-34(b), you can see that the reverse current for this particular device is approximately $1.4 \mu\text{A}$ at a reverse-bias voltage of 10 V with an irradiance of $0.5 \text{ mW}/\text{cm}^2$. Therefore, the resistance of the device is

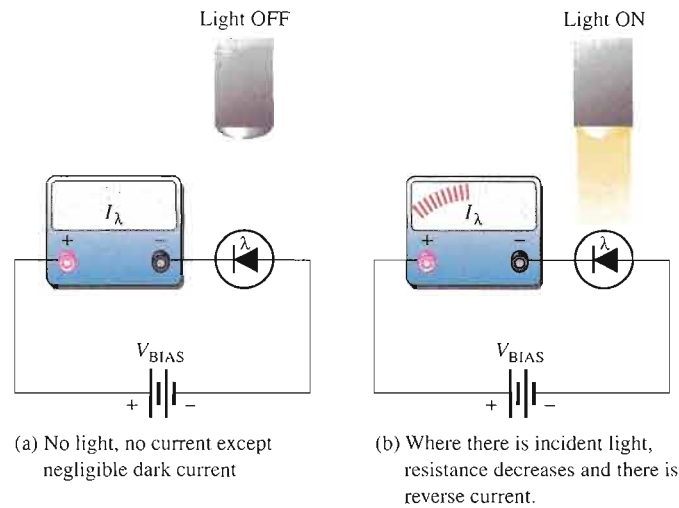
$$R_R = \frac{V_R}{I_\lambda} = \frac{10 \text{ V}}{1.4 \mu\text{A}} = 7.14 \text{ M}\Omega$$

At $20 \text{ mW}/\text{cm}^2$, the current is approximately $55 \mu\text{A}$ at $V_R = 10 \text{ V}$. 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.

Figure 3-35 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).



◀ **FIGURE 3-35**

Operation of a photodiode.

Photodiode Data Sheet Information

A partial data sheet for an MRD821 photodiode is shown in Figure 3-36. Notice that the maximum reverse voltage is 35 V and the dark current (reverse current with no light) is typically 3 nA for a reverse voltage of 10 V. As the graphs in parts (b) and (c) show, the dark current (leakage current) increases with an increase in reverse voltage and also with an increase in temperature.

Sensitivity From the graph in part (d), you can see that the maximum sensitivity for this device occurs at a wavelength of 940 nm. The angular response graph in part (e) shows a broad area of response measured as relative sensitivity. At 50° on either side of the maximum orientation, the sensitivity drops to approximately 80% of maximum.

In Figure 3-36(a), the typical sensitivity is specified as $50 \mu\text{A}/\text{mW}/\text{cm}^2$ for a wavelength of 940 nm and a reverse voltage of 20 V. This means, for example, that if the irradiance is $1 \text{ mW}/\text{cm}^2$, there are $50 \mu\text{A}$ of reverse current and if the irradiance is $0.5 \text{ mW}/\text{cm}^2$, there are $25 \mu\text{A}$ of reverse current.

EXAMPLE 3-11

An MRD821 photodiode is exposed to a 1000 nm infrared light with an irradiance (H) of $2.5 \text{ mW}/\text{cm}^2$. The angle at which the light strikes the photodiode is 35° . Determine the response of the photodiode in terms of the reverse current (I_λ) through the device.

Solution From the photodiode data sheet in Figure 3-36, the sensitivity of the photodiode is $50 \mu\text{A}/\text{mW}/\text{cm}^2$ at 940 nm. The light on the photodiode is at a wavelength of 1000 nm. From the data sheet graph in part (d), the sensitivity (S) at 1000 nm is approximately 83% of the sensitivity at 940 nm.

$$S_{1000} = 0.83S_{940} = 0.83(50 \mu\text{A}/\text{mW}/\text{cm}^2) = 41.5 \mu\text{A}/\text{mW}/\text{cm}^2$$

Also, the angle at which the light strikes the photodiode reduces the sensitivity further. From the graph in Figure 3-36(e), at an angle of 35° from the maximum orientation (0°), the relative sensitivity is approximately 90%.

$$S = 0.9(41.5 \mu\text{A}/\text{mW}/\text{cm}^2) = 37.4 \mu\text{A}/\text{mW}/\text{cm}^2$$

For an irradiance, H , of $2.5 \text{ mW}/\text{cm}^2$, the reverse current is

$$I_\lambda = S \times H = (37.4 \mu\text{A}/\text{mW}/\text{cm}^2)(2.5 \text{ mW}/\text{cm}^2) = \mathbf{93.5 \mu\text{A}}$$

Related Problem Determine the MRD821 response (reverse current) to an irradiance of 1 mW/cm² for a wavelength of 900 nm at an angle of 60° from maximum orientation.

Maximum Ratings

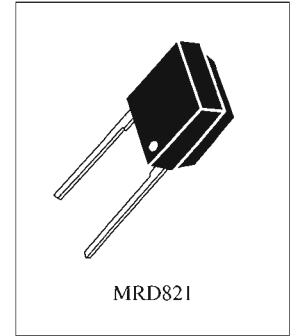
Rating	Symbol	Value	Unit
Reverse voltage	V_R	35	Volts
Forward current — continuous	I_F	100	mA
Total power dissipation @ $T_A = 25^\circ\text{C}$ Derate above 25°C	P_D	150 3.3	mW mW/°C
Ambient operating temperature range	T_A	-30 to +70	°C
Storage temperature	T_{stg}	-40 to +80	°C
Lead soldering temperature, 5 seconds max, 1/16 inch from case	—	260	°C

Electrical Characteristics ($T_A = 25^\circ\text{C}$ unless otherwise noted)

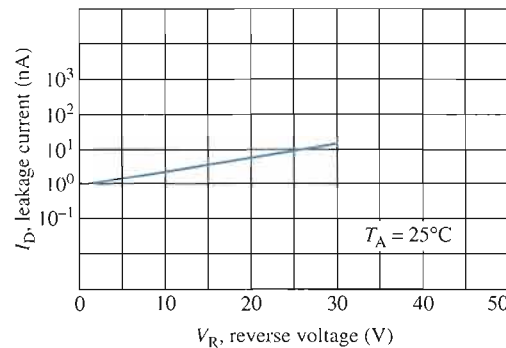
Characteristic	Symbol	Min	Typ	Max	Unit
Dark current ($V_R = 10\text{ V}$)	I_D	—	3	30	nA
Capacitance ($f = 1\text{ MHz}$, $V = 0$)	C_J	—	175	—	pF

Optical Characteristics ($T_A = 25^\circ\text{C}$ unless otherwise noted)

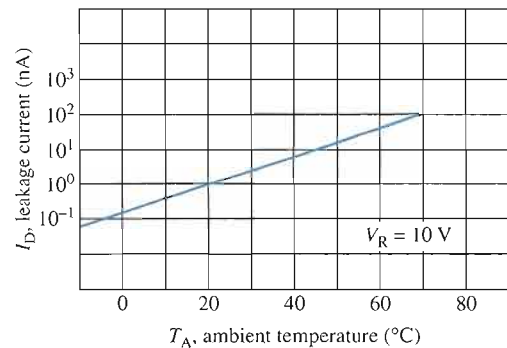
Characteristic	Symbol	Min	Typ	Max	Unit
Wavelength of maximum sensitivity	λ_{max}	—	940	—	nm
Spectral range	$\Delta\lambda$	—	170	—	nm
Sensitivity ($\lambda = 940\text{ nm}$, $V_R = 20\text{ V}$)	S	—	50	—	$\mu\text{A/mW/cm}^2$
Temperature coefficient of sensitivity	ΔS	—	0.18	—	%/K
Acceptance half-angle	ϕ	—	± 70	—	°
Short circuit current ($E_v = 1000\text{ lux}$)	I_S	—	50	—	μA
Open circuit voltage ($E_v = 1000\text{ lux}$)	V_L	—	0.3	—	V



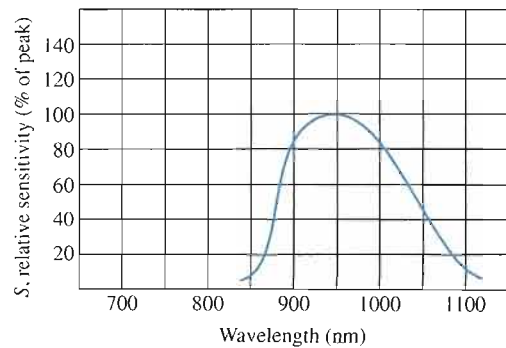
(a) Ratings and characteristics



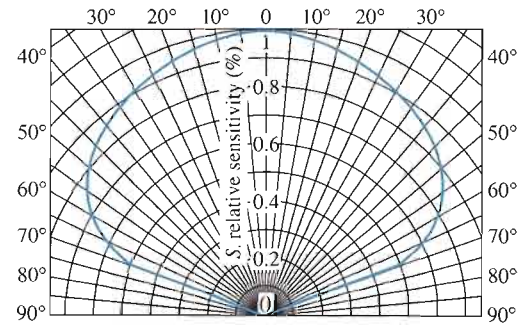
(b) Dark current versus reverse voltage



(c) Dark current versus temperature



(d) Relative spectral sensitivity



(e) Angular response

▲ **FIGURE 3-36**

Partial data sheet for the MRD821 photodiode.

SECTION 3-4 REVIEW

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. In what bias condition is a photodiode normally operated?
7. When the intensity of the incident light (irradiance) on a photodiode increases, what happens to its internal reverse resistance?
8. 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 current regulator diode, the Schottky diode, the *pin* diode, the step-recovery diode, the tunnel diode, and the laser diode.

After completing this section, you should be able to

- Discuss the basic characteristics of current regulator, Schottky, *pin*, step-recovery, tunnel, and laser diodes
- Identify the various diode symbols
- Discuss how the current regulator diode maintains a constant forward current
- Describe the characteristics of the Schottky diode
- Describe the characteristics of the *pin* diode
- Describe the characteristics of the step-recovery diode
- Describe the characteristics of the tunnel diode and explain its negative resistance
- Describe the laser diode and how it differs from an LED

Current Regulator Diode

The current regulator diode is often referred to as a constant-current diode. Rather than maintaining a constant voltage, as the zener diode does, this diode maintains a constant current. The symbol is shown in Figure 3-37.



