UNIT 3

SPECIAL-PURPOSE DIODES

3–1 ■ ZENER DIODES

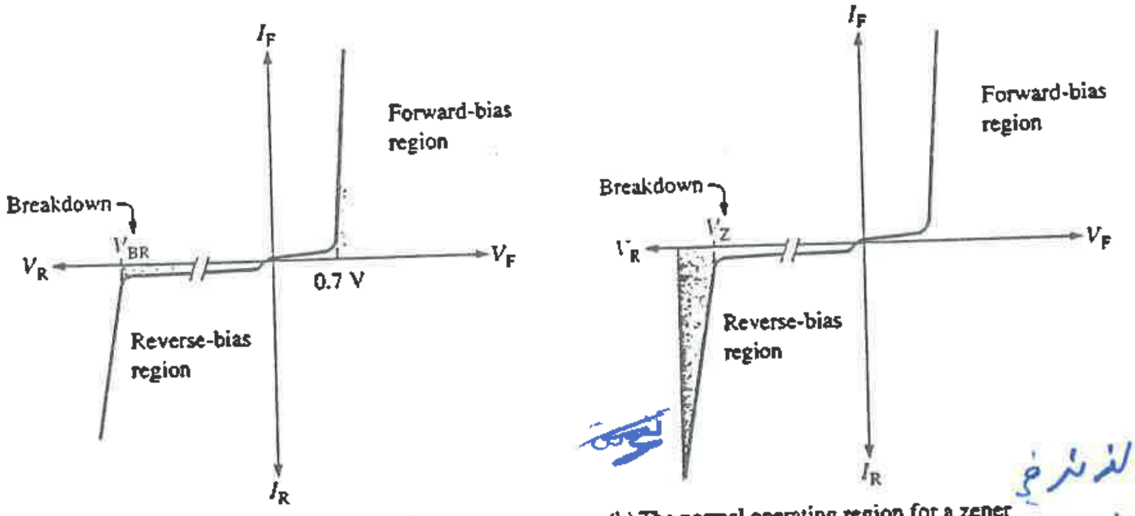
A major application for zener diodes is voltage regulation in dc power supplies. In this section, you will see how the zener maintains a nearly constant dc voltage under the proper operating conditions. You will learn the conditions and limitations for properly using the zener diode and the factors that 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 characteristic (*I*-*V*) curve of a zener
    - ☐ 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 data sheet

FIGURE 3–1
Zener diode symbol.

The symbol for a zener diode is shown in Figure 3–1. The **zener diode** is a silicon *pn* junction device that differs from rectifier diodes because it 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.



(a) The normal operating regions for a rectifier diode are shown as shaded areas.

(b) The normal operating region for a zener diode is shaded.

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FIGURE 3–2
General diode V-I characteristic.

Zener Breakdown

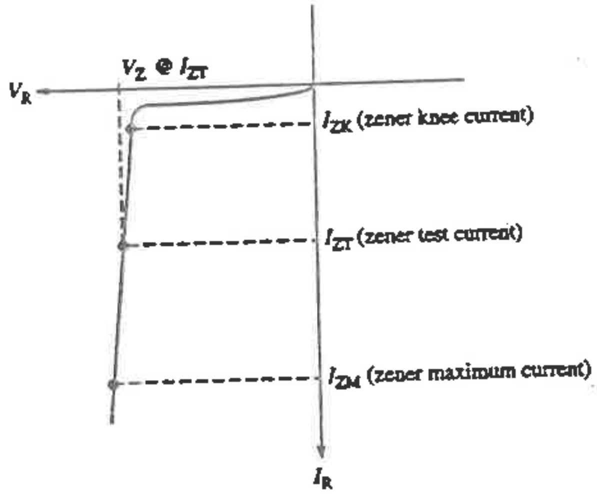
Zener diodes are designed to operate in reverse breakdown. Two types of reverse breakdown in a zener diode are *avalanche* and *zener*. The avalanche breakdown, discussed in Chapter 1, occurs in both rectifier and zener diodes at a sufficiently high reverse voltage. Zener breakdown occurs in a zener 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 predominately in zener breakdown. Those with breakdown voltages greater than approximately 5 V operate predominately in avalanche breakdown. Both types, however, are called *zener diodes*. Zeners are commercially available with breakdown voltages 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 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 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}.

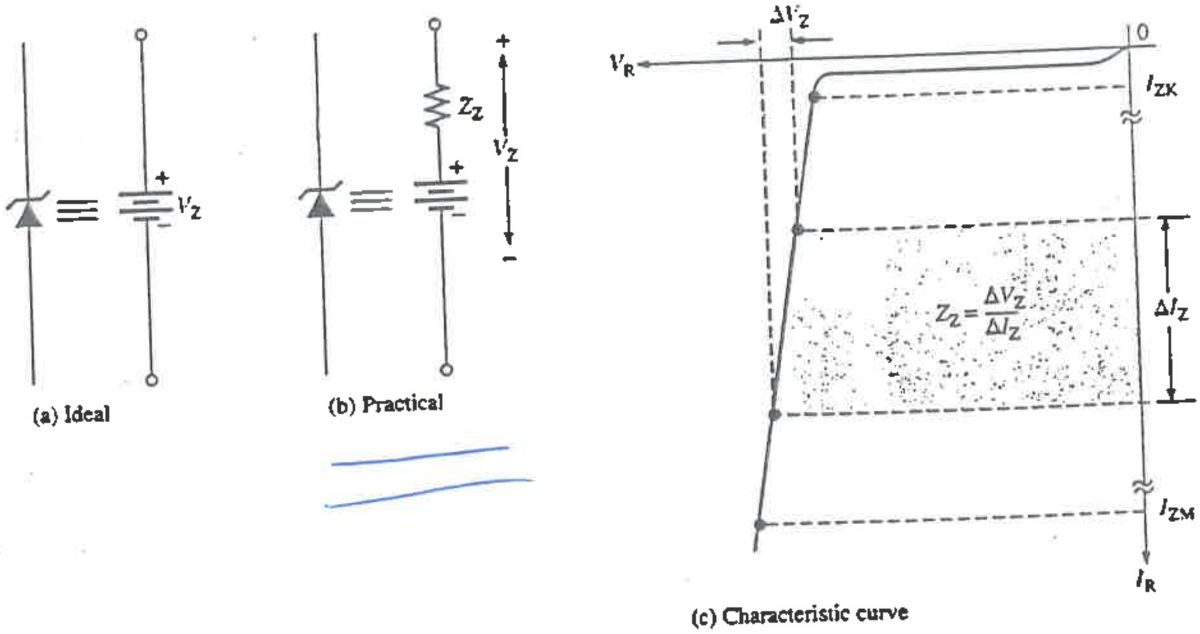
Zener Equivalent Circuit

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. 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(b) represents the practical model of a zener diode, where the zener impedance Z_Z is included. Since the voltage curve is not ideally vertical, a change in zener current produces a small change in zener voltage, as illustrated in Figure 3–4(c). The ratio of ΔV_Z to ΔI_Z is the impedance, as expressed in the following equation:

$$Z_Z = \frac{\Delta V_Z}{\Delta I_Z} \tag{3–1}$$

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.



(a) Ideal

(b) Practical

(c) Characteristic curve

FIGURE 3–4
Zener diode equivalent circuit models and the characteristic curve illustrating Z_Z.

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?

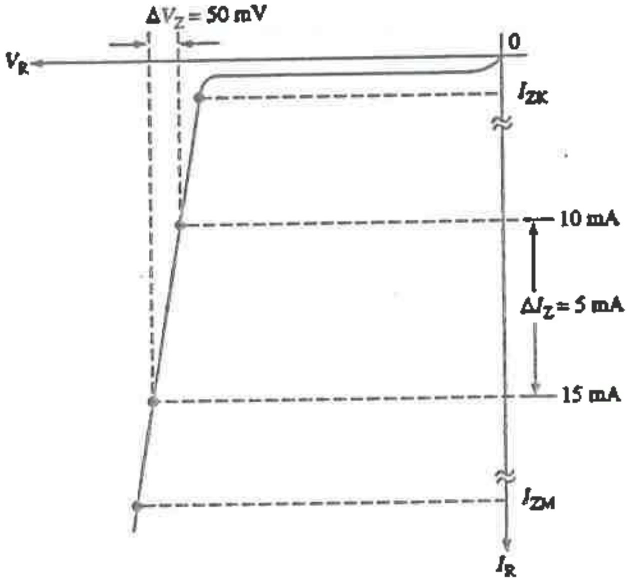


FIGURE 3–5

Solution

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

Related Exercise 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.

