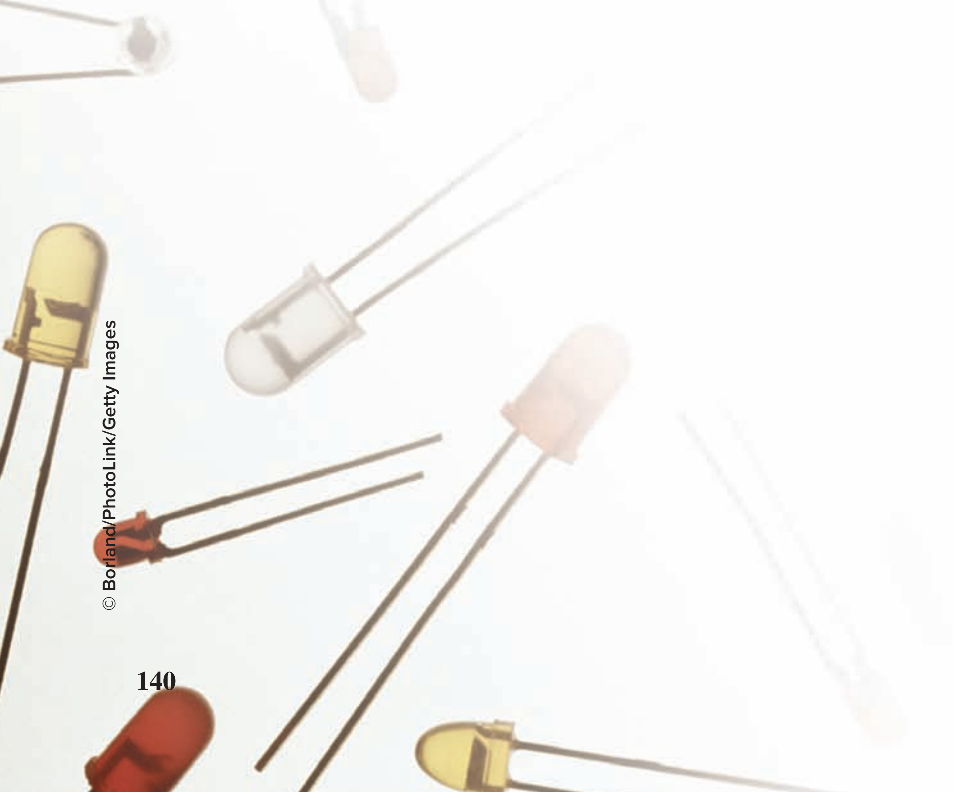
chapter 5

Special-Purpose Diodes

Rectifier diodes are the most common type of diode. They are used in power supplies to convert ac voltage to dc voltage. But rectification is not all that a diode can do. Now we will discuss diodes used in other applications. The chapter begins with the zener diode, which is optimized for its breakdown properties. Zener diodes are very important because they are the key to voltage regulation. The chapter also covers optoelectronic diodes, including light-emitting diodes (LEDs), Schottky diodes, varactors, and other diodes.



Objectives

After studying this chapter, you should be able to:

- Show how the zener diode is used and calculate various values related to its operation.
- List several optoelectronic devices and describe how each works.
- Recall two advantages Schottky diodes have over common diodes.
- Explain how a varactor works.
- State a primary use of the varistor.
- List four items of interest to the technician found on a zener diode data sheet.
- List and describe the basic function of other semiconductor diodes.

Chapter Outline

Vocabulary

back diode
common-anode
common-cathode
current-regulator diode
derating factor
electroluminescence
laser diode
leakage region
light-emitting diode
luminous efficacy
luminous intensity
negative resistance
optocoupler
optoelectronics
photodiode
PIN diode
preregulator
Schottky diode
seven-segment display
step-recovery diode
temperature coefficient
tunnel diode
varactor
varistor
zener diode
zener effect
zener regulator
zener resistance

5-1 The Zener Diode

Small-signal and rectifier diodes are never intentionally operated in the breakdown region because this may damage them. A **zener diode** is different; it is a silicon diode that the manufacturer has optimized for operation in the breakdown region. The zener diode is the backbone of voltage regulators, circuits that hold the load voltage almost constant despite large changes in line voltage and load resistance.

I-V Graph

Figure 5-1*a* shows the schematic symbol of a zener diode; Fig. 5-1*b* is an alternative symbol. In either symbol, the lines resemble a *z*, which stands for "zener." By varying the doping level of silicon diodes, a manufacturer can produce zener diodes with breakdown voltages from about 2 to over 1000 V. These diodes can operate in any of three regions: forward, leakage, and breakdown.

Figure 5-1*c* shows the *I-V* graph of a zener diode. In the forward region, it starts conducting around 0.7 V, just like an ordinary silicon diode. In the **leakage region** (between zero and breakdown), it has only a small reverse current. In a zener diode, the breakdown has a very sharp knee, followed by an almost vertical increase in current. Note that the voltage is almost constant, approximately equal to V_Z over most of the breakdown region. Data sheets usually specify the value of V_Z at a particular test current I_{ZT}.

Figure 5-1*c* also shows the maximum reverse current I_{ZM}. As long as the reverse current is less than I_{ZM}, the diode is operating within its safe range. If the current is greater than I_{ZM}, the diode will be destroyed. To prevent excessive reverse current, a *current-limiting resistor* must be used (discussed later).

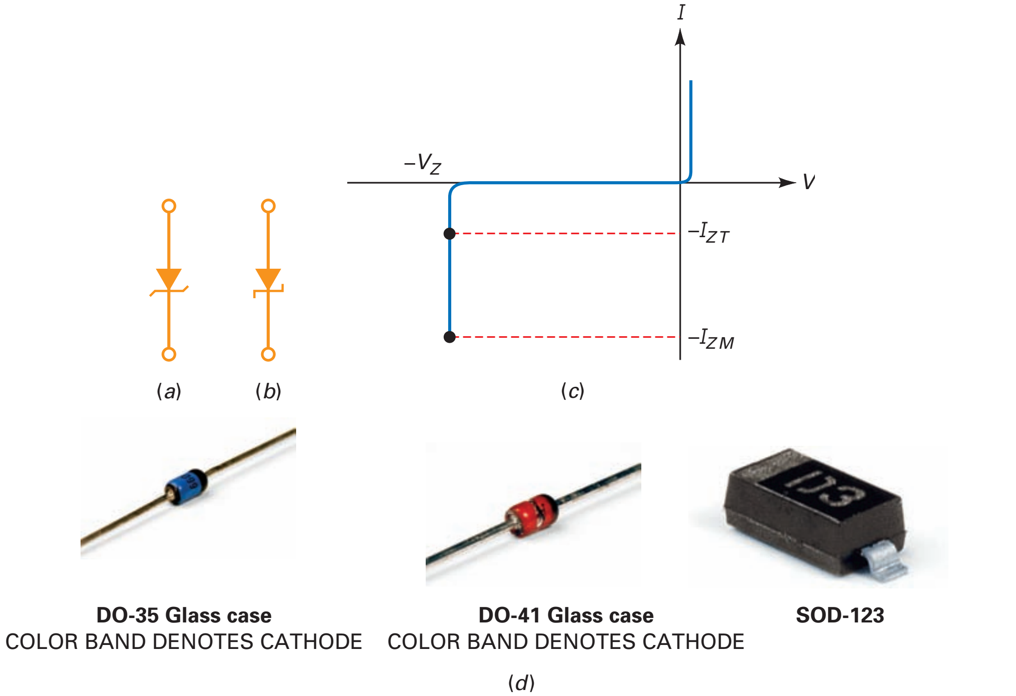
GOOD TO KNOW

As with conventional diodes, the manufacturer places a band on the cathode end of the zener diode for terminal identification.

Zener Resistance

In the third approximation of a silicon diode, the forward voltage across a diode equals the knee voltage plus the additional voltage across the bulk resistance.