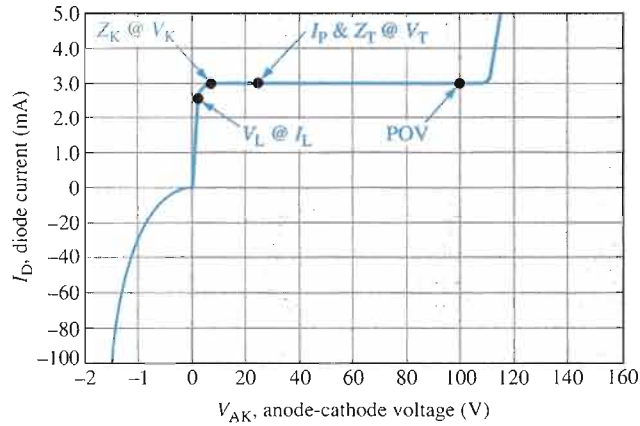
◀ **FIGURE 3-37**
Symbol for a current regulator diode.

Figure 3-38 shows a typical characteristic curve. The current regulator diode operates in forward bias (shaded region), and the forward current becomes a specified constant value at forward voltages ranging from about 1.5 V to about 6 V, depending on the diode type. The constant forward current is called the *regulator current* and is designated I_p . For

example, the 1N5283–1N5314 series of diodes have nominal regulator currents ranging from 220 μA to 4.7 mA. These diodes may be used in parallel to obtain higher currents. This diode does not have a sharply defined reverse breakdown, so the reverse current begins to increase for V_{AK} values of less than 0 V (unshaded region of the figure). This device should never be operated in reverse bias.

► **FIGURE 3-38**

Typical characteristic curve for a current regulator diode.



In forward bias, the diode regulation begins at the limiting voltage, V_L , and extends to the POV (peak operating voltage). Notice that between V_K and POV, the current is essentially constant. V_T is the test voltage at which I_p and the diode impedance, Z_T , are specified on a data sheet. The impedance Z_T has very high values ranging from 235 $\text{k}\Omega$ to 25 $\text{M}\Omega$ for the diode series mentioned before.



► **FIGURE 3-39**

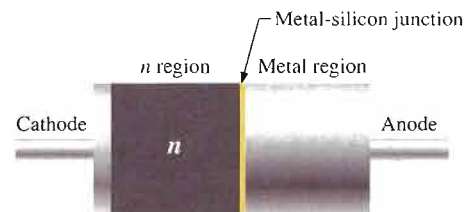
Schottky diode symbol.

The Schottky Diode

Schottky diodes are used primarily in high-frequency and fast-switching applications. They are also known as *hot-carrier diodes*. A Schottky diode symbol is shown in Figure 3-39. A Schottky diode is formed by joining a doped semiconductor region (usually n -type) with a metal such as gold, silver, or platinum. Rather than a pn junction, there is a metal-to-semiconductor junction, as shown in Figure 3-40. The forward voltage drop is typically around 0.3 V.

► **FIGURE 3-40**

Basic internal construction of a Schottky diode.

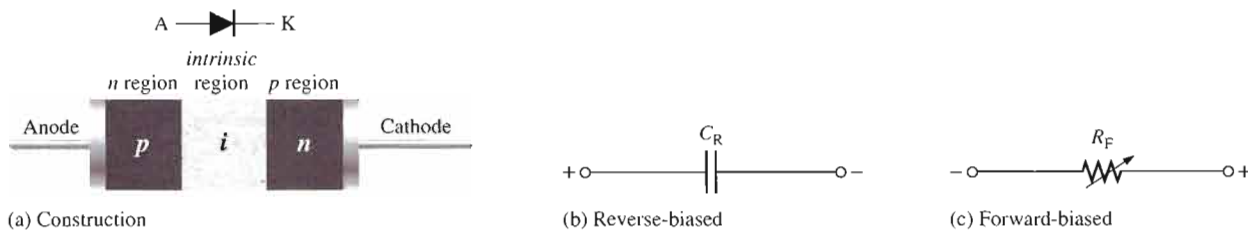


The Schottky diode operates only with majority carriers. There are no minority carriers and thus no reverse leakage current as in other types of diodes. The metal region is heavily occupied with conduction-band electrons, and the n -type semiconductor region is lightly doped. When forward-biased, the higher energy electrons in the n region are injected into the metal region where they give up their excess energy very rapidly. Since there are no minority carriers, as in a conventional rectifier diode, there is a very rapid response to a change in bias. The Schottky is a fast-switching diode, and most of its applications make use of this property. It can be used in high-frequency applications and in many digital circuits to decrease switching times.

The PIN Diode

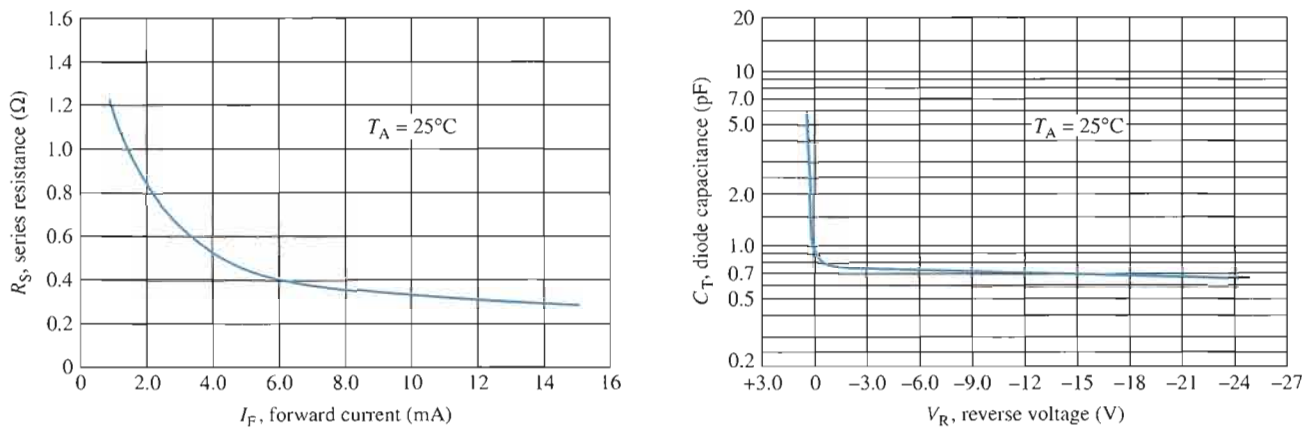
The *pin* diode consists of heavily doped *p* and *n* regions separated by an intrinsic (*i*) region, as shown in Figure 3–41(a). When reverse-biased, the *pin* diode acts like a nearly constant capacitance. When forward-biased, it acts like a current-controlled variable resistance. This is shown in Figure 3–41(b) and (c). The low forward resistance of the intrinsic region decreases with increasing current.

The forward series resistance characteristic and the reverse capacitance characteristic are shown graphically in Figure 3–42 for a typical *pin* diode.



▲ FIGURE 3–41

PIN diode.



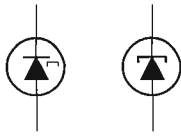
▲ FIGURE 3–42

PIN diode characteristics.

The *pin* diode is used as a dc-controlled microwave switch operated by rapid changes in bias or as a modulating device that takes advantage of the variable forward-resistance characteristic. Since no rectification occurs at the *pn* junction, a high-frequency signal can be modulated (varied) by a lower-frequency bias variation. A *pin* diode can also be used in attenuator applications because its resistance can be controlled by the amount of current. Certain types of *pin* diodes are used as photodetectors in fiber-optic systems.

The Step-Recovery Diode

The step-recovery diode uses graded doping where the doping level of the semiconductive materials is reduced as the *pn* junction is approached. This produces an abrupt turn-off time by allowing a fast release of stored charge when switching from forward to reverse bias. It also allows a rapid re-establishment of forward current when switching from reverse to forward bias. This diode is used in very high frequency (VHF) and fast-switching applications.

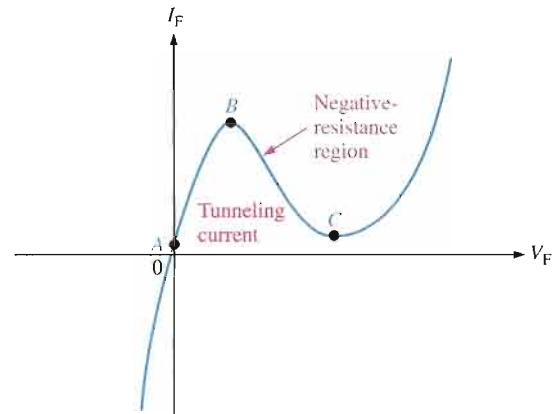


▲ FIGURE 3-43 Tunnel diode symbols.

The Tunnel Diode

The tunnel diode exhibits a special characteristic known as *negative resistance*. This feature makes it useful in oscillator and microwave amplifier applications. Two alternate symbols are shown in Figure 3-43. Tunnel diodes are constructed with germanium or gallium arsenide by doping the *p* and *n* regions much more heavily than in a conventional rectifier diode. This heavy doping results in an extremely narrow depletion region. The heavy doping allows conduction for all reverse voltages so that there is no breakdown effect as with the conventional rectifier diode. This is shown in Figure 3-44.

► FIGURE 3-44 Tunnel diode characteristic curve.

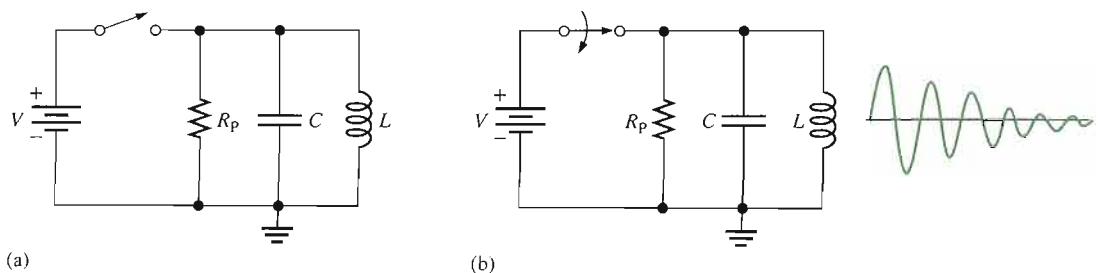


Also, the extremely narrow depletion region permits electrons to “tunnel” through the *pn* junction at very low forward-bias voltages, and the diode acts as a conductor. This is shown in Figure 3-44 between points A and B. At point B, the forward voltage begins to develop a barrier, and the current begins to decrease as the forward voltage continues to increase. This is the *negative-resistance region*.

$$R_F = \frac{\Delta V_F}{\Delta I_F}$$

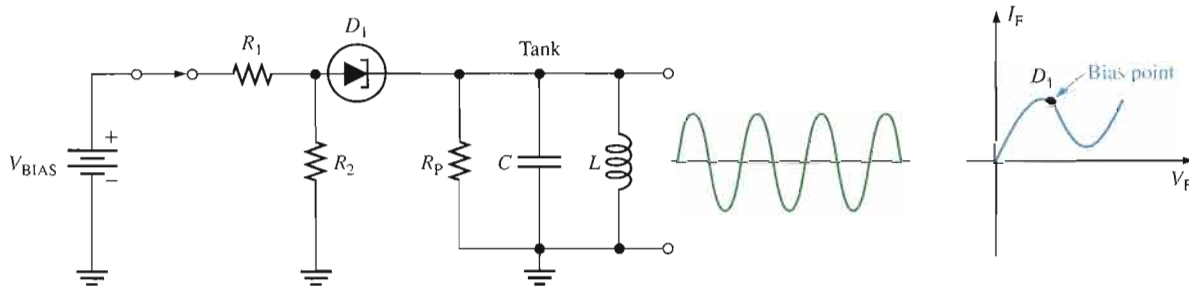
This effect is opposite to that described in Ohm’s law, where an increase in voltage results in an increase in current. At point C, the diode begins to act as a conventional forward-biased diode.