EXAMPLE 3–2

A certain zener diode has a Z_{ZT} of 5 Ω. The data sheet gives $V_{ZT} = 6.8$ V at $I_{ZT} = 20$ mA, $I_{ZK} = 1$ mA, and $I_{ZM} = 50$ mA. What is the voltage across the zener terminals when the current is 30 mA? When the current is 10 mA?

Solution Figure 3–6 represents the zener diode.

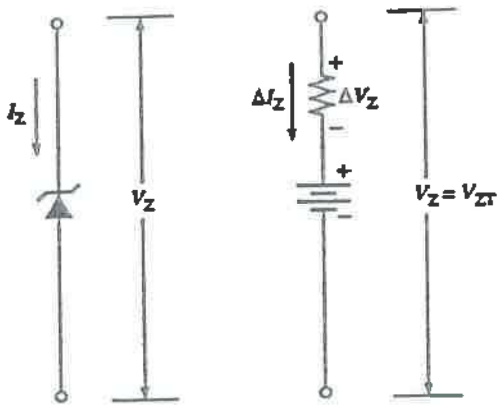
For $I_Z = 30$ mA: The 30 mA current is a 10 mA increase above $I_{ZT} = 20$ mA.

$$\Delta I_Z = I_Z - I_{ZT} = +10\text{ mA}$$
$$\Delta V_Z = \Delta I_Z Z_{ZT} = (10\text{ mA})(5\ \Omega) = +50\text{ mV}$$

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 $I_Z = 30$ mA is

$$V_Z = 6.8\text{ V} + \Delta V_Z = 6.8\text{ V} + 50\text{ mV} = 6.85\text{ V}$$

FIGURE 3–6



For $I_Z = 10$ mA: The 10 mA current is a 10 mA decrease below $I_{ZT} = 20$ mA.

$$\Delta I_Z = -10 \text{ mA}$$
$$\Delta V_Z = \Delta I_Z Z_{ZT} = (-10 \text{ mA})(5\ \Omega) = -50 \text{ mV}$$

The change in voltage due to the decrease in current below I_{ZT} causes the zener terminal voltage to decrease. The zener voltage for $I_Z = 10$ mA is

$$V_Z = 6.8 \text{ V} - \Delta V_Z = 6.8 \text{ V} - 50 \text{ mV} = 6.75 \text{ V}$$

Related Exercise Repeat the analysis for a current of 20 mA and for a current of 80 mA using a zener with $V_{ZT} = 12$ V at $I_{ZT} = 50$ mA, $I_{ZK} = 0.5$ mA, $I_{ZM} = 100$ mA, and $Z_{ZT} = 20\ \Omega$.

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).
>
> *Maximum 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 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:

$$I_{ZM} = \frac{P_{D(max)}}{V_Z} \qquad (3\text{–}6)$$

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.

Maximum Ratings

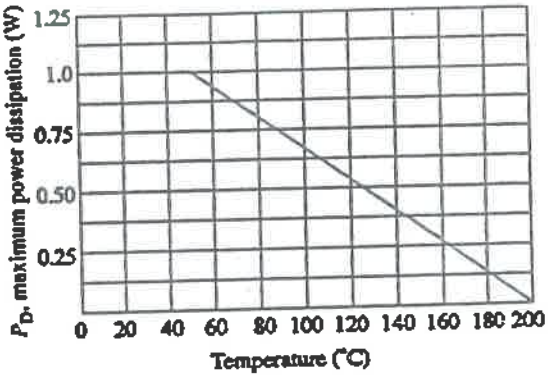
Rating	Symbol	Value	Unit
DC power dissipation @ $T_A = 50°C$ Derate above 50°C	P_D	1.0 6.67	Watt mW/C°
Operating and storage junction Temperature range	T_J, T_{stg}	−65 to +200	°C

Electrical Characteristics ($T_A = 25°C$ unless otherwise noted) $V_F = 1.2$ V max, $I_F = 200$ 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 µA 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

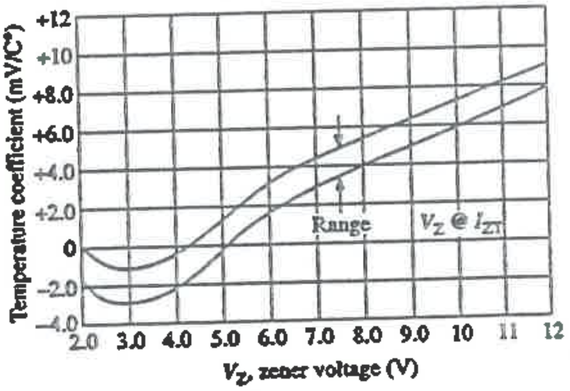
NOTE 1 — Tolerance and Type Number Designation. The JEDEC type numbers listed have a standard tolerance on the nominal zener voltage of ±10%. A standard tolerance of ±5% on individual units is also available and is indicated by suffixing "A" to the standard type number. C for ±2.0%, D for ±1.0%.

(a) Electrical characteristics

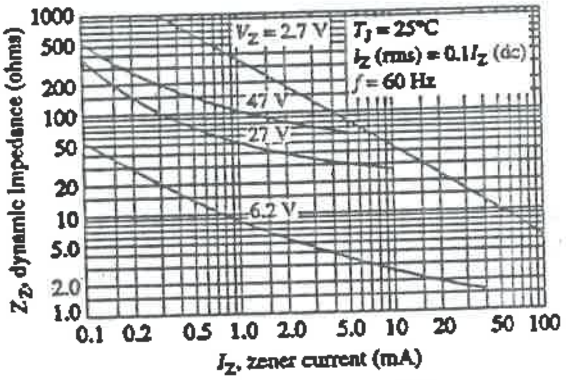


(b) Power derating

Range for Units to 12 Volts



(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.

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

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 $Z_Z = 8\ \Omega$, 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

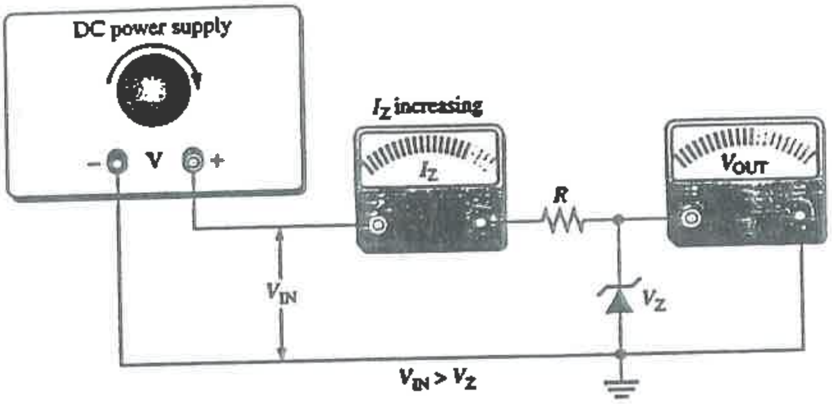
The zener diode is often used as a voltage regulator in dc power supplies. In this section, the concept of voltage regulation is introduced and two types of regulation are examined—line regulation and load regulation. Also, you will see how zeners can be used as simple limiters or clippers.

After completing this section, you should be able to

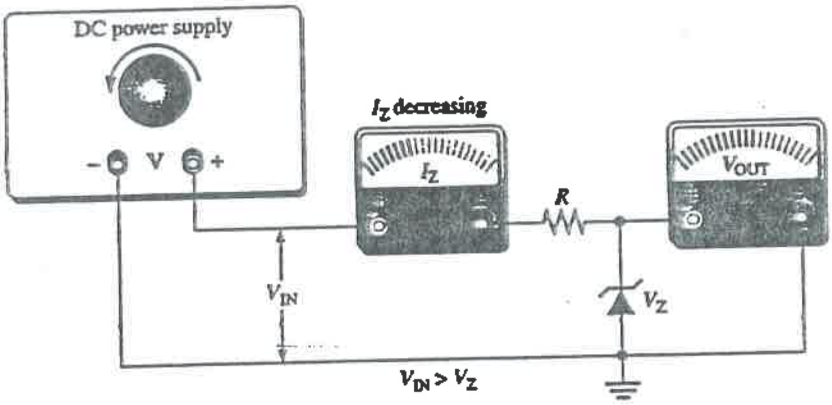
- **Explain how a zener is used in voltage regulation and limiting and analyze zener circuits**
  - ☐ Discuss input or line regulation
  - ☐ Discuss load regulation
  - ☐ Analyze zener diode regulators under both varying input and varying load conditions
  - ☐ Explain percent regulation as a figure of merit in voltage regulation
  - ☐ Analyze zener waveform-limiting circuits

Zener Regulation with a Varying Input Voltage

Zener diodes are widely used for voltage regulation. Figure 3–8 illustrates how a zener diode can be used to regulate a varying dc voltage. This is called *input* or **line regulation.** As the input voltage varies (within limits), the zener diode maintains a nearly constant output voltage across its terminals. However, as V_{IN} changes, I_Z will change proportionally so that the limitations on the input voltage variation are set by the minimum and maximum current values (I_{ZK} and I_{ZM}) with which the zener can operate. R is the series current-limiting resistor. The DMM displays indicate the relative values and trends.