Figure 5-1 Zener diode. (*a*) Schematic symbol; (*b*) alternative symbol; (*c*) graph of current versus voltage; (*d*) typical zener diodes.



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Similarly, in the breakdown region, the reverse voltage across a diode equals the breakdown voltage plus the additional voltage across the bulk resistance. In the reverse region, the bulk resistance is referred to as the **zener resistance**. This resistance equals the inverse of the slope in the breakdown region. In other words, the more vertical the breakdown region, the smaller the zener resistance.

In Fig. 5-1*c*, the zener resistance means that an increase in reverse current produces a slight increase in reverse voltage. The increase in voltage is very small, typically only a few tenths of a volt. This slight increase may be important in design work, but not in troubleshooting and preliminary analysis. Unless otherwise indicated, our discussions will ignore the zener resistance. Figure 5-1*d* shows typical zener diodes.

Zener Regulator

A zener diode is sometimes called a *voltage-regulator diode* because it maintains a constant output voltage even though the current through it changes. For normal operation, you have to reverse-bias the zener diode, as shown in Fig. 5-2*a*. Furthermore, to get breakdown operation, the source voltage V_S must be greater than the zener breakdown voltage V_Z. A series resistor R_S is always used to limit the zener current to less than its maximum current rating. Otherwise, the zener diode will burn out, like any device with too much power dissipation.

Figure 5-2*b* shows an alternative way to draw the circuit with grounds. Whenever a circuit has grounds, you can measure voltages with respect to ground.

For instance, suppose you want to know the voltage across the series resistor of Fig. 5-2*b*. Here is the one way to find it when you have a built-up circuit. First, measure the voltage from the left end of R_S to ground. Second, measure the voltage from the right end of R_S to ground. Third, subtract the two voltages to get the voltage across R_S. If you have a floating VOM or DMM, you can connect directly across the series resistor.

Figure 5-2*c* shows the output of a power supply connected to a series resistor and a zener diode. This circuit is used when you want a dc output voltage that is less than the output of the power supply. A circuit like this is called a *zener voltage regulator,* or simply a **zener regulator.**

Ohm's Law Again

In Fig. 5-2, the voltage across the series or current-limiting resistor equals the difference between the source voltage and the zener voltage. Therefore, the current through the resistor is:

$$I_S = \frac{V_S - V_Z}{R_S} \tag{5-1}$$

Figure 5-2 Zener regulator. (*a*) Basic circuit; (*b*) same circuit with grounds; (*c*) power supply drives regulator.

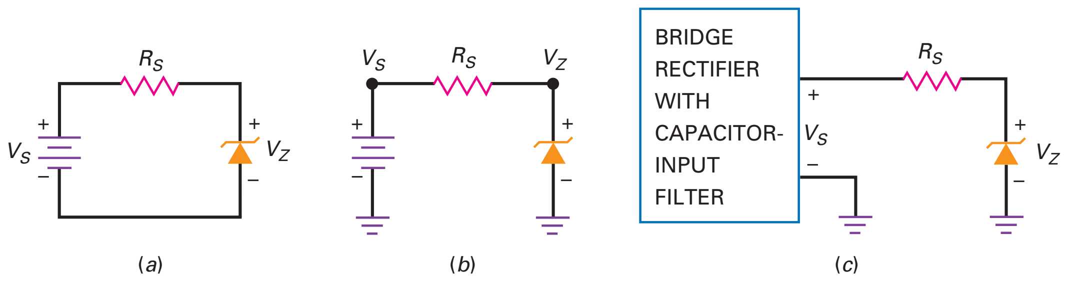
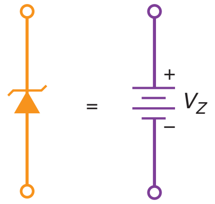


Figure 5-3 Ideal approximation of a zener diode.



Once you have the value of series current, you also have the value of zener current. This is because Fig. 5-2 is a series circuit. Note that I_S must be less than I_{ZM}.

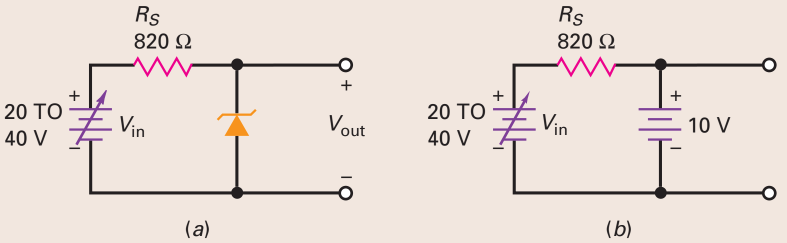
Ideal Zener Diode

For troubleshooting and preliminary analysis, we can approximate the breakdown region as vertical. Therefore, the voltage is constant even though the current changes, which is equivalent to ignoring the zener resistance. Figure 5-3 shows the ideal approximation of a zener diode. This means that a zener diode operating in the breakdown region ideally acts like a battery. In a circuit, it means that you can mentally replace a zener diode by a voltage source of V_Z, provided the zener diode is operating in the breakdown region.

Example 5-1

Suppose the zener diode of Fig. 5-4*a* has a breakdown voltage of 10 V. What are the minimum and maximum zener currents?

Figure 5-4 Example.



SOLUTION The applied voltage may vary from 20 to 40 V. Ideally, a zener diode acts like the battery shown in Fig. 5-4*b*. Therefore, the output voltage is 10 V for any source voltage between 20 and 40 V.

The minimum current occurs when the source voltage is minimum. Visualize 20 V on the left end of the resistor and 10 V on the right end. Then you can see that the voltage across the resistor is 20 V − 10 V, or 10 V. The rest is Ohm's law:

$$I_S = \frac{10\text{ V}}{820\ \Omega} = 12.2\text{ mA}$$

The maximum current occurs when the source voltage is 40 V. In this case, the voltage across the resistor is 30 V, which gives a current of

$$I_S = \frac{30\text{ V}}{820\ \Omega} = 36.6\text{ mA}$$

In a voltage regulator like Fig. 5-4*a*, the output voltage is held constant at 10 V, despite the change in source voltage from 20 to 40 V. The larger source voltage produces more zener current, but the output voltage holds rock-solid at 10 V. (If the zener resistance is included, the output voltage increases slightly when the source voltage increases.)

PRACTICE PROBLEM 5-1 Using Fig. 5-4, what is the zener current I_S if V_{in} = 30 V?

5-2 The Loaded Zener Regulator

Figure 5-5*a* shows a *loaded* zener regulator, and Fig. 5-5*b* shows the same circuit with grounds. The zener diode operates in the breakdown region and holds the load voltage constant. Even if the source voltage changes or the load resistance varies, the load voltage will remain fixed and equal to the zener voltage.

Breakdown Operation

How can you tell whether the zener diode of Fig. 5-5 is operating in the breakdown region? Because of the voltage divider, the Thevenin voltage facing the diode is:

$$V_{TH} = \frac{R_L}{R_S + R_L} V_S \tag{5-2}$$

This is the voltage that exists when the zener diode is disconnected from the circuit. This Thevenin voltage has to be greater than the zener voltage; otherwise, breakdown cannot occur.

Series Current

Unless otherwise indicated, in all subsequent discussions we assume that the zener diode is operating in the breakdown region. In Fig. 5-5, the current through the series resistor is given by:

$$I_S = \frac{V_S - V_Z}{R_S} \tag{5-3}$$

This is Ohm's law applied to the current-limiting resistor. It is the same whether or not there is a load resistor. In other words, if you disconnect the load resistor, the current through the series resistor still equals the voltage across the resistor divided by the resistance.