An Application A parallel resonant circuit can be represented by a capacitance, inductance, and resistance in parallel, as in Figure 3-45(a). R_p is the parallel equivalent of the series winding resistance of the coil. When the tank circuit is “shocked” into oscillation by an application of voltage as in Figure 3-45(b), a damped sinusoidal output results. The damping is due to the resistance of the tank, which prevents a sustained oscillation because energy is lost when there is current through the resistance.



▲ FIGURE 3-45 Parallel resonant circuit.

If a tunnel diode is placed in series with the tank circuit and biased at the center of the negative-resistance portion of its characteristic curve, as shown in Figure 3–46, a sustained oscillation (constant sinusoidal voltage) will result on the output. This is because the negative-resistance characteristic of the tunnel diode counteracts the positive-resistance characteristic of the tank resistance.

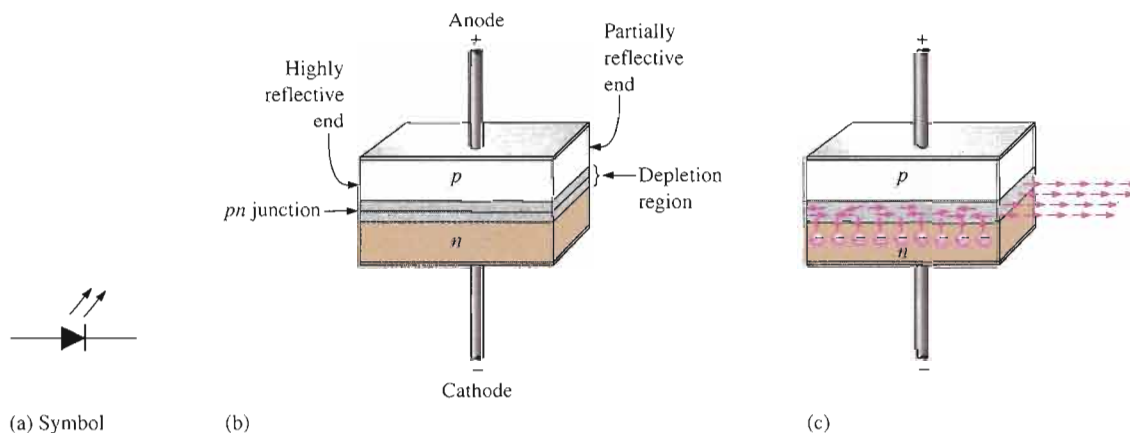


▲ FIGURE 3–46

Basic tunnel diode oscillator.

The Laser Diode

The term **laser** stands for *light amplification by stimulated emission of radiation*. Laser light is **monochromatic**, which means that it consists of a single color and not a mixture of colors. Laser light is also called **coherent light**, a single wavelength, as compared to incoherent light, which consists of a wide band of wavelengths. The laser diode normally emits coherent light, whereas the LED emits incoherent light. The symbols are the same as shown in Figure 3–47(a).



▲ FIGURE 3–47

Basic laser diode construction and operation.

The basic construction of a laser diode is shown in Figure 3–47(b). A *pn* junction is formed by two layers of doped gallium arsenide. The length of the *pn* junction bears a precise relationship with the wavelength of the light to be emitted. There is a highly reflective surface at one end of the *pn* junction and a partially reflective surface at the other end produced by “polishing” the ends. External leads provide the anode and cathode connections.

The basic operation is as follows. The laser diode is forward-biased by an external voltage source. As electrons move through the junction, recombination occurs just as in an ordinary diode. As electrons fall into holes to recombine, photons are released. A released

photon can strike an atom, causing another photon to be released. As the forward current is increased, more electrons enter the depletion region and cause more photons to be emitted. Eventually some of the photons that are randomly drifting within the depletion region strike the reflected surfaces perpendicularly. These reflected photons move along the depletion region, striking atoms and releasing additional photons due to the avalanche effect. This back-and-forth movement of photons increases as the generation of photons “snowballs” until a very intense beam of laser light is formed by the photons that pass through the partially reflective end of the *pn* junction.

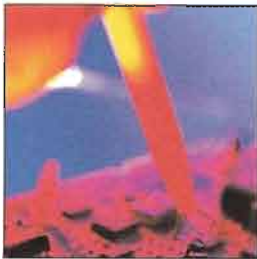
Each photon produced in this process is identical to the other photons in energy level, phase relationship, and frequency. So a single wavelength of intense light emerges from the laser diode, as indicated in Figure 3–47(c). Laser diodes have a threshold level of current above which the laser action occurs and below which the diode behaves essentially as an LED, emitting incoherent light.

An Application Laser diodes and photodiodes are used in the pick-up system of compact disk (CD) players. Audio information (sound) is digitally recorded in stereo on the surface of a compact disk in the form of microscopic “pits” and “flats.” A lens arrangement focuses the laser beam from the diode onto the CD surface. As the CD rotates, the lens and beam follow the track under control of a servomotor. The laser light, which is altered by the pits and flats along the recorded track, is reflected back from the track through a lens and optical system to infrared photodiodes. The signal from the photodiodes is then used to reproduce the digitally recorded sound.

SECTION 3–5 REVIEW

1. Between what two voltages does a current regulator diode operate?
2. What are the primary application areas for Schottky diodes?
3. What is a hot-carrier diode?
4. What is the key characteristic of a tunnel diode?
5. What is one application for a tunnel diode?
6. Name the three regions of a *pin* diode.
7. What does *laser* mean?
8. What is the difference between incoherent and coherent light and which is produced by a laser diode?

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 is required. Like other diodes, the zener can fail open, it can exhibit degraded performance in which its internal resistance increases significantly, 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 excessive impedance

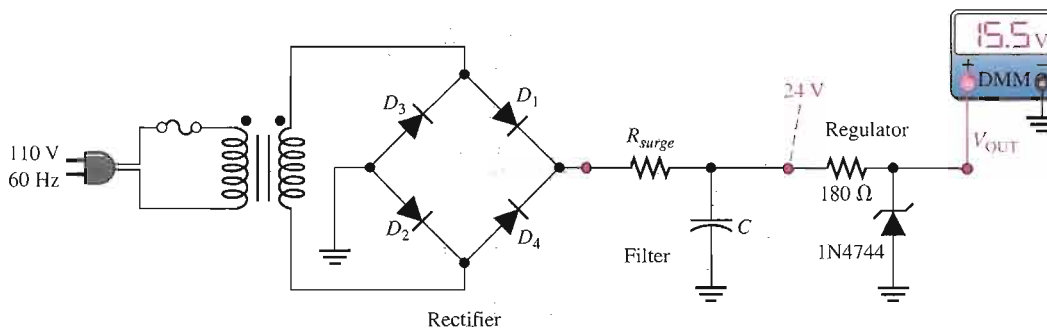
A Zener-Regulated DC Power Supply

Figure 3–48 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 1N4744 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 voltage expected at maximum zener current (I_{ZM}) for this particular diode is 15.7 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 14.76 V.

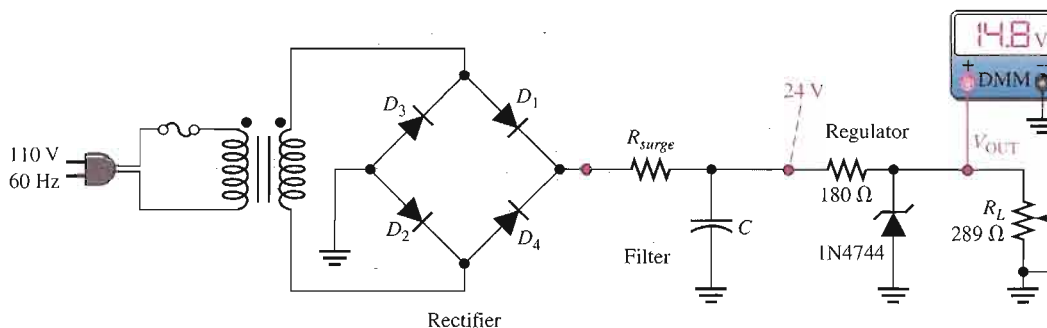
$$I_T = \frac{24 \text{ V} - 14.76 \text{ V}}{180 \Omega} = 51.3 \text{ mA}$$

$$I_L = 51.3 \text{ mA} - 0.25 \text{ mA} = 51.1 \text{ mA}$$

$$R_{L(\min)} = \frac{14.76 \text{ V}}{51.1 \text{ mA}} = 289 \Omega$$



(a) Correct output voltage with no load



(b) Correct output voltage with full load

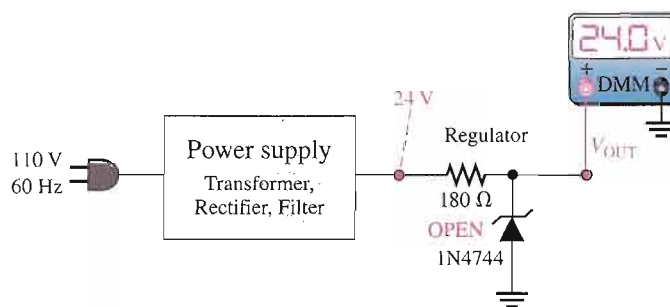
▲ FIGURE 3–48

Zener-regulated power supply test.

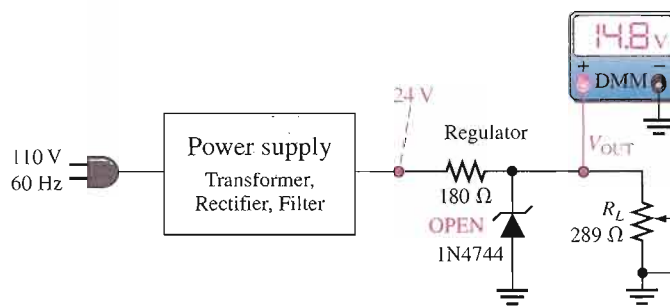
Case 1: Zener Diode Open If the zener diode fails open, the power supply test gives the approximate results indicated in Figure 3–49. In the no-load check shown in part (a), the output voltage is 24 V because there is no voltage dropped between the filtered output of the power supply and the output terminal. 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 289 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.