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



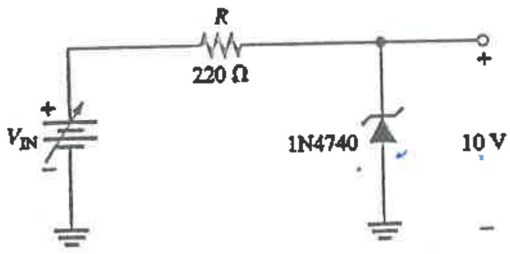
(b) As the input voltage decreases, the output voltage remains constant ($I_{ZK} < I_Z < I_{ZM}$).

FIGURE 3–8
Zener regulation of a varying input voltage.

For example, 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 ($I_{ZM} = P_{D(max)}/V_Z = 1\text{ W}/10\text{ V} = 100$ mA). For the minimum zener current, the voltage across the 220 Ω resistor is

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

FIGURE 3–9



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

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

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

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

Therefore,

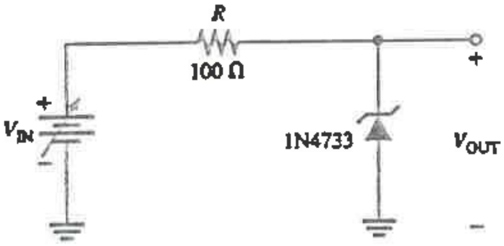
$$V_{IN(max)} \cong 22\text{ V} + 10\text{ V} = 32\text{ V}$$

This shows that this zener diode can regulate an input voltage from 10.055 V to 32 V anc maintain an approximate 10 V output. The output will vary slightly because of the zenei 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, the following information for the 1N4733 is obtained: $V_Z = 5.1$ V at $I_{ZT} = 49$ mA, $I_{ZK} = 1$ 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. At $I_{ZK} = 1$ 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,

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

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.

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

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,

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

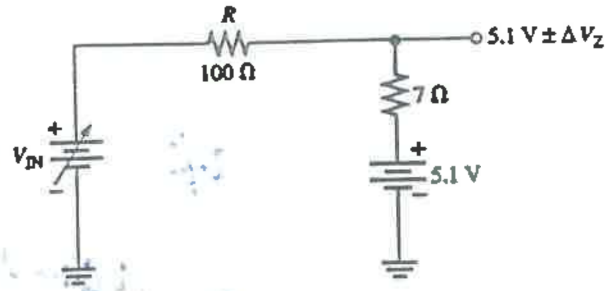


FIGURE 3–11
Equivalent of circuit in Figure 3–10.

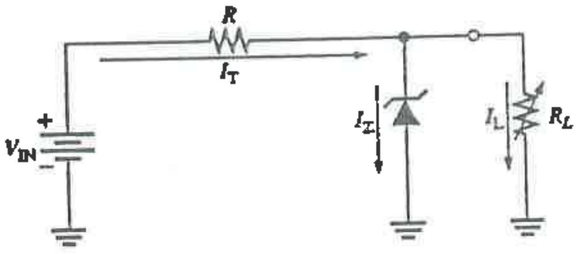
Related Exercise Determine the minimum and maximum input voltages that can be regulated if a 1N4736 zener diode is used in Figure 3–10.

Open file FG03-10.CA4 on your circuit disk. 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}. This is called **load regulation.**

FIGURE 3–12
Zener regulation with a variable load.



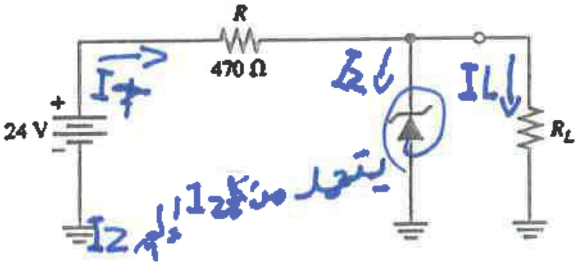
From No Load to Full Load

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. When a load resistor (R_L) is connected, part of the total current is through the zener and part through R_L. As R_L is decreased, the load current, I_L increases and I_Z decreases. The zener diode continues to regulate until I_Z reaches its minimum value, I_{ZK}. At this point the load current is maximum. The total current through R remains essentially constant. 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 R_L that can be used? $V_Z = 12$ V, $I_{ZK} = 1$ mA, and $I_{ZM} = 50$ 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.

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

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. This means that R_L can be removed from the circuit and regulation will be maintained.

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

The maximum value of I_L occurs when I_Z is minimum ($I_Z = I_{ZK}$), so solve for $I_{L(max)}$ as follows:

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

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 current away from the zener and I_Z will be reduced below I_{ZK}. This will cause the zener to lose regulation. In summary, regulation is maintained for any value of R_L between 490 Ω and infinity.

Related Exercise Find the minimum and maximum load currents for which the circuit in Figure 3–13 will maintain regulation. Determine the minimum R_L that can be used. $V_Z = 3.3$ V (constant), $I_{ZK} = 1$ mA, $I_{ZM} = 150$ mA. Assume $Z_Z = 0\ \Omega$ for simplicity.

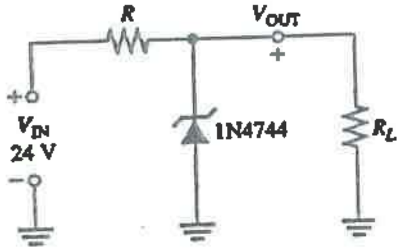
Open file FG03-13.CA4 on your circuit disk. For the calculated minimum value of load resistance, verify that regulation occurs.

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

EXAMPLE 3–7

For the circuit in Figure 3–14:
(a) Determine V_{OUT} at I_{ZK} and at I_{ZM}.
(b) Calculate the value of R that should be used.
(c) Determine the minimum value of R_L that can be used.

FIGURE 3–14



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فورصد لا يثبة الجهد
كلي 3.3

وسعد رهويفير سر
كلشد يثبة الجهد كلي
0.7

Solution 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: $V_Z = 15$ V @ I_{ZT}, $I_{ZK} = 0.25$ mA, $I_{ZT} = 17$ mA, and $Z_{ZT} = 14\ \Omega$.

(a) For I_{ZK}:

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

17-0.25

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}:

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

(b) The value of R is calculated 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).

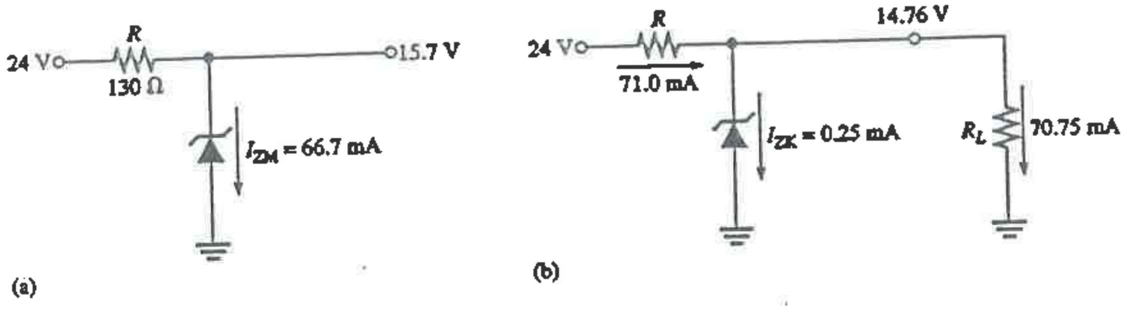


FIGURE 3–15

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

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

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

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

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

Percent Regulation

Regulation expressed as a percentage is a figure of merit used to specify the performance of a voltage regulator. It can be in terms of input (line) regulation or load regulation. *Line regulation* specifies the change in the output voltage (ΔV_{OUT}) for a given change in input voltage (ΔV_{IN}) expressed as a percentage.

$$\text{Line regulation} = \left(\frac{\Delta V_{OUT}}{\Delta V_{IN}}\right)100\% \qquad (3\text{–}6)$$

Load regulation specifies the change in the output voltage over a certain range of load current values, usually from minimum current (no load, NL) to maximum current (full load, FL). It is normally expressed as a percentage and can be calculated with the following formula:

$$\text{Load regulation} = \left(\frac{V_{NL} - V_{FL}}{V_{FL}}\right)100\% \qquad (3\text{–}7)$$

where V_{NL} is the output voltage with no load, and V_{FL} is the output voltage with full (maximum current) load.