Load Current

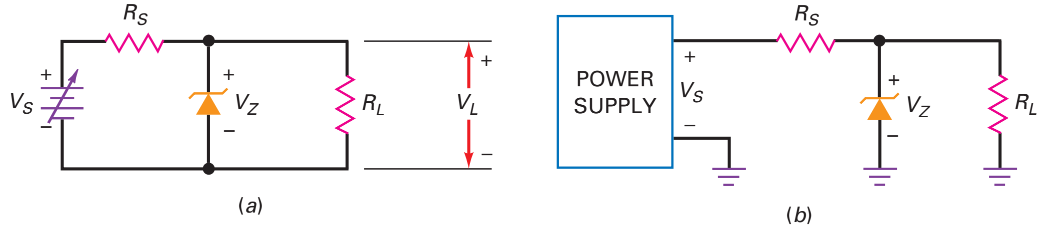
Ideally, the load voltage equals the zener voltage because the load resistor is in parallel with the zener diode. As an equation:

$$V_L = V_Z \tag{5-4}$$

This allows us to use Ohm's law to calculate the load current:

$$I_L = \frac{V_L}{R_L} \tag{5-5}$$

Figure 5-5 Loaded zener regulator. (*a*) Basic circuit; (*b*) practical circuit.



Zener Current

With Kirchhoff's current law:

$$I_S = I_Z + I_L$$

The zener diode and the load resistor are in parallel. The sum of their currents has to equal the total current, which is the same as the current through the series resistor.

We can rearrange the foregoing equation to get this important formula:

$$\boldsymbol{I_Z = I_S - I_L} \quad \textbf{(5-6)}$$

This tells you that the zener current no longer equals the series current, as it does in an unloaded zener regulator. Because of the load resistor, the zener current now equals the series current minus the load current.

Summary Table 5-1 summarizes the steps in the analysis of a loaded zener regulator. You start with the series current, followed by the load voltage and load current, and finally the zener current.

Zener Effect

When the breakdown voltage is greater than 6 V, the cause of the breakdown is the avalanche effect, discussed in Chap. 2. The basic idea is that minority carriers are accelerated to high enough speeds to dislodge other minority carriers, producing a chain or avalanche effect that results in a large reverse current.

The zener effect is different. When a diode is heavily doped, the depletion layer becomes very narrow. Because of this, the electric field across the depletion layer (voltage divided by distance) is very intense. When the field strength reaches approximately 300,000 V/cm, the field is intense enough to pull electrons out of their valence orbits. The creation of free electrons in this way is called the **zener effect** (also known as *high-field emission*). This is distinctly different from the avalanche effect, which depends on high-speed minority carriers dislodging valence electrons.

When the breakdown voltage is less than 4 V, only the zener effect occurs. When the breakdown voltage is greater than 6 V, only the avalanche effect occurs. When the breakdown voltage is between 4 and 6 V, both effects are present.

The zener effect was discovered before the avalanche effect, so all diodes used in the breakdown region came to be known as zener diodes. Although you may occasionally hear the term *avalanche diode,* the name *zener diode* is in general use for all breakdown diodes.

GOOD TO KNOW

For zener voltages between approximately 3 and 8 V, the temperature coefficient is also strongly affected by the reverse current in the diode. The temperature coefficient becomes more positive as current increases.

Summary Table 5-1 Analyzing a Loaded Zener Regulator

	Process	Comment
Step 1	Calculate the series current, Eq. (5-3)	Apply Ohm's law to R_S
Step 2	Calculate the load voltage, Eq. (5-4)	Load voltage equals diode voltage
Step 3	Calculate the load current, Eq. (5-5)	Apply Ohm's law to R_L
Step 4	Calculate the zener current, Eq. (5-6)	Apply the current law to the diode

GOOD TO KNOW

In applications requiring a highly stable reference voltage, a zener diode is connected in series with one or more semiconductor diodes whose voltage drops change with temperature in the opposite direction that V_Z changes. The result is that V_Z remains *very* stable even though the temperature may vary over a wide range.

Temperature Coefficients

When the ambient temperature changes, the zener voltage will change slightly. On data sheets, the effect of temperature is listed under the **temperature coefficient,** which is defined as the change in breakdown voltage per degree of increase. The temperature coefficient is negative for breakdown voltages less than 4 V (zener effect). For instance, a zener diode with a breakdown voltage of 3.9 V may have a temperature coefficient of −1.4 mV/°C. If temperature increases by 1°, the breakdown voltage decreases by 1.4 mV.

On the other hand, the temperature coefficient is positive for breakdown voltages greater than 6 V (avalanche effect). For instance, a zener diode with a breakdown voltage of 6.2 V may have a temperature coefficient of 2 mV/°C. If the temperature increases by 1°, the breakdown voltage increases by 2 mV.

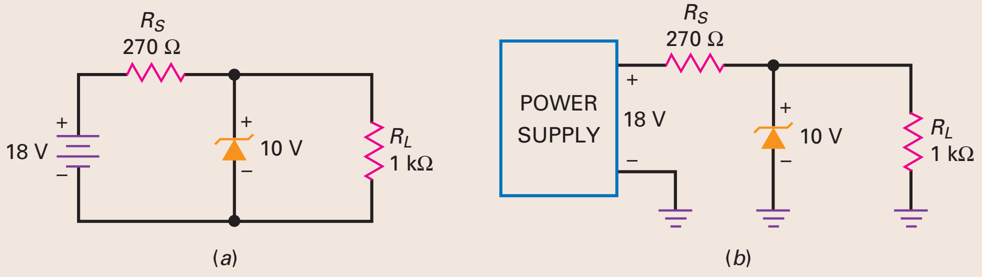
Between 4 and 6 V, the temperature coefficient changes from negative to positive. In other words, there are zener diodes with breakdown voltages between 4 and 6 V in which the *temperature coefficient equals zero*. This is important in some applications when a solid zener voltage is needed over a large temperature range.

Example 5-2

Multisim

Is the zener diode of Fig. 5-6*a* operating in the breakdown region?

Figure 5-6 Example.



SOLUTION With Eq. (5-2):

$$V_{TH} = \frac{1\text{ k}\Omega}{270\ \Omega + 1\text{ k}\Omega}(18\ \text{V}) = 14.2\ \text{V}$$

Since this Thevenin voltage is greater than the zener voltage, the zener diode is operating in the breakdown region.

Example 5-3

Multisim

What does the zener current equal in Fig. 5-6*b*?

SOLUTION You are given the voltage on both ends of the series resistor. Subtract the voltages, and you can see that 8 V is across the series resistor. Then Ohm's law gives:

$$I_S = \frac{8\text{ V}}{270\ \Omega} = 29.6\text{ mA}$$

Since the load voltage is 10 V, the load current is:

$$I_L = \frac{10\text{ V}}{1\text{ k}\Omega} = 10\text{ mA}$$

The zener current is the difference between the two currents:

$$I_Z = 29.6\text{ mA} - 10\text{ mA} = 19.6\text{ mA}$$

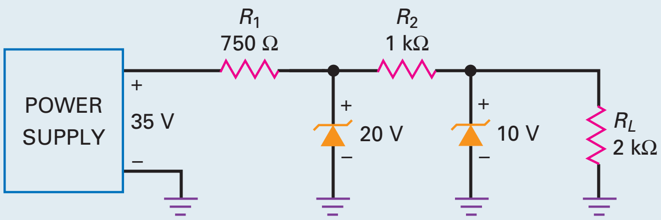
PRACTICE PROBLEM 5-3 Using Fig. 5-6*b*, change the power supply to 15 V and calculate I_S, I_L, and I_Z.

Application Example 5-4

Multisim

What does the circuit of Fig. 5-7 do?

Figure 5-7 Preregulator.



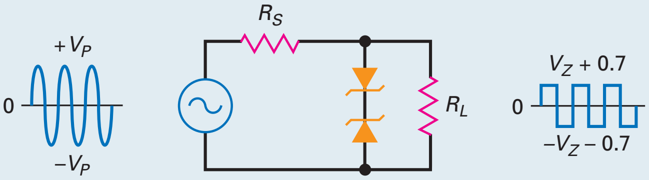
SOLUTION This is an example of a **preregulator** (the first zener diode) driving a zener regulator (the second zener diode). First, notice that the preregulator has an output voltage of 20 V. This is the input to the second zener regulator, whose output is 10 V. The basic idea is to provide the second regulator with a well-regulated input so that the final output is extremely well regulated.