► FIGURE 3-49

Indications of an open zener.



(a) Open zener diode with no load

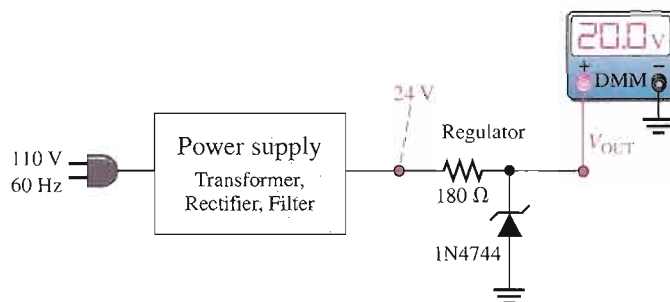


(b) Open zener diode cannot be detected by full-load measurement in this case.

Case 2: Excessive Zener Impedance As indicated in Figure 3-50, 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 is caused by the drop across the excessive internal impedance of the zener.

► FIGURE 3-50

Indication of excessive zener impedance.



Multisim Troubleshooting Exercises

These file circuits are in the Troubleshooting Exercises folder on your CD-ROM.

1. Open file TSE03-01. Determine if the circuit is working properly and, if not, determine the fault.
2. Open file TSE03-02. Determine if the circuit is working properly and, if not, determine the fault.
3. Open file TSE03-03. Determine if the circuit is working properly and, if not, determine the fault.
4. Open file TSE03-04. Determine if the circuit is working properly and, if not, determine the fault.

SECTION 3-6 REVIEW

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?



SYSTEM APPLICATION

You have been assigned to modify the power supply circuit board from the system application of Chapter 2. You are to incorporate voltage regulation and light emission and detection circuits to be used in a new system your company is

developing. This system will be used in a sporting goods manufacturing plant for counting and controlling the number of baseballs going into various sizes of boxes for shipment. You will apply the knowledge you have gained in this chapter to complete your assignment.

The Counting and Control System

This particular system is used to count baseballs as they are fed down a chute into a box for shipping. It can also be applied to inventory and shipping control for many other types of products. The portion of the system for which you are responsible consists of the regulated power supply, an infrared emitter circuit, and an infrared detector circuit that are all on the same board.

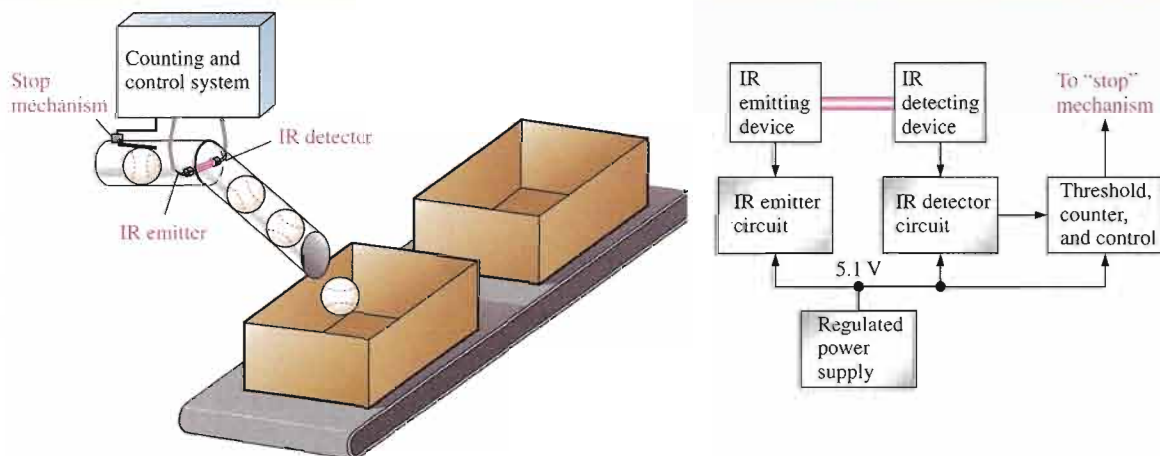
The complete system also includes a threshold circuit that senses the output of

the infrared detector and provides a pulse output to a digital counter. The output of the counter goes to a display and a control mechanism for stopping the baseballs when a box is full. The system concept and block diagram are shown in Figure 3-51.

The Power Supply Circuit

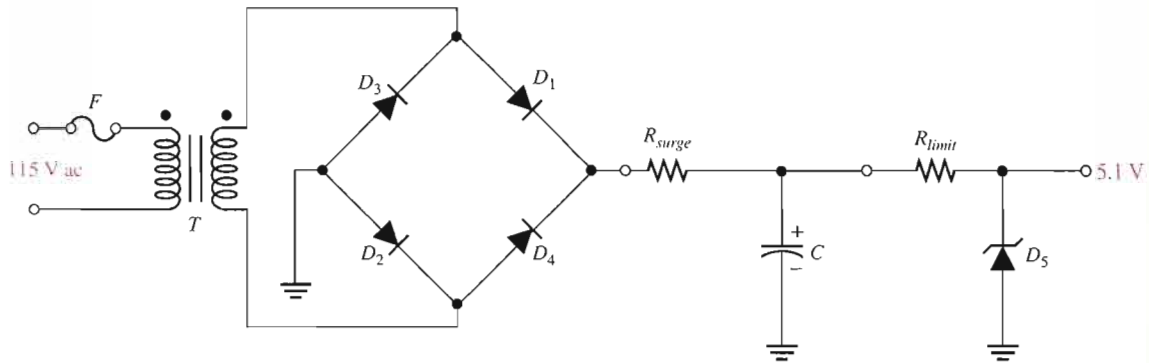
The dc power supply circuit is the same as the one developed in the system application of Chapter 2 except that it is modified by the addition of a zener voltage regulator as shown in the schematic of Figure 3-52. Also, the new circuit board will include the IR emitter and IR detector circuits. The basic power supply specifications are

1. Input voltage: 115 V rms at 60 Hz



▲ FIGURE 3-51

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



▲ FIGURE 3-52
Zener regulated power supply preliminary schematic.

2. Unregulated output voltage:
12 V dc $\pm 10\%$
3. Regulated output voltage:
5.1 V $\pm 10\%$
4. Maximum ripple factor: 3%
5. Maximum load current: 100 mA

The Power Supply Components

- *The unregulated portion of the power supply* This portion of the circuit is the same as the one developed in Chapter 2.
- *The regulator* Select a zener diode to be used as the regulator. Refer to the data sheet in Figure 3-7(a).

- *The limiting resistor* Determine a value of limiting resistor to be used in the regulator.
- *The fuse* Determine a rating for the fuse to be used in the power supply.

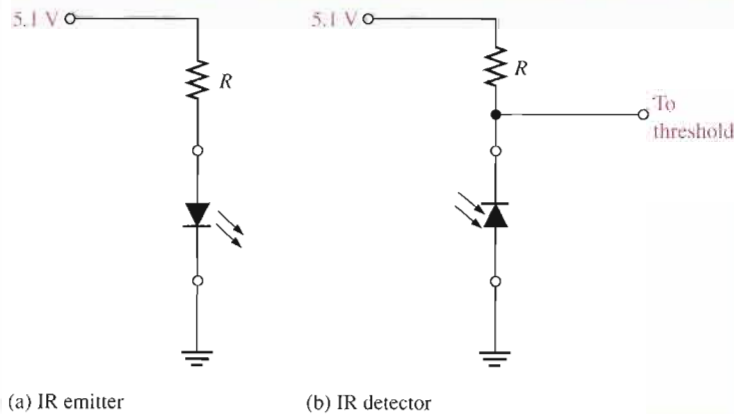
The IR Emitter and IR Detector Circuits

The MLED81 light-emitting diode is used as the IR emitter, and the MRD821 photodiode is used as the IR detector. These devices are located on either side of the tube through which the baseballs are routed. The diameter of the tube is 1.5 cm greater than the diameter of a baseball. The LED emits a constant beam of infrared light directly toward the photodiode; this

beam of light is interrupted as a baseball passes in the tube.

The IR detector senses the interruption in the LED emission and produces a minimum positive-going output transition of 3 V for the threshold circuit that generates a pulse to advance the digital counter. The counter is advanced by one count for each baseball that passes the IR beam. When a preset number of baseballs has been packed into a box, the control circuit produces a signal to activate the stop mechanism. The system is reset for the next box.

Both the LED and photodiode are connected to their series-limiting resistors and the voltage source on the circuit board with a four-wire cable. Figure 3-53



▲ FIGURE 3-53
Basic schematics of the IR emitter and IR detector circuits.

shows the basic IR emitter and IR detector circuits.

The IR Emitter and IR Detector Components

- **The distance between emitter and detector** Determine the distance from the LED to the photodiode (diameter of the tube) based on the diameter of a baseball (7.3 cm) plus a clearance of 1.5 cm.
- **The IR emitter series-limiting resistor** Determine a value for the current-limiting series resistor to achieve the maximum possible irradiance (H) at the detector. Assume the emitter and detector are aligned for maximum angular response. Refer to the data sheet in Figure 3–31.
- **The IR detector resistor** Determine a value of resistor in the IR detector to produce minimum voltage transitions of 3 V on the threshold output when the photodiode turns on and off. Refer to the data sheet in Figure 3–36.

The Schematic

Produce a complete schematic that includes the regulated power supply, the IR emitter, and the IR detector.

The Printed Circuit Board

- Check out the printed circuit board in Figure 3–54 to verify that it is correct according to the schematic.
- Label a copy of the board with the component and input/output designations in agreement with the schematic.

A Test Procedure

- Develop a step-by-step set of instructions on how to completely check the power supply and IR emitter/detector for proper operation using the test points (circled numbers) indicated in the test bench setup of Figure 3–55. There is a test fixture that simulates the operation of the LED and photodiode by momentarily inserting a

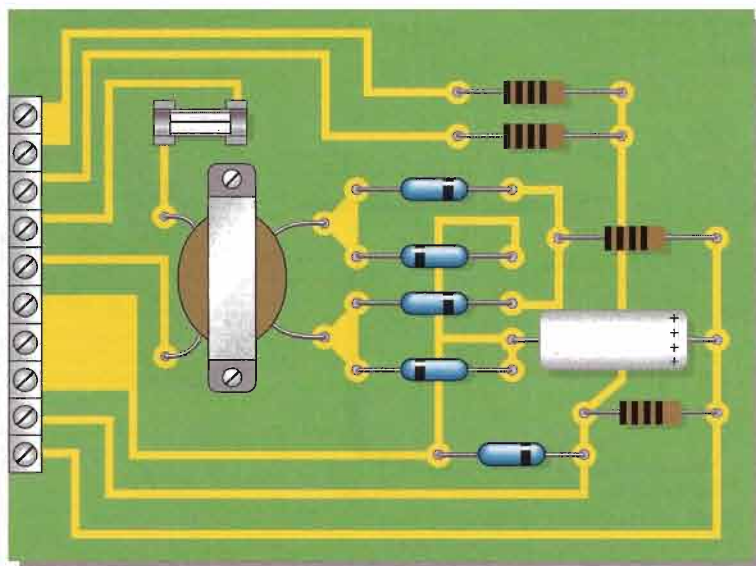
blocking plate for the IR beam in a tube-type mounting device. The IR beam is shown as a red beam for illustration.