EXAMPLE 3–8

A certain regulator has a no-load output voltage of 6 V and has a full-load output of 5.82 V. What is the load regulation expressed as a percentage?

Solution

$$\text{Load regulation} = \left(\frac{V_{NL} - V_{FL}}{V_{FL}}\right)100\% = \left(\frac{6\text{ V} - 5.82\text{ V}}{5.82\text{ V}}\right)100\% = 3.09\%$$

Related Exercise If the no-load output voltage of a regulator is 24.8 V and the full-load output is 23.9 V, what is the load regulation expressed as a percentage?

Related Exercise

(a) If the no-load output voltage of a regulator is 24.8 V and the full-load output is 23.9 V, what is the percent load regulation?

(b) If the output voltage changes 0.035 V for a 2 V change in the input voltage, what is the line regulation expressed as %/V?

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 V. Two back-to-back zeners limit both peaks to the zener voltage plus 0.7 V, as shown in part (c). During the positive alternation, D_2 is functioning as the zener limiter and D_1 is functioning as a forward-biased diode. During the negative alternation, the roles are reversed.

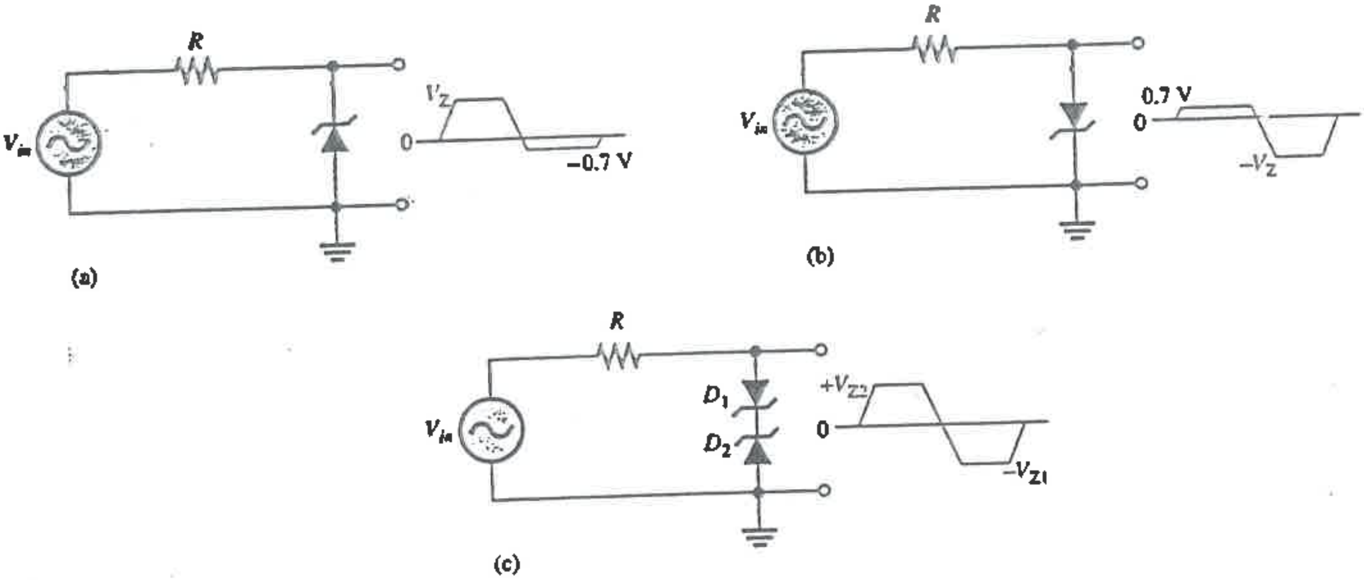
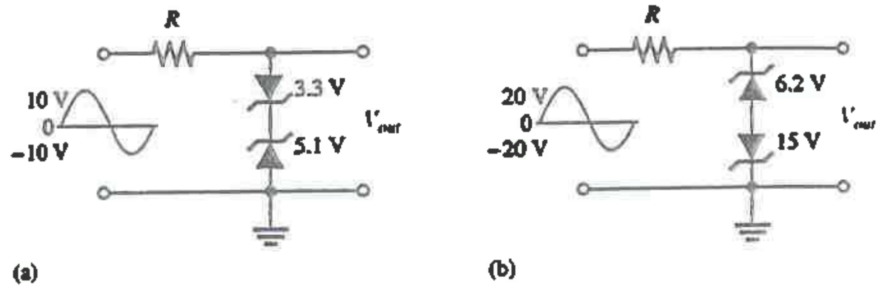


FIGURE 3–16
Basic zener limiting action with a sinusoidal input voltage.

EXAMPLE 3–9

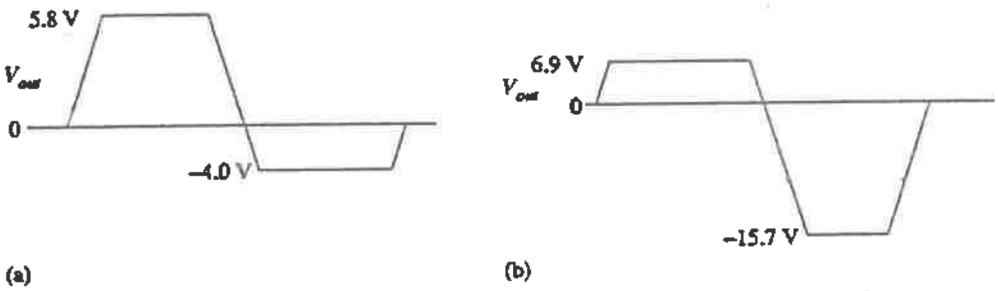
Determine the output voltage for each zener limiting circuit in Figure 3–17.



(a) (b)

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.



(a) (b)

FIGURE 3–18

Related Exercise

(a) What is the output in Figure 3–17(a) if the input voltage is increased to a peak value of 20 V?

(b) What is the output in Figure 3–17(b) if the input voltage is decreased to a peak value of 5 V?

SECTION 3–2 REVIEW

1. Explain the difference between line regulation and load regulation.
2. In a zener diode regulator, what value of load resistance results in the maximum zener current?
3. Define the terms *no-load* and *full-load.*
4. A regulator has an output voltage of 12 V with no load and 11.9 V with full load. What is the percent load regulation?
5. How much voltage appears across a zener diode when it is forward-biased?

3–3 ■ VARACTOR DIODES

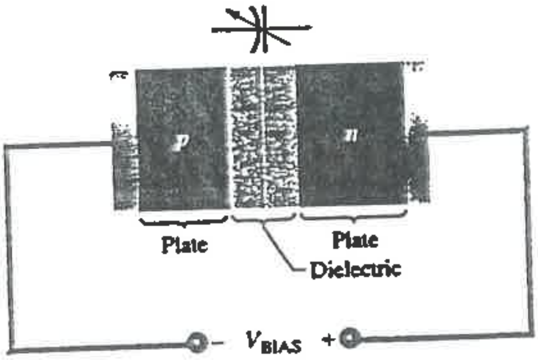
Varactor diodes are also known as voltage-variable-capacitance diodes because the junction capacitance varies with the amount of reverse-bias voltage. Varactors are specifically designed to take advantage of this variable-capacitance characteristic. The capacitance can be changed by changing the reverse voltage. 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 *figure-of-merit*
  - ☐ Discuss varactor temperature coefficients
  - ☐ Analyze a varactor-tuned band-pass filter