Application Example 5-5

Multisim

What does the circuit of Fig. 5-8 do?

Figure 5-8 Zener diodes used for waveshaping.



SOLUTION In most applications, zener diodes are used in voltage regulators where they remain in the breakdown region. But there are exceptions. Sometimes, zener diodes are used in waveshaping circuits like Fig. 5-8.

Notice the back-to-back connection of two zener diodes. On the positive half-cycle, the upper diode conducts and the lower diode breaks down. Therefore, the output is clipped as shown. The clipping level equals the zener voltage (broken-down diode) plus 0.7 V (forward-biased diode).

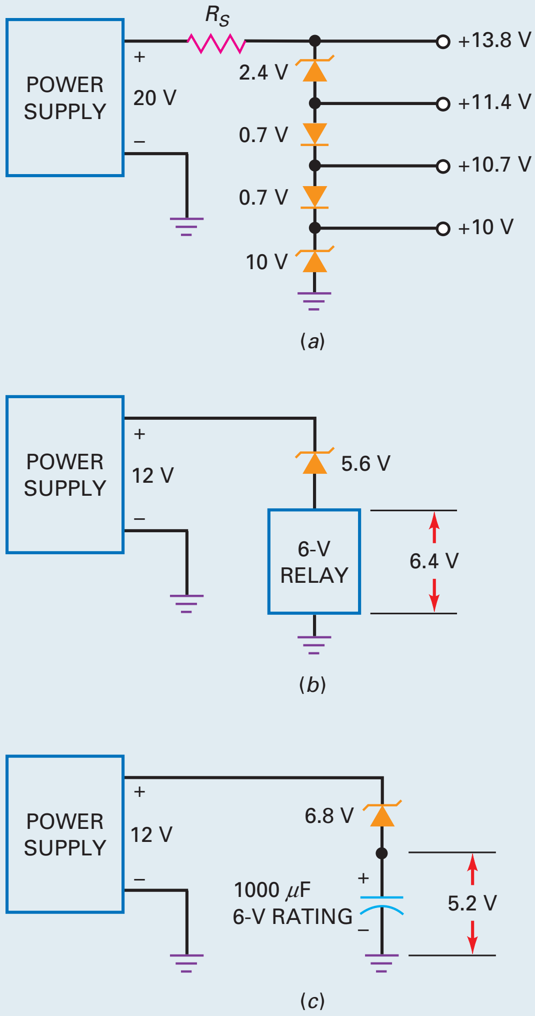
On the negative half-cycle, the action is reversed. The lower diode conducts, and the upper diode breaks down. In this way, the output is almost a square wave. The larger the input sine wave, the better looking the output square wave.

PRACTICE PROBLEM 5-5 In Fig. 5-8, the V_Z for each diode is 3.3 V. What would the voltage across R_L be?

Application Example 5-6

Briefly describe the circuit action for each of the circuits in Fig. 5-9.

Figure 5-9 Zener applications. (*a*) Producing nonstandard output voltages; (*b*) using a 6-V relay in a 12-V system; (*c*) using a 6-V capacitor in a 12-V system.



SOLUTION Figure 5-9*a* shows how zener diodes and ordinary silicon diodes can produce several dc output voltages, given a 20-V power supply. The bottom diode produces an output of 10 V. Each silicon diode is forward biased, producing outputs of 10.7 V and 11.4 V, as shown. The top diode has a breakdown voltage of 2.4 V, giving an output of 13.8 V. With other combinations of zener and silicon diodes, a circuit like this can produce different dc output voltages.

If you try to connect a 6-V relay to a 12-V system, you will probably damage the relay. It is necessary to drop some of the voltage. Figure 5-9*b* shows one way to do this. By connecting a 5.6-V zener diode in series with the relay, only 6.4 V appears across the relay, which is usually within the tolerance of the relay's voltage rating.

Large electrolytic capacitors often have small voltage ratings. For instance, an electrolytic capacitor of 1000 μF may have a voltage rating of only 6 V. This means that the maximum voltage across the capacitor should be less than 6 V. Figure 5-9*c* shows a workaround solution in which a 6-V electrolytic capacitor is used with a 12-V power supply. Again, the idea is to use a zener diode to drop some of the voltage. In this case, the zener diode drops 6.8 V, leaving only 5.2 V across the capacitor. This way, the electrolytic capacitor can filter the power supply and still remain with its voltage rating.

5-3 Second Approximation of a Zener Diode

GOOD TO KNOW

Zener diodes with breakdown voltages near 7 V have the smallest zener impedance.

Figure 5-10*a* shows the second approximation of a zener diode. A zener resistance is in series with an ideal battery. The total voltage across the zener diode equals the breakdown voltage plus the voltage drop across the zener resistance. Since R_Z is relatively small in a zener diode, it has only a minor effect on the total voltage across the zener diode.

Effect on Load Voltage

How can we calculate the effect of the zener resistance on the load voltage? Figure 5-10*b* shows a power supply driving a loaded zener regulator. Ideally, the load voltage equals the breakdown voltage V_Z. But in the second approximation, we include the zener resistance as shown in Fig. 5-10*c*. The additional voltage drop across R_Z will slightly increase the load voltage.

Since the zener current flows through the zener resistance in Fig. 5-10*c*, the load voltage is given by:

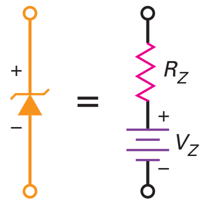
$$V_L = V_Z + I_Z R_Z$$

As you can see, the change in the load voltage from the ideal case is:

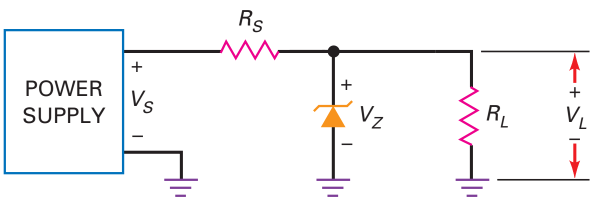
$$\Delta V_L = I_Z R_Z \tag{5-7}$$

Usually, R_Z is small, so the voltage change is small, typically in tenths of a volt. For instance, if I_Z = 10 mA and R_Z = 10 Ω, then ΔV_L = 0.1 V.

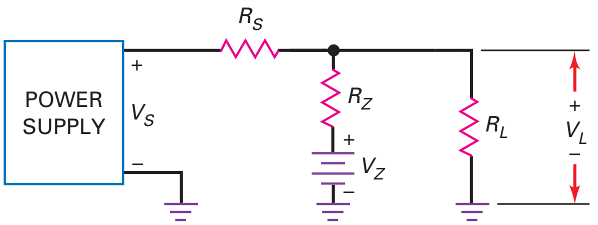
Figure 5-10 Second approximation of a zener diode. (*a*) Equivalent circuit; (*b*) power supply drives zener regulator; (*c*) zener resistance included in analysis.



(*a*)

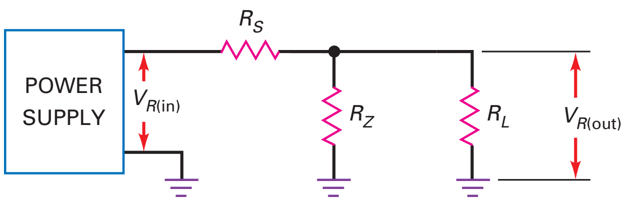


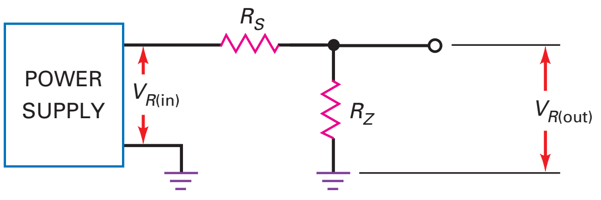
(*b*)



(*c*)

Figure 5-11 Zener regulator reduces ripple. (a) Complete ac-equivalent circuit; (b) simplified ac-equivalent circuit.