- Specify voltage values and appropriate waveforms for all the measurements to be made.
- Provide a fault analysis for all possible component failures.
- Expand the test procedure you developed for the unregulated portion of the power supply circuit in Chapter 2 to include the additional circuits.

Troubleshooting

Several prototype boards have been assembled and are ready for testing. The test bench setup is shown in Figure 3–55. Based on the sequence of measurements for each board indicated in Figure 3–56, determine the most likely fault in each case.

The circled numbers indicate test point connections to the circuit board. The DMM function setting is indicated below



▲ FIGURE 3–54

Power supply and IR emitter/detector printed circuit board. All black resistor bands indicate values to be determined.

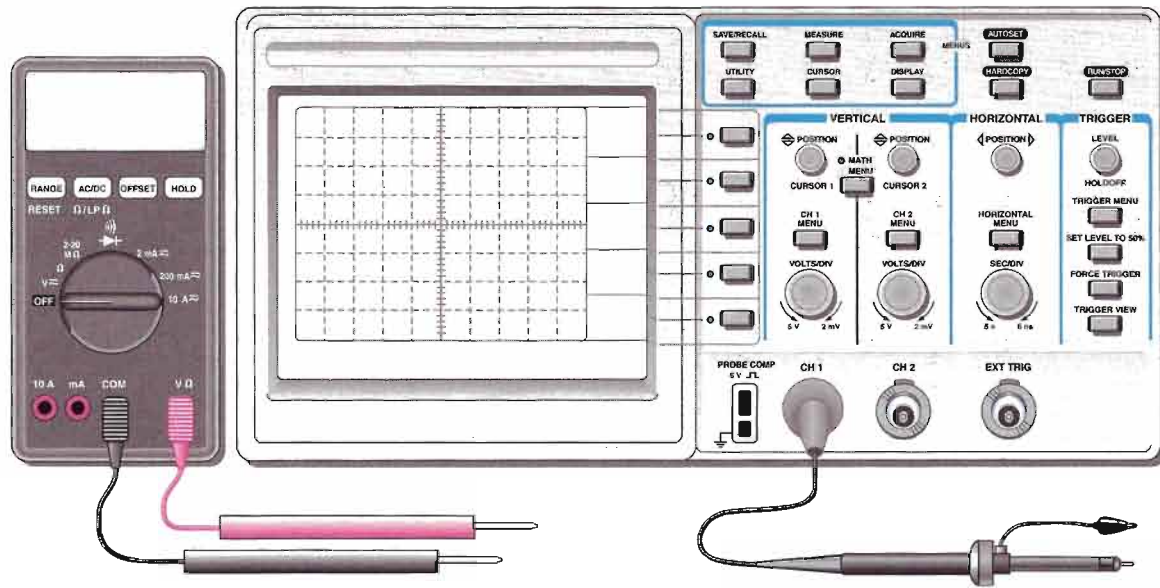
the display and the volt/div and sec/div settings for the oscilloscope are shown on the screen in each case.

Final Report (Optional)

Submit a final written report on the power supply and IR emitter/detector circuit

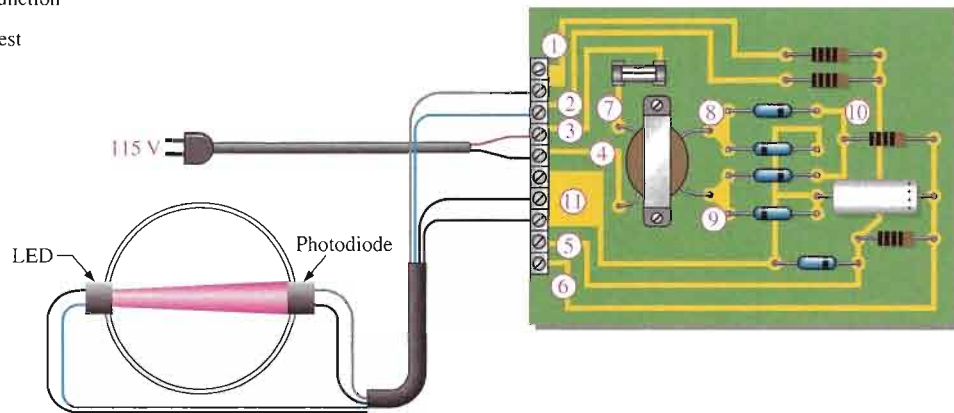
board using an organized format that includes the following:

1. A physical description of the circuits.
2. A discussion of the operation of each circuit.
3. A list of the specifications.
4. A list of parts with part numbers if available.
5. A list of the types of problems on the three circuit boards.
6. A complete description of how you determined the problem on each of the three circuit boards.



V \approx indicates dc/ac function

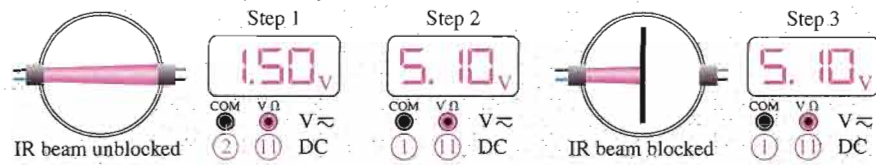
➔ indicates diode test



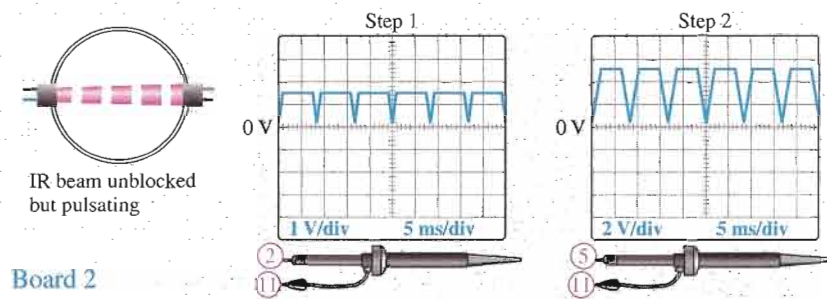
Tube fixture for testing IR emitter and detector. Beam (red) is shown unblocked.

▲ FIGURE 3-55

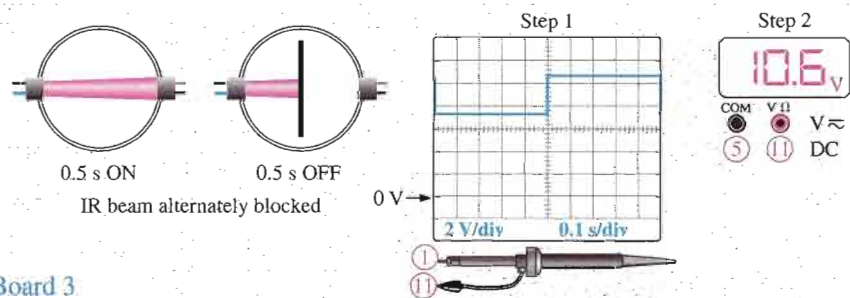
Power supply and IR emitter/detector test bench.



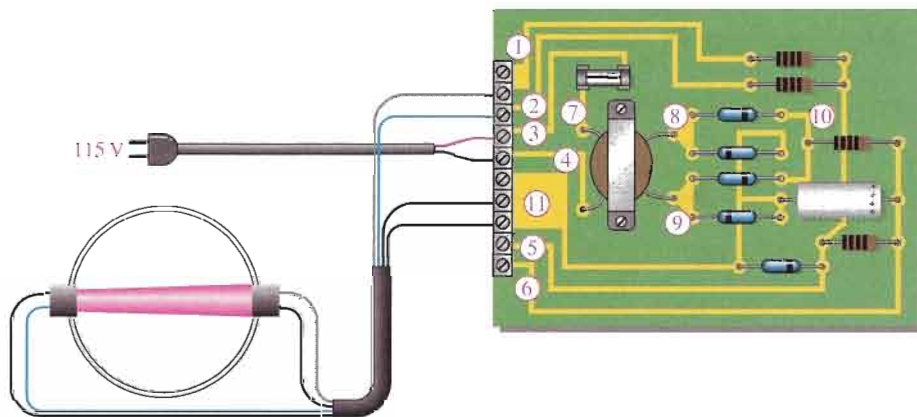
Board 1



Board 2



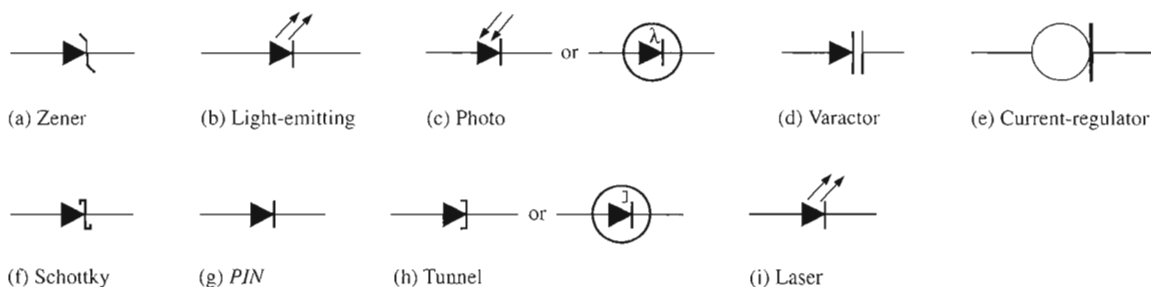
Board 3



▲ FIGURE 3-56 Test results of three prototype circuit boards.