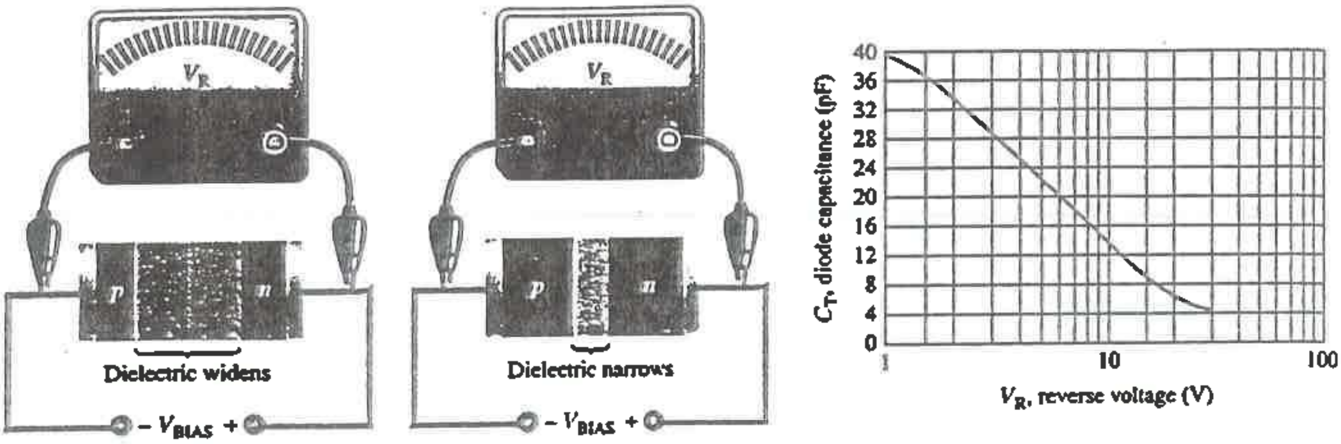
A varactor is a *pn* junction diode that operates in reverse-bias and is doped to maximize the inherent capacitance of the depletion region. The depletion region, widened by the reverse bias, acts as a capacitor dielectric because of its nonconductive characteristic. The *p* and *n* regions are conductive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



(a) Greater reverse bias, less capacitance (b) Less reverse bias, greater capacitance (c) Graph of diode capacitance versus reverse voltage

FIGURE 3–20
Varactor diode capacitance varies with reverse voltage.

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

$$C = \frac{A\epsilon}{d} \tag{3-9}$$

FIGURE 3–21
Varactor diode symbol.

In a varactor diode, the 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(a) shows a common symbol for a varactor.

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

Maximum Ratings ($T_C = 25°C$ 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 @ $T_A = 25°C$ Derate above 25°C	P_D	400 2.67	mW mW/C°
Device dissipation @ $T_C = 25°C$ Derate above 25°C	P_C	2.0 13.3	Watts mW/C°
Junction temperature	T_J	+175	°C
Storage temperature range	T_{stg}	−65 to +200	°C

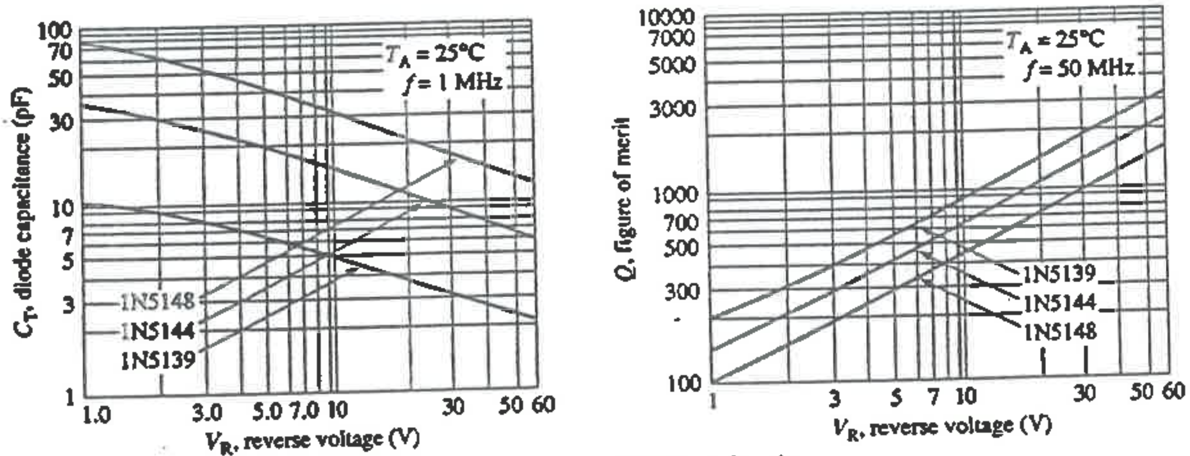
*The RF power input rating assumes that an adequate heatsink is provided.

Electrical Characteristics ($T_A = 25°C$ unless otherwise noted)

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

	C_T, Diode Capacitance $V_R = 4.0$ V dc, $f = 1.0$ MHz pF			Q, Figure of Merit $V_R = 4.0$ V dc $f = 50$ MHz	TR, Tuning Ratio C_4/C_{60} $f = 1.0$ MHz	
Device	Min	Typ	Max	Min	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.

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

The 1N51xx series of varactors 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 varactors such as the MV1401 are hyper-abrupt devices in which the doping pattern results in an even more abrupt junction. Many hyper-abrupt varactors 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 by the capacitor (or inductor) and returned to the energy dissipated in the resistance. The 1N5139 has a minimum Q of 350, 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 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, the varactor acts as a variable capacitor, thus allowing the resonant frequency to be adjusted by a variable voltage level, as illustrated in Figure 3–23 where 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 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.

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

$$f_r \cong \frac{1}{2\pi\sqrt{LC}} \qquad (3\text{–}10)$$

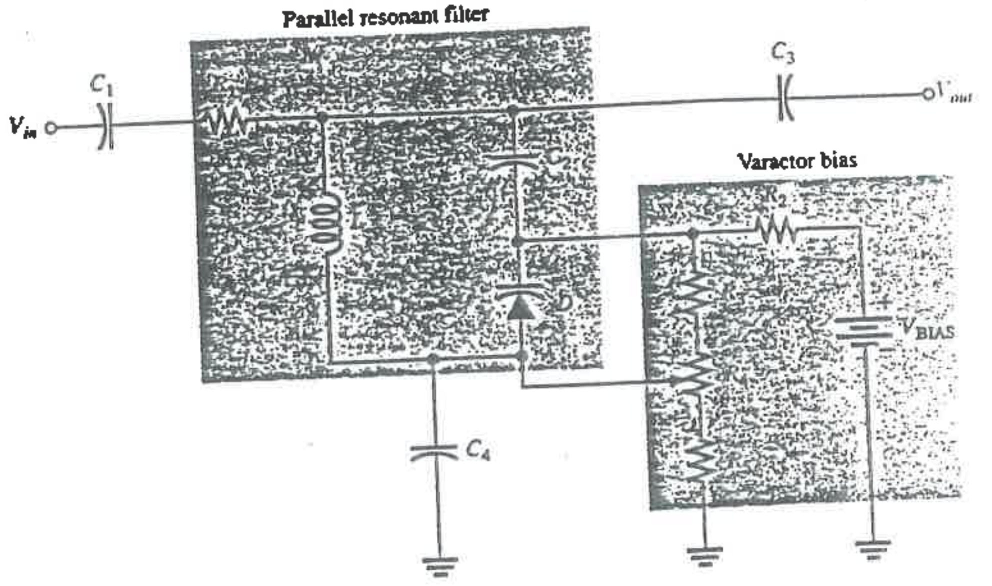


FIGURE 3–23
A resonant band-pass filter using a varactor diode for adjusting the resonant frequency over a specified range.

EXAMPLE 3–10

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.

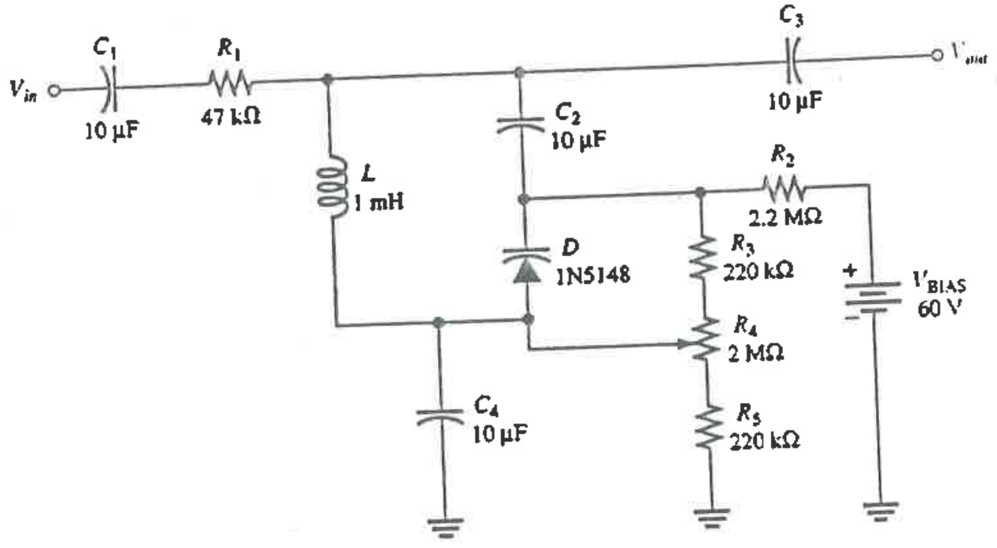


FIGURE 3–24

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

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

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.