Effect on Ripple

As far as ripple is concerned, we can use the equivalent circuit shown in Fig. 5-11*a*. In other words, the only components that affect the ripple are the three resistances shown. We can simplify this even further. In a typical design, R_Z is much smaller than R_L. Therefore, the only two components that have a significant effect on ripple are the series resistance and zener resistance shown in Fig. 5-11*b*.

Since Fig. 5-11*b* is a voltage divider, we can write the following equation for the output ripple:

$$V_{R(\text{out})} = \frac{R_Z}{R_S + R_Z} V_{R(\text{in})}$$

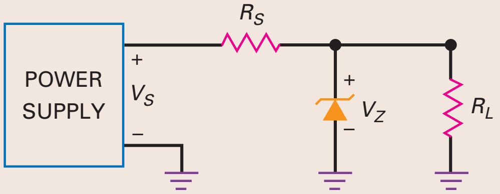
Ripple calculations are not critical; that is, they don't have to be exact. Since R_S is always much greater than R_Z in a typical design, we can use this approximation for all troubleshooting and preliminary analysis:

$$\mathbf{V_{R(out)} \approx \frac{R_Z}{R_S} V_{R(in)}} \qquad \textbf{(5-8)}$$

Example 5-7

The zener diode of Fig. 5-12 has a breakdown voltage of 10 V and a zener resistance of 8.5 Ω. Use the second approximation to calculate the load voltage when the zener current is 20 mA.

Figure 5-12 Loaded zener regulator.



SOLUTION The change in load voltage equals the zener current times the zener resistance:

$$\Delta V_L = I_Z R_Z = (20 \text{ mA})(8.5\ \Omega) = 0.17 \text{ V}$$

To a second approximation, the load voltage is:

$$V_L = 10 \text{ V} + 0.17 \text{ V} = 10.17 \text{ V}$$

PRACTICE PROBLEM 5-7 Use the second approximation to calculate the load voltage of Fig. 5-12 when $I_Z = 12$ mA.

Example 5-8

In Fig. 5-12, $R_S = 270\ \Omega$, $R_Z = 8.5\ \Omega$, and $V_{R(\text{in})} = 2$ V. What is the approximate ripple voltage across the load?

SOLUTION The load ripple approximately equals the ratio of R_Z to R_S multiplied by the input ripple:

$$V_{R(\text{out})} \approx \frac{8.5\ \Omega}{270\ \Omega} 2 \text{ V} = 63 \text{ mV}$$

PRACTICE PROBLEM 5-8 Using Fig. 5-12, what is the approximate load ripple voltage if $V_{R\,(\text{in})} = 3$ V?

Application Example 5-9

The zener regulator of Fig. 5-13 has $V_Z = 10$ V, $R_S = 270\ \Omega$, and $R_Z = 8.5\ \Omega$, the same values used in Examples 5-7 and 5-8. Describe the measurements being made in this Multisim circuit analysis.

Multisim Figure 513 Multisim analysis of ripple in zener regulator.

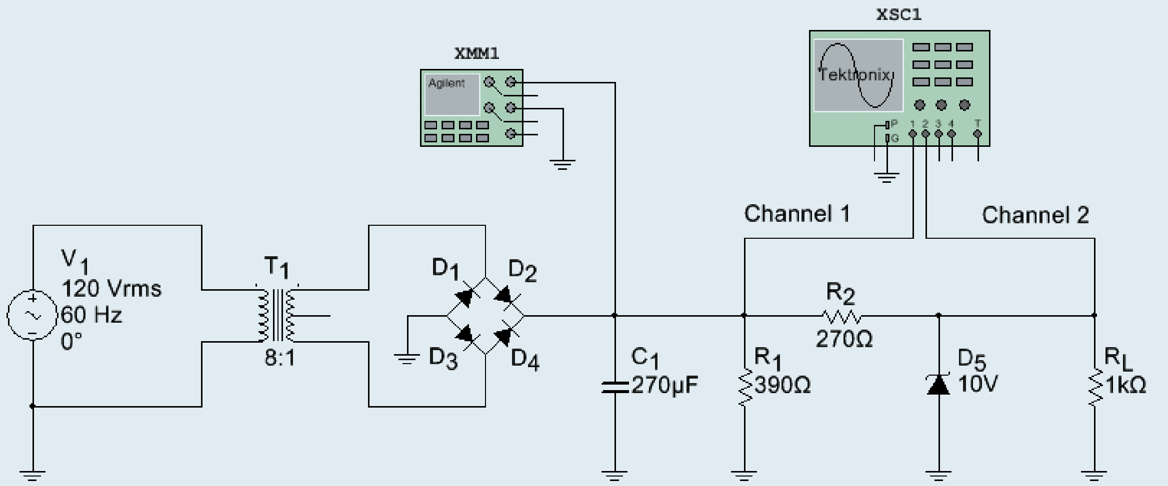
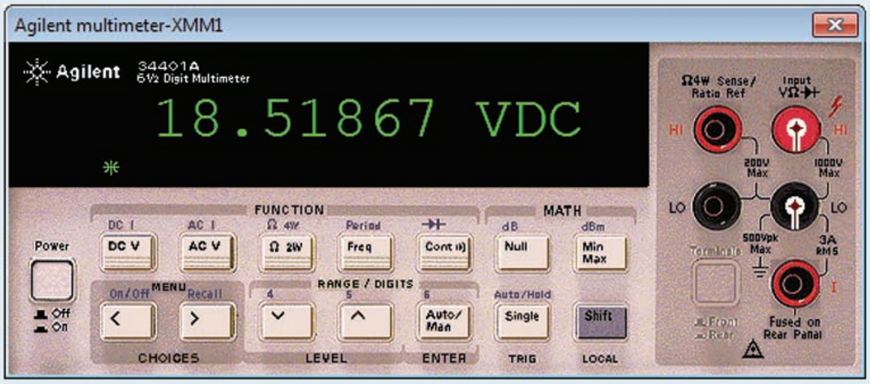
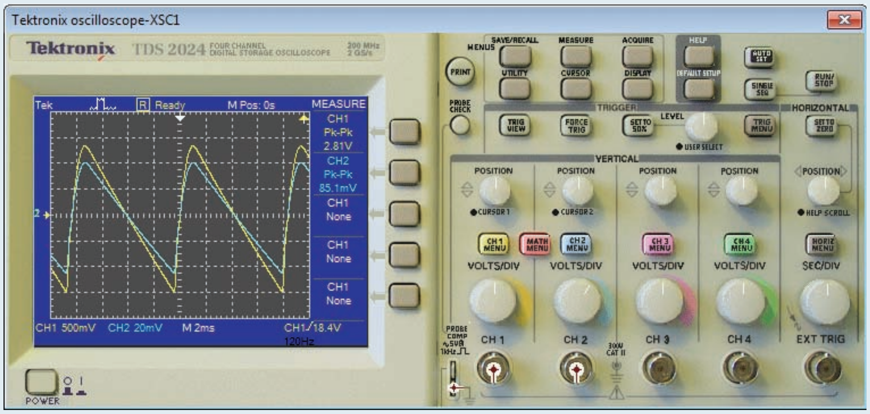


Figure 5-13 (continued)





SOLUTION If we calculate the voltages in Fig. 5-13 using the methods discussed earlier, we will get the following results. With an 8 : 1 transformer, the peak secondary voltage is 21.2 V. Subtract two diode drops, and you get a peak of 19.8 V across the filter capacitor. The current through the 390-Ω resistor is 51 mA, and the current through R_S is 36 mA. The capacitor has to supply the sum of these two currents, which is 87 mA. With Eq. (4-10), this current results in a ripple across the capacitor of approximately 2.7 $V_{p\text{-}p}$. With this, we can calculate the ripple out of the zener regulator, which is approximately 85 $mV_{p\text{-}p}$.