CHAPTER SUMMARY

- The zener diode operates in reverse breakdown.
- There are two breakdown mechanisms in a zener diode: avalanche breakdown and zener breakdown.
- When $V_Z < 5$ V, zener breakdown is predominant.
- When $V_Z > 5$ V, avalanche breakdown is predominant.
- A zener diode maintains a nearly constant voltage across its terminals over a specified range of zener currents.
- Zener diodes are used as voltage regulators and limiters.
- Zener diodes are available in many voltage ratings ranging from 1.8 V to 200 V.
- A varactor diode acts as a variable capacitor under reverse-bias conditions.
- The capacitance of a varactor varies inversely with reverse-bias voltage.
- The current regulator diode keeps its forward current at a constant specified value.
- The Schottky diode has a metal-to-semiconductor junction. It is used in fast-switching applications.
- The tunnel diode is used in oscillator circuits.
- An LED emits light when forward-biased.
- LEDs are available for either infrared or visible light.
- The photodiode exhibits an increase in reverse current with light intensity.
- The *pin* diode has a *p* region, an *n* region, and an intrinsic (*i*) region and displays a variable resistance characteristic when forward-biased and a constant capacitance when reverse-biased.
- A laser diode is similar to an LED except that it emits coherent (single wavelength) light when the forward current exceeds a threshold value.
- A summary of special-purpose diode symbols is given in Figure 3–57.



▲ FIGURE 3–57

Diode symbols.

KEY TERMS

Key terms and other bold terms in the chapter are defined in the end-of-book glossary.

Electroluminescence The process of releasing light energy by the recombination of electrons in a semiconductor.

Laser Light amplification by stimulated emission of radiation.

Light-emitting diode (LED) A type of diode that emits light when there is forward current.

Photodiode A diode in which the reverse current varies directly with the amount of light.

Varactor A variable capacitance diode.

Zener breakdown The lower voltage breakdown in a zener diode.

Zener diode A diode designed for limiting the voltage across its terminals in reverse bias.

KEY FORMULAS

3-1	$Z_Z = \frac{\Delta V_Z}{\Delta I_Z}$	Zener impedance
3-2	$\Delta V_Z = V_Z \times TC \times \Delta T$	V_Z temperature change when TC is $\%/^{\circ}\text{C}$
3-3	$\Delta V_Z = TC \times \Delta T$	V_Z temperature change when TC is $\text{mV}/^{\circ}\text{C}$
3-4	$P_{D(\text{derated})} = P_{D(\text{max})} - (\text{mW}/^{\circ}\text{C})\Delta T$	Derated power dissipation
3-5	$I_{ZM} = \frac{P_{D(\text{max})}}{V_Z}$	Maximum zener current
3-6	$H = \frac{I_c}{d^2}$	Irradiance

CIRCUIT-ACTION QUIZ

Answers are at the end of the chapter.

- If the input voltage in Figure 3-10 is increased from 5 V to 10 V, ideally the output voltage will
(a) increase (b) decrease (c) not change
- If the input voltage in Figure 3-13 is reduced by 2 V, the zener current will
(a) increase (b) decrease (c) not change
- If R_L in Figure 3-13 is removed, the current through the zener diode will
(a) increase (b) decrease (c) not change
- If the zener opens in Figure 3-13, the output voltage will
(a) increase (b) decrease (c) not change
- If R in Figure 3-13 is increased, the current to the load resistor will
(a) increase (b) decrease (c) not change
- If the input voltage amplitude in Figure 3-16(a) is increased, the positive output voltage will
(a) increase (b) decrease (c) not change
- If the input voltage amplitude in Figure 3-17(a) is reduced, the amplitude of the output voltage will
(a) increase (b) decrease (c) not change
- If the varactor capacitance is increased in Figure 3-24, the resonant frequency will
(a) increase (b) decrease (c) not change
- If the reverse voltage across the varactor in Figure 3-24 is increased, the frequency will
(a) increase (b) decrease (c) not change
- If the bias voltage in Figure 3-27 is increased, the light output of the LED will
(a) increase (b) decrease (c) not change
- If the bias voltage in Figure 3-27 is reversed, the light output of the LED will
(a) increase (b) decrease (c) not change

SELF-TEST

Answers are at the end of the chapter.

1. The cathode of a zener diode in a voltage regulator is normally
 - (a) more positive than the anode
 - (b) more negative than the anode
 - (c) at +0.7 V
 - (d) grounded
2. If a certain zener diode has a zener voltage of 3.6 V, it operates in
 - (a) regulated breakdown
 - (b) zener breakdown
 - (c) forward conduction
 - (d) avalanche breakdown
3. For a certain 12 V zener diode, a 10 mA change in zener current produces a 0.1 V change in zener voltage. The zener impedance for this current range is
 - (a) 1 Ω
 - (b) 100 Ω
 - (c) 10 Ω
 - (d) 0.1 Ω
4. The data sheet for a particular zener gives $V_Z = 10$ V at $I_{ZT} = 500$ mA. Z_Z for these conditions is
 - (a) 50 Ω
 - (b) 20 Ω
 - (c) 10 Ω
 - (d) unknown
5. A no-load condition means that
 - (a) the load has infinite resistance
 - (b) the load has zero resistance
 - (c) the output terminals are open
 - (d) answers (a) and (c)
6. A varactor diode exhibits
 - (a) a variable capacitance that depends on reverse voltage
 - (b) a variable resistance that depends on reverse voltage
 - (c) a variable capacitance that depends on forward current
 - (d) a constant capacitance over a range of reverse voltages
7. An LED
 - (a) emits light when reverse-biased
 - (b) senses light when reverse-biased
 - (c) emits light when forward-biased
 - (d) acts as a variable resistance
8. Compared to a visible red LED, an infrared LED
 - (a) produces light with shorter wavelengths
 - (b) produces light of all wavelengths
 - (c) produces only one color of light
 - (d) produces light with longer wavelengths
9. The internal resistance of a photodiode
 - (a) increases with light intensity when reverse-biased
 - (b) decreases with light intensity when reverse-biased
 - (c) increases with light intensity when forward-biased
 - (d) decreases with light intensity when forward-biased
10. A diode that has a negative resistance characteristic is the
 - (a) Schottky diode
 - (b) tunnel diode
 - (c) laser diode
 - (d) hot-carrier diode
11. An infrared LED is optically coupled to a photodiode. When the LED is turned off, the reading on an ammeter in series with the reverse-biased photodiode will
 - (a) not change
 - (b) decrease
 - (c) increase
 - (d) fluctuate
12. In order for a system to function properly, the various types of circuits that make up the system must be
 - (a) properly biased
 - (b) properly connected
 - (c) properly interfaced
 - (d) all of the above
 - (e) answers (a) and (b)

PROBLEMS

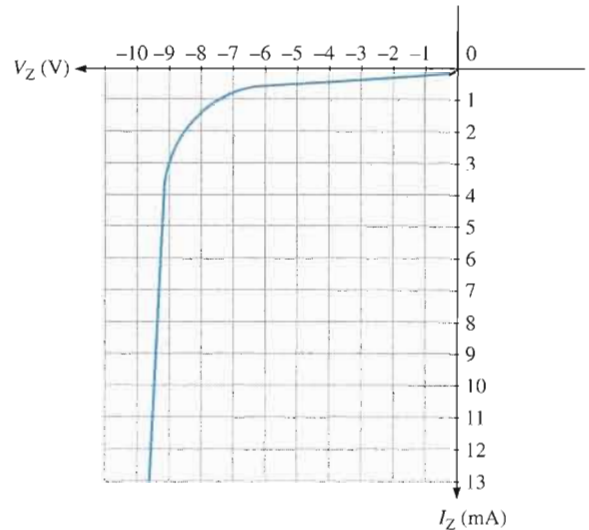
Answers to all odd-numbered problems are at the end of the book.

BASIC PROBLEMS

SECTION 3-1 Zener Diodes

1. A certain zener diode has a $V_Z = 7.5\text{ V}$ and an $Z_Z = 5\ \Omega$ at a certain current. Draw the equivalent circuit.
2. From the characteristic curve in Figure 3-58, what is the approximate minimum zener current (I_{ZK}) and the approximate zener voltage at I_{ZK} ?

► FIGURE 3-58

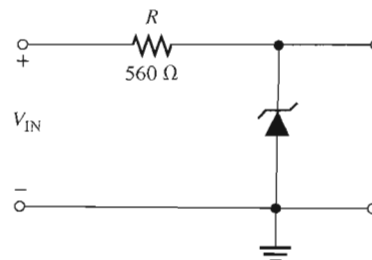


3. When the reverse current in a particular zener diode increases from 20 mA to 30 mA, the zener voltage changes from 5.6 V to 5.65 V. What is the impedance of this device?
4. A zener has an impedance of $15\ \Omega$. What is its terminal voltage at 50 mA if $V_{ZT} = 4.7\text{ V}$ at $I_{ZT} = 25\text{ mA}$?
5. A certain zener diode has the following specifications: $V_Z = 6.8\text{ V}$ at 25°C and $TC = +0.04\%/^\circ\text{C}$. Determine the zener voltage at 70°C .

SECTION 3-2 Zener Diode Applications

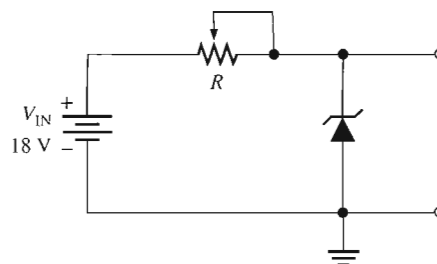
6. Determine the minimum input voltage required for regulation to be established in Figure 3-59. Assume an ideal zener diode with $I_{ZK} = 1.5\text{ mA}$ and $V_Z = 14\text{ V}$.
7. Repeat Problem 6 with $Z_Z = 20\ \Omega$ and $V_{ZT} = 14\text{ V}$ at 30 mA.

► FIGURE 3-59



8. To what value must R be adjusted in Figure 3–60 to make $I_Z = 40$ mA? Assume $V_Z = 12$ V at 30 mA and $Z_Z = 30 \Omega$.
9. A 20 V peak sinusoidal voltage is applied to the circuit in Figure 3–60 in place of the dc source. Draw the output waveform. Use the parameter values established in Problem 8.

► FIGURE 3–60

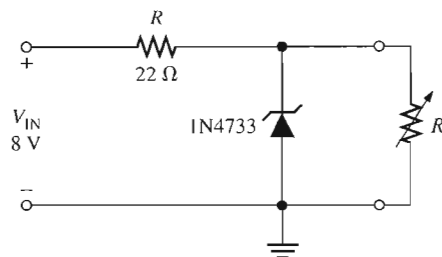


10. A loaded zener regulator is shown in Figure 3–61. $V_Z = 5.1$ V at $I_{ZT} = 49$ mA, $I_{ZK} = 1$ mA, $Z_Z = 7 \Omega$, and $I_{ZM} = 70$ mA. Determine the minimum and maximum permissible load currents.



► FIGURE 3–61

Multisim file circuits are identified with a CD logo and are in the Problems folder on your CD-ROM. Filenames correspond to figure numbers (e.g., F03–61).