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

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

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

$$V_{R(min)} = V_K - V_{A(max)} = 31.6\text{ V} - 28.7\text{ V} = 2.9\text{ V}$$
$$V_{R(max)} = V_K - V_{A(min)} = 31.6\text{ V} - 2.85\text{ V} = 29\text{ V}$$

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 $C_{2.9} \cong 55$ pF and $C_{29} \cong 17$ pF. The minimum resonant frequency for the filter is

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

The maximum resonant frequency for the filter is

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

Related Exercise 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 in the last section 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**

The Light-Emitting Diode (LED)

FIGURE 3–25
Symbol for an 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 level 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 semiconductor material permits the photons to be emitted as visible light. Figure 3–26 illustrates this process, called electroluminescence. Various impurities are added during the doping process to establish the wavelength of the emitted light. The wavelength determines the color of the light and if it is visible or invisible (infrared).

Semiconductor Materials LEDs are made of gallium arsenide (GaAs), gallium arsenide phosphide (GaAsP), or gallium phosphide (GaP). Silicon and germanium are not used because they are essentially heat-producing materials and are very poor at producing light. GaAs LEDs emit infrared (IR) radiation, which is nonvisible. GaAsP produces either red or yellow visible light, and GaP emits red or green visible light. Red is the most common.

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). The greater I_F is, the greater the light output.

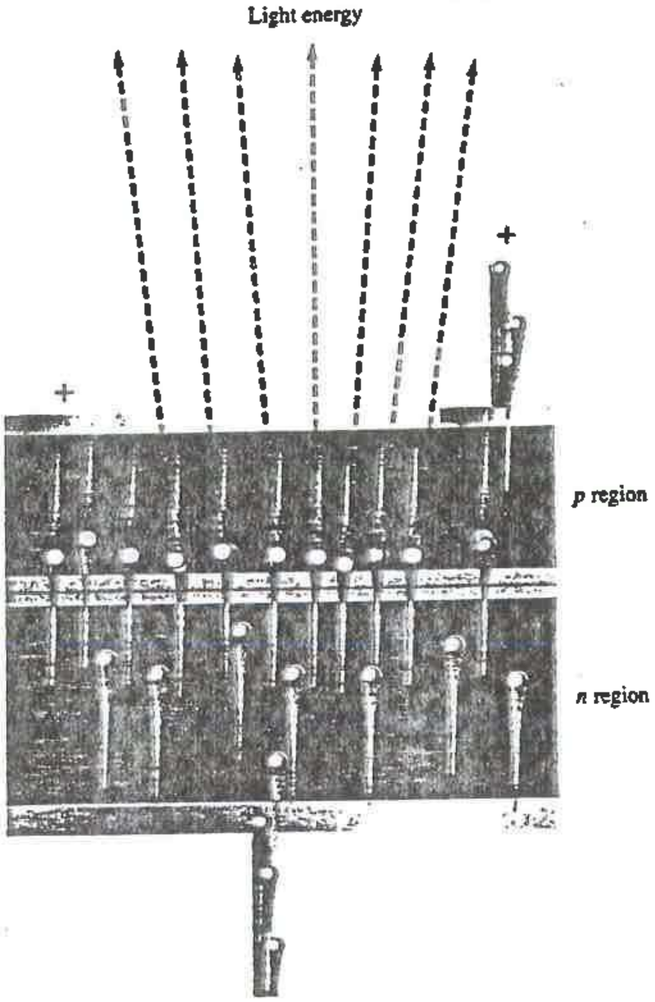
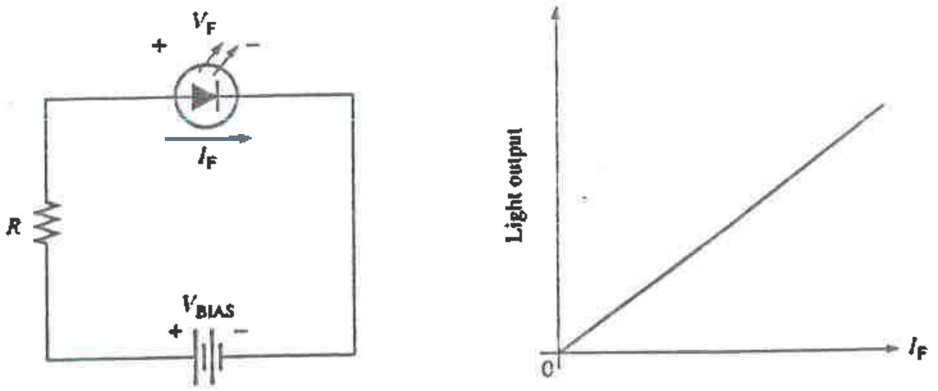


FIGURE 3–26
Electroluminescence in a forward-biased LED.



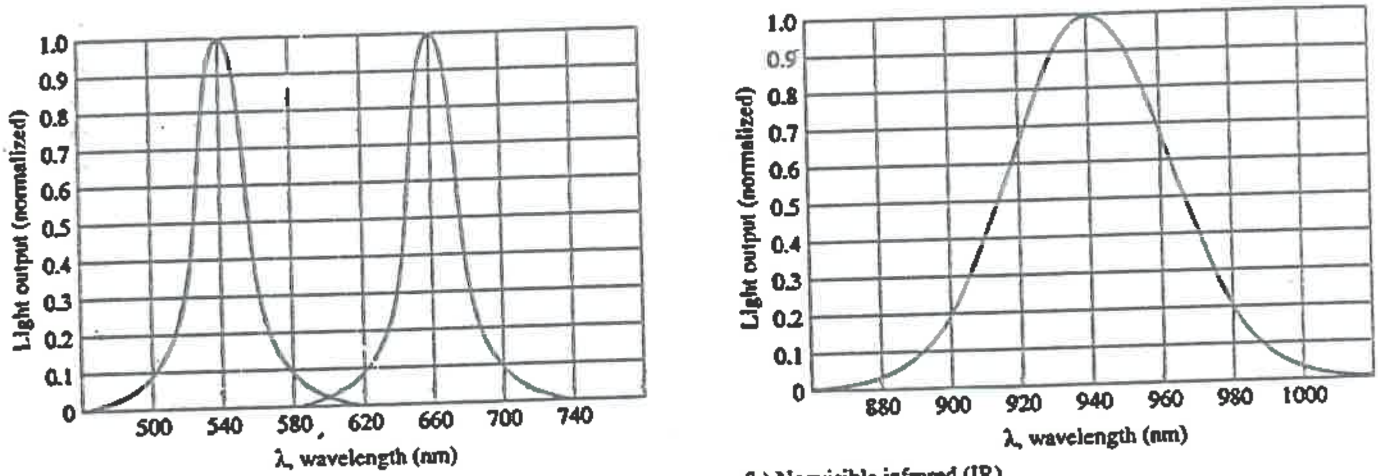
(a) Forward-biased operation

(b) General light output versus forward current

FIGURE 3–27
Basic operation of an LED.

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, and green at 540 nm. The output for the infrared LED peaks at 940 nm.

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.



(a) Visible light

(b) Nonvisible infrared (IR)

FIGURE 3–28
Examples of typical spectral output curves for LEDs.

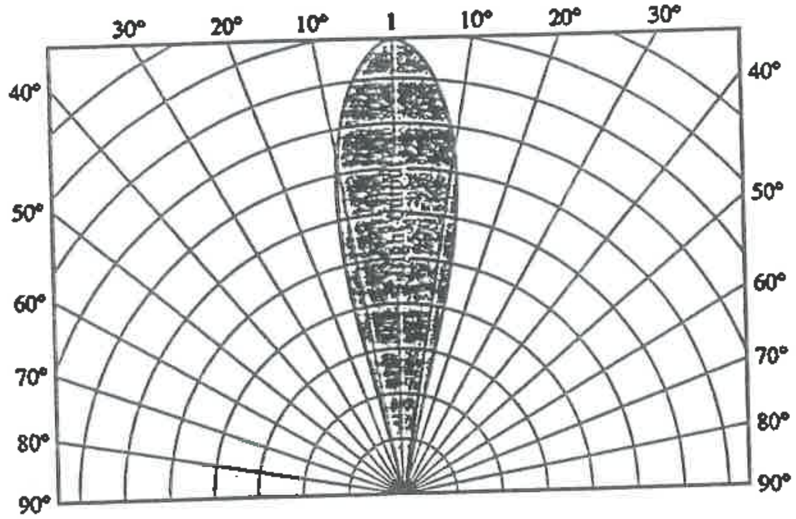


FIGURE 3–29
General radiation pattern of a typical LED.