Since the ripple is large, the voltage across the capacitor swings from a high of 19.8 V to a low of 17.1 V. If you average these two values, you get 18.5 V as the approximate dc voltage across the filter capacitor. This lower dc voltage means that the input and output ripple calculated earlier will also be lower. As discussed in the preceding chapter, calculations like these are only estimates because the exact analysis has to include higher-order effects.

Now, let us look at the Multisim measurements, which are almost exact answers. The multimeter reads 18.52 V, very close to the estimated value of 18.5 V. Channel 1 of the oscilloscope shows the ripple across the capacitor. It is approximately 2.8 $V_{p\text{-}p}$, very close to the estimated 2.7 $V_{p\text{-}p}$. And finally, the output ripple of the zener regulator is approximately 85 $mV_{p\text{-}p}$ (channel 2).

5-4 Zener Drop-Out Point

For a zener regulator to hold the output voltage constant, the zener diode must remain in the breakdown region under all operating conditions. This is equivalent to saying that there must be zener current for all source voltages and load currents.

Worst-Case Conditions

Figure 5-14*a* shows a zener regulator. It has the following currents:

$$I_S = \frac{V_S - V_Z}{R_S} = \frac{20\text{ V} - 10\text{ V}}{200\ \Omega} = 50\text{ mA}$$

$$I_L = \frac{V_L}{R_L} = \frac{10\text{ V}}{1\text{ k}\Omega} = 10\text{ mA}$$

and

$$I_Z = I_S - I_L = 50\text{ mA} - 10\text{ mA} = 40\text{ mA}$$

Now, consider what happens when the source voltage decreases from 20 to 12 V. In the foregoing calculations, you can see that I_S will decrease, I_L will remain the same, and I_Z will decrease. When V_S equals 12 V, I_S will equal 10 mA, and $I_Z = 0$. At this low source voltage, the zener diode is about to come out of the breakdown region. If the source decreases any further, regulation will be lost. In other words, the load voltage will become less than 10 V. Therefore, a low source voltage can cause the zener circuit to fail to regulate.

Another way to get a loss of regulation is by having too much load current. In Fig. 5-14*a*, consider what happens when the load resistance decreases from 1 kΩ to 200 Ω. When the load resistance is 200 Ω, the load current increases to 50 mA, which is equal to the current through R_S, and the zener current decreases to zero. Again, the zener diode is about to come out of breakdown. Therefore, a zener circuit will fail to regulate if the load resistance is too low.

Finally, consider what happens when R_S increases from 200 Ω to 1 kΩ. In this case, the series current decreases from 50 to 10 mA. Therefore, a high series resistance can bring the circuit out of regulation.

Figure 5-14 Zener regulator. (*a*) Normal operation; (*b*) worst-case conditions at drop-out point.

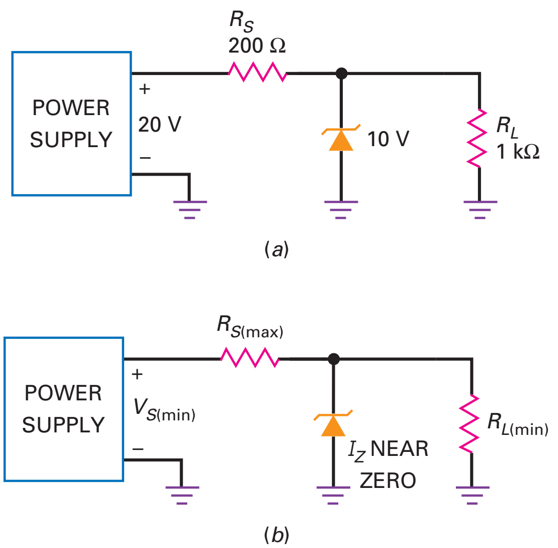


Figure 5-14*b* summarizes the foregoing ideas by showing the worst-case conditions. When the zener current is near zero, the zener regulation is approaching a drop-out or failure condition. By analyzing the circuit for these worst-case conditions, it is possible to derive the following equation:

$$R_{S(\max)} = \left(\frac{V_{S(\min)}}{V_Z} - 1\right) R_{L(\min)} \tag{5-9}$$

An alternative form of this equation is also useful:

$$R_{S(\max)} = \frac{V_{S(\min)} - V_Z}{I_{L(\max)}} \tag{5-10}$$

These two equations are useful because you can check a zener regulator to see whether it will fail under any operating conditions.

Example 5-10

A zener regulator has an input voltage that may vary from 22 to 30 V. If the regulated output voltage is 12 V and the load resistance varies from 140 Ω to 10 kΩ, what is the maximum allowable series resistance?

SOLUTION Use Eq. (5-9) to calculate the maximum series resistance as follows:

$$R_{S(\max)} = \left(\frac{22\text{ V}}{12\text{ V}} - 1\right)140\ \Omega = 117\ \Omega$$

As long as the series resistance is less than 117 Ω, the zener regulator will work properly under all operating conditions.

PRACTICE PROBLEM 5-10 Using Example 5-10, what is the maximum allowable series resistance if the regulated output voltage is 15 V?

Example 5-11

A zener regulator has an input voltage ranging from 15 to 20 V and a load current ranging from 5 to 20 mA. If the zener voltage is 6.8 V, what is the maximum allowable series resistance?

SOLUTION Use Eq. (5-10) to calculate the maximum series resistance as follows:

$$R_S(\max) = \frac{15\text{ V} - 6.8\text{ V}}{20\text{ mA}} = 410\ \Omega$$

If the series resistance is less than 410 Ω, the zener regulator will work properly under all conditions.

PRACTICE PROBLEM 5-11 Repeat Example 5-11 using a zener voltage of 5.1 V.

5-5 Reading a Data Sheet

Figure 5-15 shows the data sheets for the 1N5221B and 1N4728A series of zener diodes. Refer to these data sheets during the following discussion. Again, most of the information on a data sheet is for designers, but there are a few items that even troubleshooters and testers will want to know about.

Maximum Power

The power dissipation of a zener diode equals the product of its voltage and current:

$$P_Z = V_Z I_Z \tag{5-11}$$

For instance, if $V_Z = 12$ V and $I_Z = 10$ mA, then

$$P_Z = (12\text{ V})(10\text{ mA}) = 120\text{ mW}$$

As long as P_Z is less than the power rating, the zener diode can operate in the breakdown region without being destroyed. Commercially available zener diodes have power ratings from ¼ to more than 50 W.

For example, the data sheet for the 1N5221B series lists a maximum power rating of 500 mW. A safe design includes a safety factor to keep the power dissipation well below this 500-mW maximum. As mentioned elsewhere, safety factors of 2 or more are used for conservative designs.

Maximum Current

Data sheets often include the *maximum current* I_{ZM} a zener diode can handle without exceeding its power rating. If this value is not listed, the maximum current can be found as follows:

$$I_{ZM} = \frac{P_{ZM}}{V_Z} \tag{5-12}$$

where I_{ZM} = maximum rated zener current
P_{ZM} = power rating
V_Z = zener voltage

For example, the 1N4742A has a zener voltage of 12 V and a 1 W power rating. Therefore, it has a maximum current rating of

$$I_{ZM} = \frac{1\text{ W}}{12\text{ V}} = 83.3\text{ mA}$$

If you satisfy the current rating, you automatically satisfy the power rating. For instance, if you keep the maximum zener current less than 83.3 mA, you are also keeping the maximum power dissipation to less than 1 W. If you throw in the safety factor of 2, you don't have to worry about a marginal design blowing the diode. The I_{ZM} value, either listed or calculated, is a continuous current rating. Nonrepetitive peak reverse current values are often given, which include notes on how this device was tested.