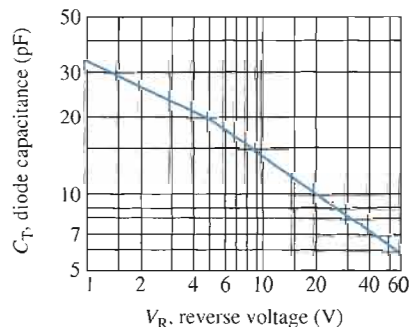


11. Find the load regulation expressed as a percentage in Problem 10. Refer to Chapter 2, Equation 2–15.
12. Analyze the circuit in Figure 3–61 for percent line regulation using an input voltage from 6 V to 12 V with no load. Refer to Chapter 2, Equation 2–14.
13. The no-load output voltage of a certain zener regulator is 8.23 V, and the full-load output is 7.98 V. Calculate the load regulation expressed as a percentage. Refer to Chapter 2, Equation 2–15.
14. In a certain zener regulator, the output voltage changes 0.2 V when the input voltage goes from 5 V to 10 V. What is the input regulation expressed as a percentage? Refer to Chapter 2, Equation 2–14.
15. The output voltage of a zener regulator is 3.6 V at no load and 3.4 V at full load. Determine the load regulation expressed as a percentage. Refer to Chapter 2, Equation 2–15.

SECTION 3–3 Varactor Diodes

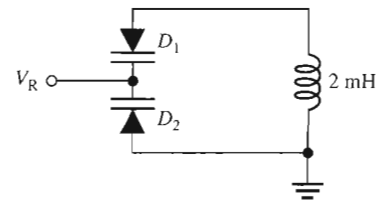
16. Figure 3–62 is a curve of reverse voltage versus capacitance for a certain varactor. Determine the change in capacitance if V_R varies from 5 V to 20 V.
17. Refer to Figure 3–62 and determine the value of V_R that produces 25 pF.

► FIGURE 3–62



18. What capacitance value is required for each of the varactors in Figure 3–63 to produce a resonant frequency of 1 MHz?

► FIGURE 3–63

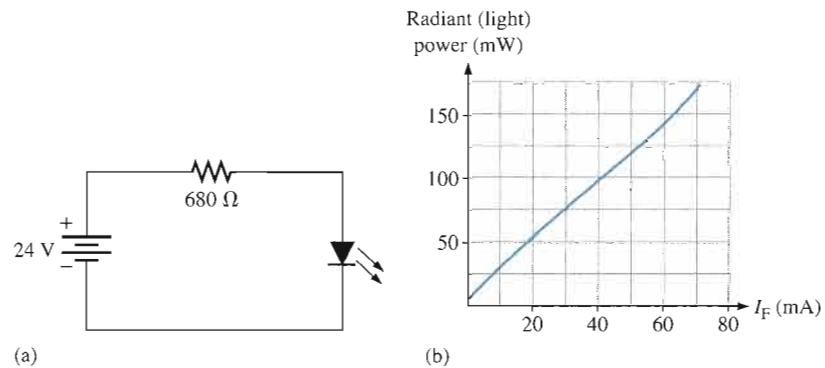


19. At what value must the voltage V_R be set in Problem 18 if the varactors have the characteristic curve in Figure 3–62?

SECTION 3–4 Optical Diodes

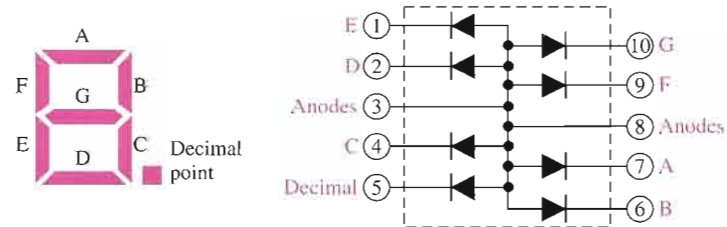
20. The LED in Figure 3–64(a) has a light-producing characteristic as shown in part (b). Neglecting the forward voltage drop of the LED, determine the amount of radiant (light) power produced in mW.

► FIGURE 3–64

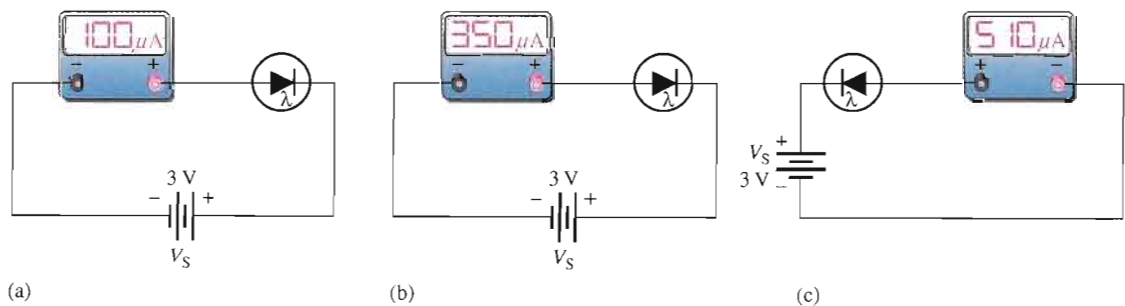


21. Determine how to connect the seven-segment display in Figure 3–65 to display “5.” The maximum continuous forward current for each LED is 30 mA and a +5 V dc source is to be used.

► FIGURE 3–65



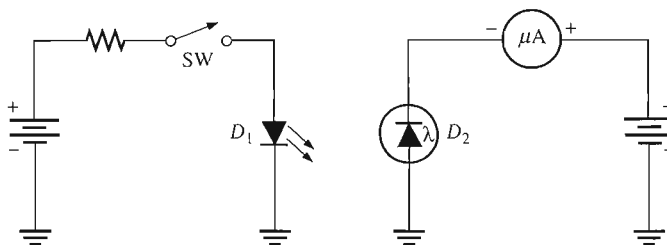
22. For a certain photodiode at a given irradiance, the reverse resistance is 200 k Ω and the reverse voltage is 10 V. What is the current through the device?
23. What is the resistance of each photodiode in Figure 3–66?



► FIGURE 3–66

24. When the switch in Figure 3–67 is closed, will the microammeter reading increase or decrease? Assume D_1 and D_2 are optically coupled.

► FIGURE 3–67



SECTION 3–5 Other Types of Diodes

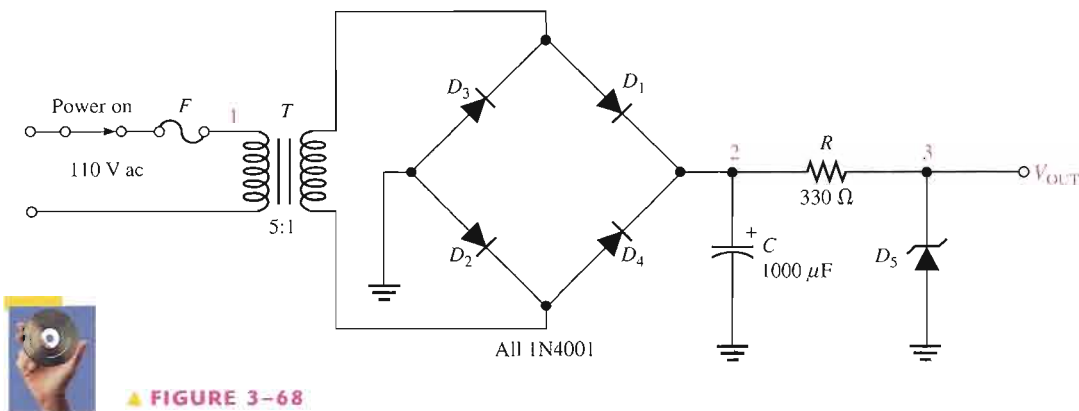
25. The V - I characteristic of a certain tunnel diode shows that the current changes from 0.25 mA to 0.15 mA when the voltage changes from 125 mV to 200 mV. What is the resistance?
26. In what type of circuit are tunnel diodes commonly used?
27. What purpose do the reflective surfaces in the laser diode serve? Why is one end only partially reflective?

TROUBLESHOOTING PROBLEMS



SECTION 3–6 Troubleshooting

28. For each set of measured voltages at the points (1, 2, and 3) indicated in Figure 3–68, determine if they are correct and if not, identify the most likely fault(s). State what you would do to correct the problem once it is isolated. The zener is rated at 12 V.
- (a) $V_1 = 110$ V rms, $V_2 = 30$ V dc, $V_3 = 12$ V dc
 - (b) $V_1 = 100$ V rms, $V_2 = 30$ V dc, $V_3 = 30$ V dc
 - (c) $V_1 = 0$ V, $V_2 = 0$ V, $V_3 = 0$ V
 - (d) $V_1 = 110$ V rms, $V_2 = 30$ V peak full-wave 120 Hz, $V_3 = 12$ V 120 Hz pulsating voltage
 - (e) $V_1 = 110$ V rms, $V_2 = 9$ V, $V_3 = 0$ V



▲ FIGURE 3–68

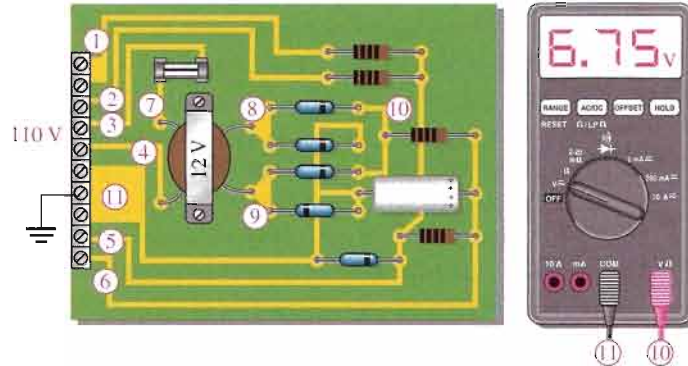


29. What is the output voltage in Figure 3–68 for each of the following faults?
- (a) D_3 open
 - (b) R open
 - (c) C leaky
 - (d) C open
 - (e) D_3 open
 - (f) D_2 open
 - (g) T open
 - (h) F open

SYSTEM APPLICATION PROBLEMS

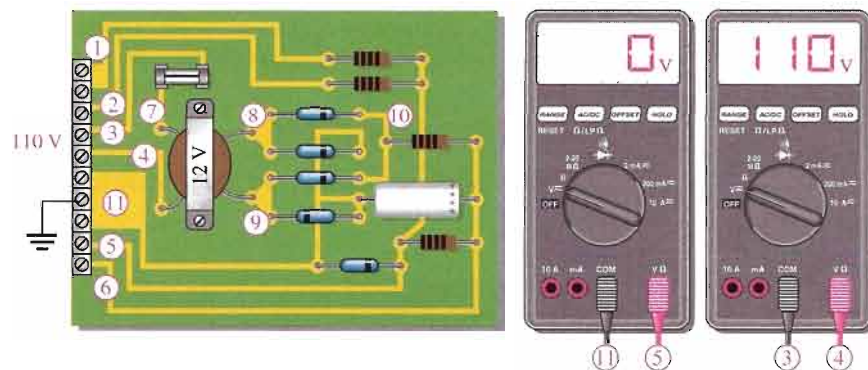
30. The counting and control system has been installed at a customer's location. The system is performing erratically, so you decide to first check the power supply and IR emitter/detector board. Based on Figure 3-69, determine the problem.