FIGURE 3–30
Typical LEDs.

Typical LEDs are shown in Figure 3–30. Photodiodes, to be studied next, generally have the same appearance.

LED Data Sheet Information

A partial data sheet for an MLED81 infrared 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 and 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 the LED source expressed in mW/cm^2 and can be calculated using radiant intensity and the distance in centimeters (cm) using the following formula:

$$H = \frac{I_e}{d^2} \qquad (3\text{–}11)$$

Irradiance is important because the response of a detector (photodiode) used in conjunction with the LED depends on the irradiance of the light it receives. We will discuss this further in relation to photodiodes.

EXAMPLE 3–11

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

(a) The radiant intensity at 900 nm if the maximum output is 15 mW/sr.

(b) The forward voltage drop for $I_F = 20$ mA.

(c) The radiant intensity for $I_F = 30$ mA.

(d) 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,

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

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 @ $T_A = 25°C$ 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

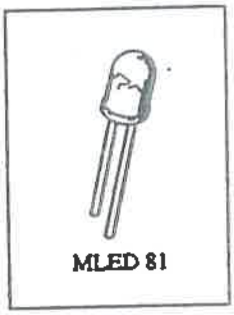
Electrical Characteristics ($T_A = 25°C$ unless otherwise noted)

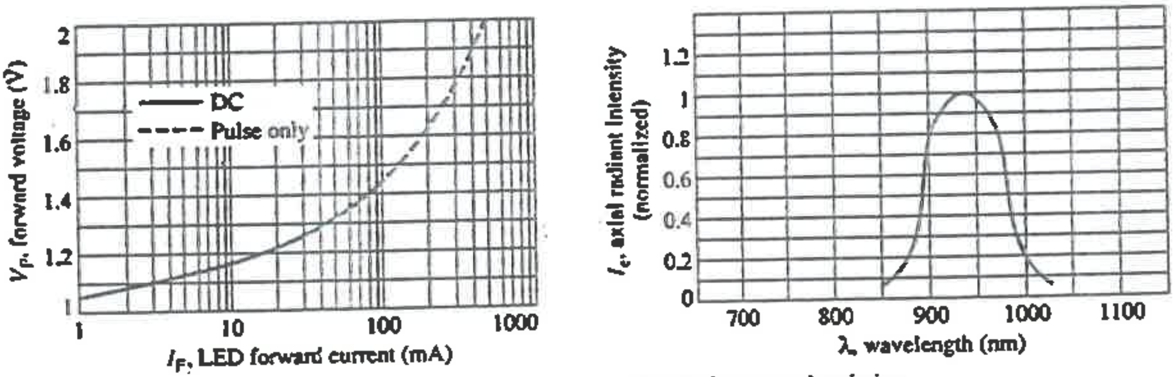
Characteristic	Symbol	Min	Typ	Max	Unit
Reverse leakage current ($V_R = 3$ V)	I_R	—	10	—	nA
Reverse leakage current ($V_R = 5$ V)	I_R	—	1	10	μA
Forward voltage ($I_F = 100$ mA)	V_F	—	1.35	1.7	V
Temperature coefficient of forward voltage	ΔV_F	—	–1.6	—	mV/K
Capacitance ($f = 1$ MHz)	C	—	25	—	pF

Optical Characteristics ($T_A = 25°C$ unless otherwise noted)

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

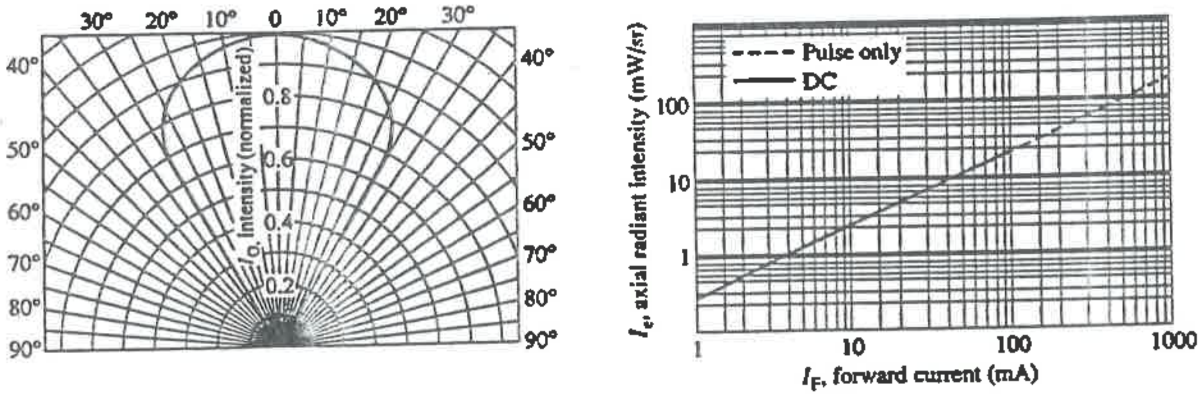
(a) Ratings and characteristics





(b) LED forward voltage versus forward current

(c) Relative spectral emission



(d) Spatial radiation pattern

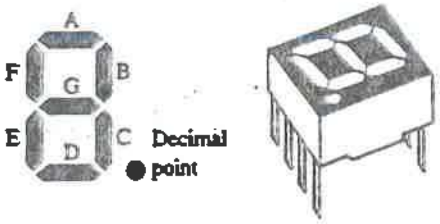
(e) Intensity versus forward current

FIGURE 3–31
Partial data sheet for an MLED81 IR light-emitting diode.

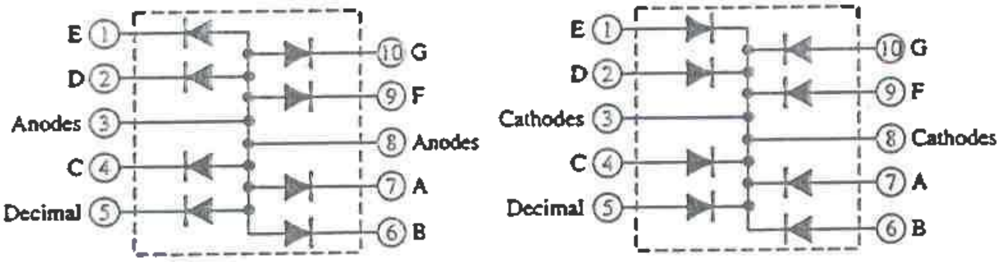
(b) From the graph in part (b), $V_F = 1.23$ V for $I_F = 20$ mA.
(c) From the graph in part (e), $I_e = 5$ mW/sr for $I_F = 30$ mA.
(d) $H = \frac{I_e}{d^2} = \frac{15\text{ mW/sr}}{(10\text{ cm})^2} = 0.15\text{ mW/cm}^2$

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

Applications 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.



(a) LED segment arrangement and typical device



(b) Common anode

(c) Common cathode

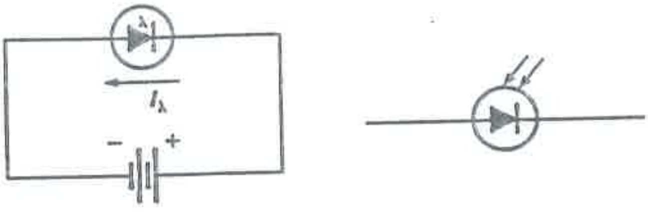
FIGURE 3–32
The 7-segment LED display.

IR-emitting diodes are employed 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.

The Photodiode

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

FIGURE 3–33
Photodiode.