Tolerance

Most zener diodes will have a suffix A, B, C, or D to identify the zener voltage tolerance. Because these suffix markings are not always consistent, be sure to identify any special notes included on the zener's data sheet that indicate that specific tolerance. For instance, the data sheet for the 1N4728A series shows its tolerance to equal ±5 percent, while the 1N5221B series also has a tolerance of ±5 percent. A suffix of C generally indicates ±2 percent, D ±1 percent, and no suffix ±20 percent.

Figure 5-15(*a*) Zener "Partial" data sheets. (Copyright of Fairchild Semiconductor. Used by Permission.)

FAIRCHILD SEMICONDUCTOR®

Tolerance = 5%

July 2013

1N5221B - 1N5263B Zener Diodes

DO-35 Glass case

COLOR BAND DENOTES CATHODE

Absolute Maximum Ratings

Symbol	Parameter	Value	Units
P_D	Power Dissipation	500	mW
	Derate above 50°C	4.0	mW°C
T_{STG}	Storage Temperature Range	-65 to +200	°C
T_J	Operating Junction Temperature Range	-65 to +200	°C
	Lead Temperature (1/16 inch from case for 10 s)	+230	°C

Electrical Characteristics

Values are at T_A = 25°C unless otherwise noted .

Device	V_Z (V) @ I_Z (2)			Z_Z (Ω) @ I_Z (mA)		Z_{ZK} (Ω) @ I_{ZK}(mA)		I_R (μA) @ V_R (V)		T_C (%/°C)
	Min.	Typ.	Max.							
1N5221B	2.28	2.4	2.52	30	20	1,200	0.25	100	1.0	-0.085
1N5222B	2.375	2.5	2.625	30	20	1,250	0.25	100	1.0	-0.085
1N5223B	2.565	2.7	2.835	30	20	1,300	0.25	75	1.0	-0.080
1N5224B	2.66	2.8	2.94	30	20	1,400	0.25	75	1.0	-0.080
1N5225B	2.85	3	3.15	29	20	1,600	0.25	50	1.0	-0.075
1N5226B	3.135	3.3	3.465	28	20	1,600	0.25	25	1.0	-0.07
1N5227B	3.42	3.6	3.78	24	20	1,700	0.25	15	1.0	-0.065
1N5228B	3.705	3.9	4.095	23	20	1,900	0.25	10	1.0	-0.06
1N5229B	4.085	4.3	4.515	22	20	2,000	0.25	5.0	1.0	+/-0.055
1N5230B	4.465	4.7	4.935	19	20	1,900	0.25	2.0	1.0	+/-0.03
1N5231B	4.845	5.1	5.355	17	20	1,600	0.25	5.0	2.0	+/-0.03
1N5232B	5.32	5.6	5.88	11	20	1,600	0.25	5.0	3.0	0.038
1N5233B	5.7	6	6.3	7.0	20	1,600	0.25	5.0	3.5	0.038
1N5234B	5.89	6.2	6.51	7.0	20	1,000	0.25	5.0	4.0	0.045
1N5235B	6.46	6.8	7.14	5.0	20	750	0.25	3.0	5.0	0.05
1N5236B	7.125	7.5	7.875	6.0	20	500	0.25	3.0	6.0	0.058
1N5237B	7.79	8.2	8.61	8.0	20	500	0.25	3.0	6.5	0.062
1N5238B	8.265	8.7	9.135	8.0	20	600	0.25	3.0	6.5	0.065
1N5239B	8.645	9.1	9.555	10	20	600	0.25	3.0	7.0	0.068
1N5240B	9.5	10	10.5	17	20	600	0.25	3.0	8.0	0.075
1N5241B	10.45	11	11.55	22	20	600	0.25	2.0	8.4	0.076
1N5242B	11.4	12	12.6	30	20	600	0.25	1.0	9.1	0.077
1N5243B	12.35	13	13.65	13	9.5	600	0.25	0.5	9.9	0.079
1N5244B	13.3	14	14.7	15	9.0	600	0.25	0.1	10	0.080
1N5245B	14.25	15	15.75	16	8.5	600	0.25	0.1	11	0.082
1N5246B	15.2	16	16.8	17	7.8	600	0.25	0.1	12	0.083
1N5247B	16.15	17	17.85	19	7.4	600	0.25	0.1	13	0.084
1N5248B	17.1	18	18.9	21	7.0	600	0.25	0.1	14	0.085
1N5249B	18.05	19	19.95	23	6.6	600	0.25	0.1	14	0.085
1N5250B	19	20	21	25	6.2	600	0.25	0.1	15	0.086
V_F Forward Voltage = 1.2V Max. @ I_F = 200mA										

Note:

1. These ratings are limiting values above which the serviceability of any semiconductor device may be impaired. Non-recurrent square wave Pulse Width = 8.3 ms, T_A = 50°C
2. Zener Voltage (V_Z)
   The zener voltage is measured with the device junction in the thermal equilibrium at the lead temperature (T_L) at 30°C ± 1°C and 3/8" lead length.

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April 2009

1N4728A - 1N4758A
Zener Diodes

1N4728A - 1N4758A — Zener Diodes

Tolerance = 5%

DO-41 Glass case
COLOR BAND DENOTES CATHODE

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

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

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

Electrical Characteristics T_a = 25°C unless otherwise noted

Device	V_Z (V) @ I_Z (Note 1)			Test Current	Max. Zener Impedance			Leakage Current		Non-Repetitive Peak Reverse Current
	Min.	Typ.	Max.	I_Z (mA)	Z_Z@I_Z (Ω)	Z_{ZK} @ I_{ZK} (Ω)	I_{ZK} (mA)	I_R (μA)	V_R (V)	I_{ZSM} (mA) (Note 2)
1N4728A	3.135	3.3	3.465	76	10	400	1	100	1	1380
1N4729A	3.42	3.6	3.78	69	10	400	1	100	1	1260
1N4730A	3.705	3.9	4.095	64	9	400	1	50	1	1190
1N4731A	4.085	4.3	4.515	58	9	400	1	10	1	1070
1N4732A	4.465	4.7	4.935	53	8	500	1	10	1	970
1N4733A	4.845	5.1	5.355	49	7	550	1	10	1	890
1N4734A	5.32	5.6	5.88	45	5	600	1	10	2	810
1N4735A	5.89	6.2	6.51	41	2	700	1	10	3	730
1N4736A	6.46	6.8	7.14	37	3.5	700	1	10	4	660
1N4737A	7.125	7.5	7.875	34	4	700	0.5	10	5	605
1N4738A	7.79	8.2	8.61	31	4.5	700	0.5	10	6	550
1N4739A	8.645	9.1	9.555	28	5	700	0.5	10	7	500
1N4740A	9.5	10	10.5	25	7	700	0.25	10	7.6	454
1N4741A	10.45	11	11.55	23	8	700	0.25	5	8.4	414
1N4742A	11.4	12	12.6	21	9	700	0.25	5	9.1	380
1N4743A	12.35	13	13.65	19	10	700	0.25	5	9.9	344
1N4744A	14.25	15	15.75	17	14	700	0.25	5	11.4	304
1N4745A	15.2	16	16.8	15.5	16	700	0.25	5	12.2	285
1N4746A	17.1	18	18.9	14	20	750	0.25	5	13.7	250
1N4747A	19	20	21	12.5	22	750	0.25	5	15.2	225
1N4748A	20.9	22	23.1	11.5	23	750	0.25	5	16.7	205
1N4749A	22.8	24	25.2	10.5	25	750	0.25	5	18.2	190
1N4750A	25.65	27	28.35	9.5	35	750	0.25	5	20.6	170
1N4751A	28.5	30	31.5	8.5	40	1000	0.25	5	22.8	150
1N4752A	31.35	33	34.65	7.5	45	1000	0.25	5	25.1	135
1N4753A	34.2	36	37.8	7	50	1000	0.25	5	27.4	125
1N4754A	37.05	39	40.95	6.5	60	1000	0.25	5	29.7	115
1N4755A	40.85	43	45.15	6	70	1500	0.25	5	32.7	110
1N4756A	44.65	47	49.35	5.5	80	1500	0.25	5	35.8	95
1N4757A	48.45	51	53.55	5	95	1500	0.25	5	38.8	90
1N4758A	53.2	56	58.8	4.5	110	2000	0.25	5	42.6	80

Notes:

1. Zener Voltage (V_Z)
   The zener voltage is measured with the device junction in the thermal equilibrium at the lead temperature (T_L) at 30°C ± 1°C and 3/8" lead length.
2. 2 Square wave Reverse Surge at 8.3 msec soak time.