► FIGURE 3-69



31. Another problem has developed with the counter and control system. This time, the system completely quits working and again you decide to first check the power supply board. Based on Figure 3-70, determine the problem.

► FIGURE 3-70



32. List the possible reasons for the LED in Figure 3-55 not emitting infrared light when the power supply is plugged in.
33. List the possible reasons for the photodiode in Figure 3-55 not responding to the infrared light from the LED. List the steps in sequence that you would take to isolate the problem.

DATA SHEET PROBLEMS

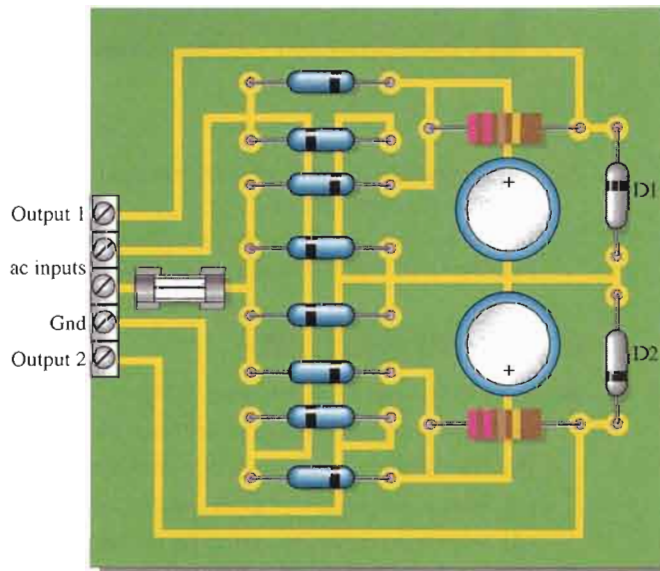
34. Refer to the zener diode data sheet in Figure 3-7.
- What is the maximum dc power dissipation at 25°C for a 1N4738?
 - Determine the maximum power dissipation at 70°C and at 100°C for a 1N4751.
 - What is the minimum current required by the 1N4738 for regulation?
 - What is the maximum current for the 1N4750 at 25°C?
 - The current through a 1N4740 changes from 25 mA to 0.25 mA. How much does the zener impedance change?
 - What is the maximum zener voltage of a 1N4736 at 50°C?
 - What is the minimum zener voltage for a 1N4747 at 75°C?

35. Refer to the varactor diode data sheet in Figure 3–22.
- What is the maximum reverse voltage for the 1N5139?
 - Determine the maximum power dissipation for a 1N5141 at an ambient temperature of 60°C.
 - Determine the maximum power dissipation for a 1N5148 at a case temperature of 80°C.
 - What is the capacitance of a 1N5148 at a reverse voltage of 20 V?
 - If figure of merit were the only criteria, which varactor diode would you select?
 - What is the typical capacitance at $V_R = 60$ V for a 1N5142?
36. Refer to the LED data sheet in Figure 3–31.
- Can 9 V be applied in reverse across an MLED81?
 - Determine the minimum value of series resistor for the MLED81 when a voltage of 5.1 V is used to forward-bias the diode.
 - Assume the forward current is 50 mA and the forward voltage drop is 1.5 V at an ambient temperature of 45°C. Is the maximum power rating exceeded?
 - Determine the axial radiant intensity for a forward current of 30 mA.
 - What is the radiant intensity at an angle of 20° from the axis if the forward current is 100 mA?
37. Refer to the photodiode data sheet in Figure 3–36.
- An MRD821 is connected in series with a 10 k Ω resistor and a reverse-bias voltage source. There is no incident light on the diode. What is the voltage drop across the resistor?
 - At what wavelength will the reverse current be the greatest for a given irradiance?
 - What is the dark current at an ambient temperature of 60°C?
 - At what wavelength is sensitivity of the MRD821 at a maximum?
 - If the maximum sensitivity is 50 $\mu\text{A}/\text{mW}/\text{cm}^2$, what is the sensitivity at 900 nm?
 - An infrared light with a wavelength of 900 nm strikes an MRD821 with an irradiance of 3 mW/cm^2 and an angle of 40° from the maximum axis. Determine the reverse current.

ADVANCED PROBLEMS

38. Develop the schematic for the circuit board in Figure 3–71 and determine what type of circuit it is.

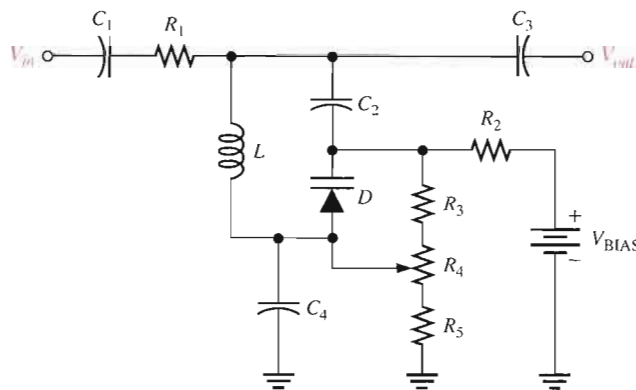
► FIGURE 3–71



Rectifier diodes: 1N4001
 Zener diodes: D1-1N4736, D2-1N4749
 Filter capacitors: 100 μF

39. If a 110 V rms, 60 Hz input voltage is connected to the ac inputs, determine the output voltages on the circuit board in Figure 3–71.
40. If each output of the board in Figure 3–71 is loaded with 1.0 k Ω , what fuse rating should be used?
41. Design a zener voltage regulator to meet the following specifications: The input voltage is 24 V dc, the load current is 35 mA, and the load voltage is 8.2 V.
42. The varactor-tuned band-pass filter in Figure 3–24 is to be redesigned to produce a bandwidth of from 350 kHz to 850 kHz within a 10% tolerance. Using the basic circuit in Figure 3–72, determine all components necessary to meet the specification. Use the nearest standard values.

▶ FIGURE 3–72



43. Design a seven-segment LED display circuit in which any of the ten digits can be displayed using a set of switches. Each LED segment is to have a current of 20 mA \pm 10% from a 12 V source and the circuit must be designed with a minimum number of switches.
44. If you used a common-anode seven-segment display in Problem 43, redesign it for a common-cathode display or vice versa.



MULTISIM TROUBLESHOOTING PROBLEMS

These file circuits are in the Troubleshooting Problems folder on your CD-ROM.

45. Open file TSP03-45 and determine the fault.
46. Open file TSP03-46 and determine the fault.
47. Open file TSP03-47 and determine the fault.
48. Open file TSP03-48 and determine the fault.

ANSWERS

SECTION REVIEWS

SECTION 3–1 Zener Diodes

1. Zener diodes are operated in the reverse-breakdown region.
2. The test current, I_{ZT}
3. The zener impedance causes the voltage to vary slightly with current.
4. $V_Z = 10\text{ V} + (20\text{ mA})(8\ \Omega) = 10.16\text{ V}$
5. The zener voltage increases (or decreases) 0.05% for each degree centigrade increase (or decrease).
6. Power derating is the reduction in the power rating of a device as a result of an increase in temperature.

SECTION 3-2 Zener Diode Applications

1. An infinite resistance (open)
2. With no load, there is no current to a load. With full load, there is maximum current to the load.
3. Approximately 0.7 V, just like a rectifier diode

SECTION 3-3 Varactor Diodes

1. A varactor exhibits variable capacitance.
2. A varactor is operated in reverse bias.
3. The depletion region
4. Capacitance decreases with more reverse bias.
5. The tuning ratio is the ratio of a varactor's capacitance at a specified minimum voltage to the capacitance at a specified maximum voltage.

SECTION 3-4 Optical Diodes

1. Infrared and visible light
2. Infrared has the greater wavelength.
3. An LED operates in forward bias.
4. Light emission increases with forward current.
5. False, V_F of an LED is usually greater than 1.2 V.
6. A photodiode operates in reverse bias.
7. The internal resistance decreases.
8. Dark current is the reverse photodiode current when there is no light.

SECTION 3-5 Other Types of Diodes

1. A current regulator operates between V_L (limiting voltage) and POV (peak operating voltage).
2. High-frequency and fast-switching circuits
3. *Hot carrier* is another name for Schottky diodes.
4. Tunnel diodes have negative resistance.
5. Oscillators
6. p region, n region, and intrinsic (i) region
7. *light amplification by stimulated emission of radiation*
8. Coherent light has only a single wavelength, but incoherent light has a wide band of wavelengths. A laser diode produces coherent light.

SECTION 3-6 Troubleshooting

1. The output voltage is too high and equal to the rectifier output.
2. More
3. Series limiting resistor open, fuse blown
4. The output voltage changes as the load resistance changes.

RELATED PROBLEMS FOR EXAMPLES3-1 5Ω 3-2 $V_Z = -11.9 \text{ V}$ at 10 mA; $V_Z = 12.08 \text{ V}$ at 30 mA

3-3 The voltage will decrease by 0.45 V.

3-4 7.5 W

3-5 $V_{IN(min)} = 6.77 \text{ V}$; $V_{IN(max)} = 21.9 \text{ V}$ 3-6 $I_{L(min)} = 0 \text{ A}$; $I_{L(max)} = 43 \text{ mA}$; $R_{L(min)} = 76.7 \Omega$

- 3-7 (a) 11.8 V at I_{ZK} ; 12.6 V at I_{ZM}
 (b) 144 Ω
 (c) 140 Ω
- 3-8 (a) A waveform identical to Figure 3-18(a)
 (b) A sine wave with a peak value of 5 V
- 3-9 $V_{R(\min)} = 1.43$ V; $V_{R(\max)} = 14.4$ V
- 3-10 2.4 mW/sr
- 3-11 29.8 μ A

CIRCUIT-ACTION QUIZ

1. (c) 2. (b) 3. (a) 4. (a) 5. (b) 6. (c) 7. (c) 8. (b) 9. (a)
 10. (a) 11. (b)

SELF-TEST

1. (a) 2. (b) 3. (c) 4. (b) 5. (d) 6. (a) 7. (c) 8. (d) 9. (b)
 10. (b) 11. (b) 12. (d)