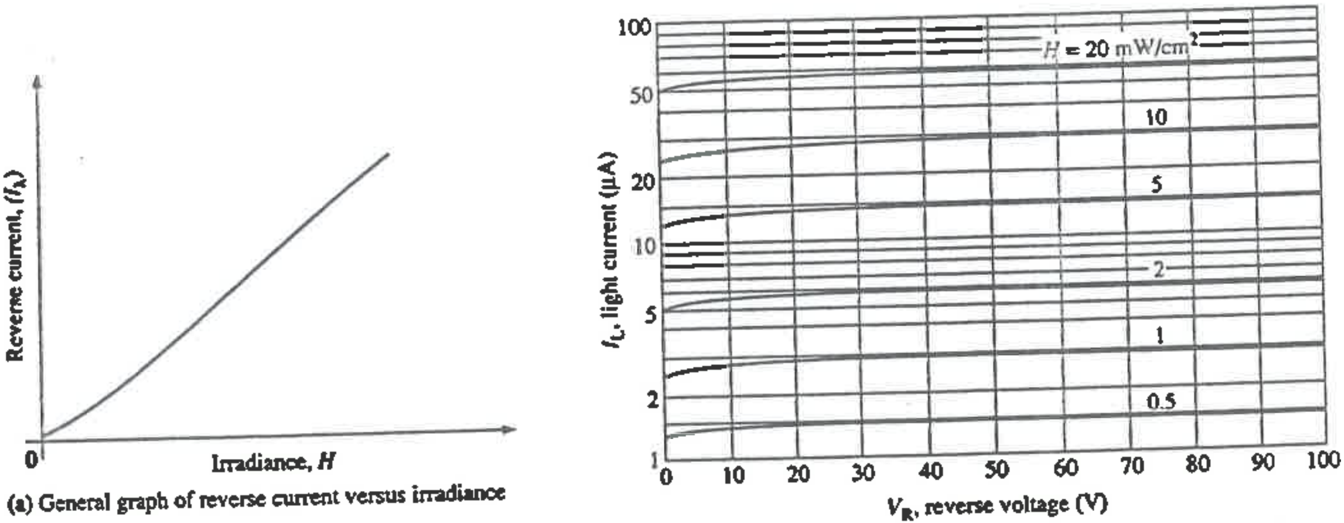
(a) Reverse-bias operation (b) Alternate symbol

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

A photodiode differs from a rectifier diode in that when its *pn* junction is exposed to light, the reverse current increases with the light intensity. When there is no incident light, the reverse current I_λ is almost negligible and is called the dark current. An increase in the amount of light intensity, expressed as irradiance (mW/cm^2), produces an increase in the reverse current, as shown by the graph in Figure 3–34(a).

From the graph in Figure 3–34(b), the light current for this particular device is approximately 0.9 μA at a reverse-bias voltage of 10 V. Therefore, the resistance of the device with an irradiance of 0.5 mW/cm^2 is

$$R_R = \frac{V_R}{I_\lambda} = \frac{10\text{ V}}{0.9\ \mu\text{A}} = 11\text{ M}\Omega$$



(a) General graph of reverse current versus irradiance

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

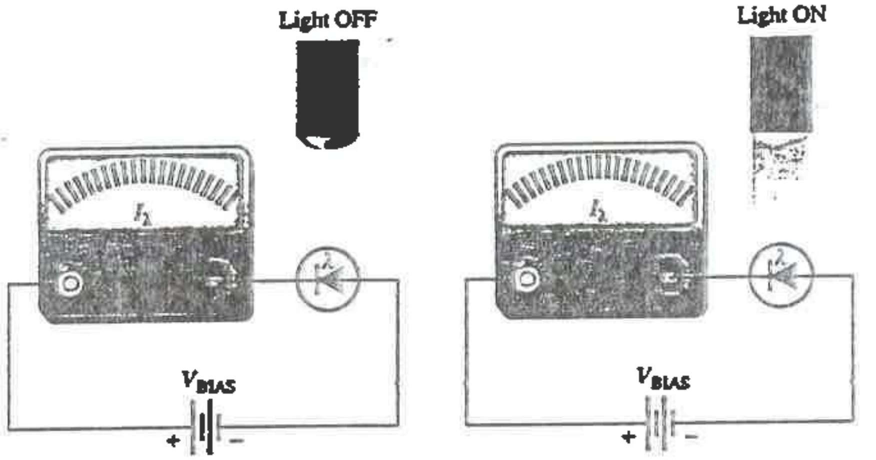
FIGURE 3–34
Typical photodiode characteristics.

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

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

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

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).



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

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

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 μA/mW/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 mW/cm^2, there are 50 μA of reverse (light) current and if the irradiance is 0.5 mW/cm^2, there are 25 μA of reverse current.

Maximum Ratings

Rating	Symbol	Value	Unit
Reverse voltage	V_R	35	Volts
Forward current — continuous	I_F	100	mA
Total power dissipation @ $T_A = 25°C$ 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

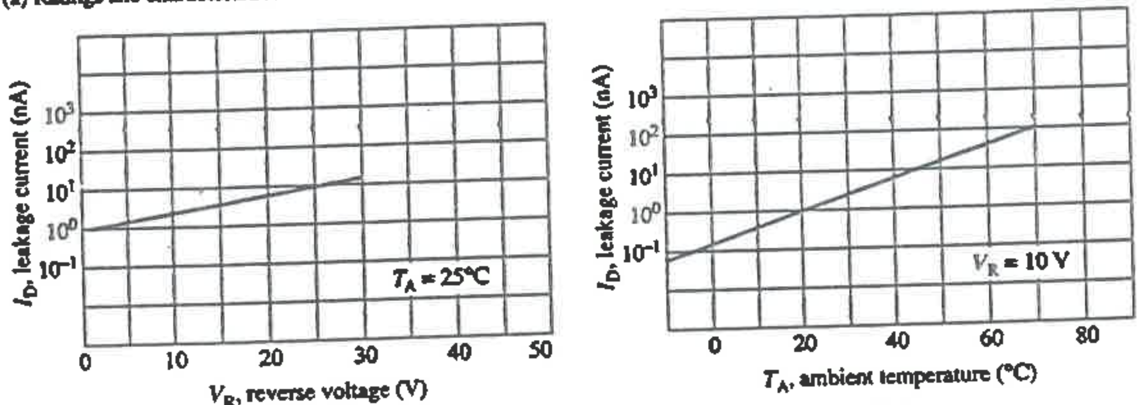
Electrical Characteristics ($T_A = 25°C$ unless otherwise noted)

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

Optical Characteristics ($T_A = 25°C$ unless otherwise noted)

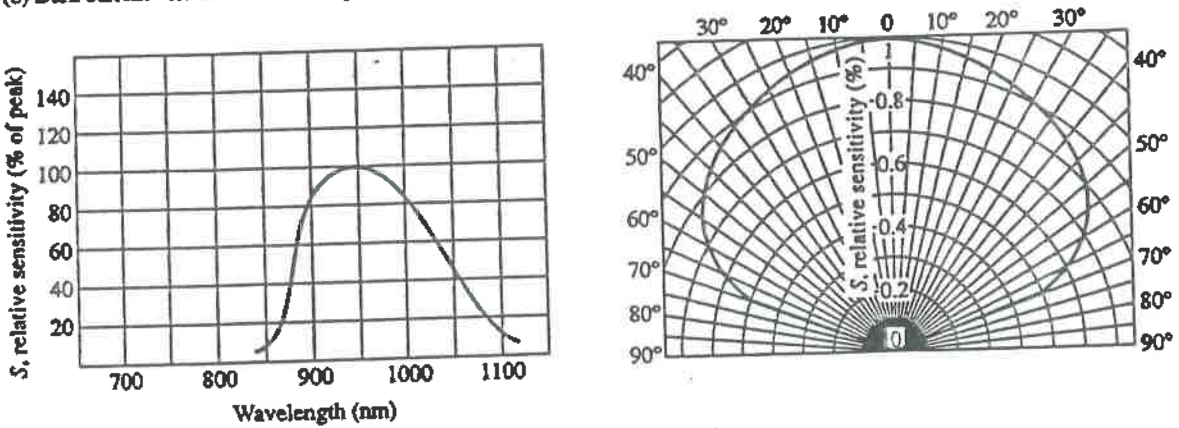
Characteristic	Symbol	Min	Typ	Max	Unit
Wavelength of maximum sensitivity	λmax	—	940	—	nm
Spectral range	$\Delta\lambda$	—	170	—	nm
Sensitivity ($\lambda = 940$ nm, $V_R = 20$ V)	S	—	50	—	μA/mW/cm^2
Temperature coefficient of sensitivity	ΔS	—	0.18	—	%/K
Acceptance half-angle	φ	—	±70	—	°
Short circuit current (Ev = 1000 lux)	I_s	—	50	—	μA
Open circuit voltage (Ev = 1000 lux)	V_1	—	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.

EXAMPLE 3–12

An MRD821 photodiode is exposed to a 1000 nm infrared light with an irradiance (H) of 2.5 mW/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 µA/mW/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.

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

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%.

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

For an irradiance, H, of 2.5 mW/cm^2, the reverse (light) current is

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

Related Exercise Determine the MRD821 response (reverse current) to an irradiance of 1 mW/cm^2 for a wavelength of 900 nm at an angle of 60° from maximum orientation.

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?*