1N4728A - 1N4758A Rev. H3
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Zener Resistance

The zener resistance (also called *zener impedance*) may be designated R_{ZT} or Z_{ZT}. For instance, the 1N5237B has a zener resistance of 8.0 Ω measured at a test current of 20.0 mA. As long as the zener current is beyond the knee of the curve, you can use 8.0 Ω as the approximate value of the zener resistance. But note how the zener resistance increases at the knee of the curve (1000 Ω). The point is this: Operation should be at or near the test current, if at all possible. Then you know that the zener resistance is relatively small.

The data sheet contains a lot of additional information, but it is primarily aimed at designers. If you do get involved in design work, then you have to read the data sheet carefully, including the notes that specify how quantities were measured.

Derating

The **derating factor** shown on a data sheet tells you how much you have to reduce the power rating of a device. For instance, the 1N4728A series has a power rating of 1 W for a lead temperature of 50°C. The derating factor is given as 6.67 mW/°C. This means that you have to subtract 6.67 mW for each degree above 50°C. Even though you may not be involved in design, you have to be aware of the effect of temperature. If it is known that the lead temperature will be above 50°C, the designer has to derate or reduce the power rating of the zener diode.

5-6 Troubleshooting

Figure 5-16 shows a zener regulator. When the circuit is working properly, the voltage between *A* and ground is +18 V, the voltage between *B* and ground is +10 V, and the voltage between *C* and ground is +10 V.

Unique Symptoms

Now, let's discuss what can go wrong with the circuit. When a circuit is not working as it should, a troubleshooter usually starts by measuring voltages. These voltage measurements give clues that help isolate the trouble. For instance, suppose these voltages are measured:

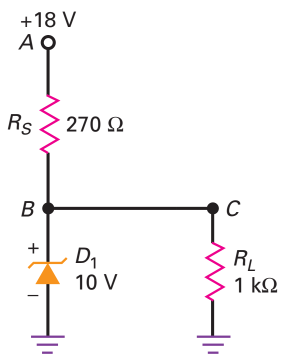
$$V_A = +18\text{ V} \qquad V_B = +10\text{ V} \qquad V_C = 0$$

Here is what may go through a troubleshooter's mind after measuring the foregoing voltages:

> ***What if the load resistor were open? No, the load voltage would still be 10 V. What if the load resistor were shorted? No, that would pull B and C down to ground, producing 0 V. All right, what if the connecting wire between B and C were open? Yes, that would do it.***

This trouble produces unique symptoms. The only way you can get this set of voltages is with an open connection between *B* and *C*.

Figure 5-16 Troubleshooting a zener regulator.



Ambiguous Symptoms

Not all troubles produce unique symptoms. Sometimes, two or more troubles produce the same set of voltages. Here is an example. Suppose the troubleshooter measures these voltages:

$$V_A = +18\text{ V} \qquad V_B = 0 \qquad V_C = 0$$

What do you think the trouble is? Think about this for a few minutes. When you have an answer, read what follows.

Here is a way that a troubleshooter might find the trouble. The thinking goes like this:

> ***I've got voltage at A, but not at B and C. What if the series resistor were open? Then no voltage could reach B or C, but I would still measure 18 V between A and ground. Yes, the series resistor is probably open.***

At this point, the troubleshooter would disconnect the series resistor and measure its resistance with an ohmmeter. Chances are that it would be open. But suppose it measures OK. Then the troubleshooter's thinking continues like this:

> ***That's strange. Well, is there any other way I can get 18 V at A and 0 V at B and C? What if the zener diode were shorted? What if the load resistor were shorted? What if a solder splash were between B or C and ground? Any of these will produce the symptoms I'm getting.***

Now the troubleshooter has more possible troubles to check out. Eventually, he or she will find the trouble.

When components burn out, they may become open, but not always. Some semiconductor devices can develop internal shorts, in which case they are like zero resistances. Other ways to get shorts include a solder splash between traces on a printed-circuit board, a solder ball touching two traces, and so on. Because of this, you must include what-if questions in terms of shorted components, as well as open components.

Table of Troubles

Summary Table 5-2 shows the possible troubles for the zener regulator in Fig. 5-16. In working out the voltages, remember this: A shorted component is equivalent to a resistance of zero, and an open component is equivalent to a resistance of infinity. If you have trouble calculating with 0 and ∞, use 0.001 Ω and 1000 MΩ. In other words, use a very small resistance for a short and a very large resistance for an open.

In Fig. 5-16, the series resistor R_S may be shorted or open. Let us designate these troubles as R_{SS} and R_{SO}. Similarly, the zener diode may be shorted or open, symbolized by D_{1S} and D_{1O}. Also, the load resistor may be shorted or open, R_{LS} and R_{LO}. Finally, the connecting wire between B and C may be open, designated BC_O.

Summary Table 5-2 — Zener Regulator Troubles and Symptoms

Trouble	V_A, V	V_B, V	V_C, V	Comments
None	18	10	10	No trouble
R_{SS}	18	18	18	D_1 and R_L may be open
R_{SO}	18	0	0	
D_{1S}	18	0	0	R_S may be open
D_{1O}	18	14.2	14.2	
R_{LS}	18	0	0	R_S may be open
R_{LO}	18	10	10	
BC_O	18	10	0	
No supply	0	0	0	Check power supply

In Summary Table 5-2, the second row shows the voltages when the trouble is R_{SS}, a shorted series resistor. When the series resistor is shorted in Fig. 5-16, 18 V appears at B and C. This destroys the zener diode and possibly the load resistor. For this trouble, a voltmeter measures 18 V at points A, B, and C. This trouble and its voltages are shown in Summary Table 5-2.

If the series resistor were open in Fig. 5-16, the voltage could not reach point B. In this case, B and C would have zero voltage, as shown in Summary Table 5-2. Continuing like this, we can get the remaining entries of Summary Table 5-2.

In Summary Table 5-2, the comments indicate troubles that might occur as a direct result of the original short circuits. For instance, a shorted R_S will destroy the zener diode and may also open the load resistor. It depends on the power rating of the load resistor. A shorted R_S means that there's 18 V across 1 kΩ. This produces a power of 0.324 W. If the load resistor is rated at only 0.25 W, it may open.

Some of the troubles in Summary Table 5-2 produce unique voltages, and others produce ambiguous voltages. For instance, the voltages for R_{SS}, D_{1O}, BC_O, and No supply are unique. If you measure these unique voltages, you can identify the trouble without breaking into the circuit to make an ohmmeter measurement.

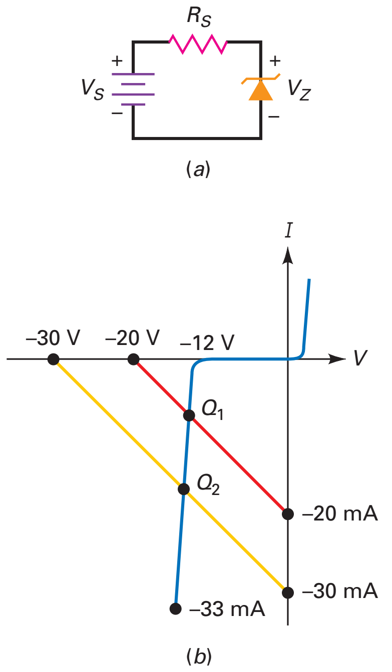
On the other hand, all the other troubles in Summary Table 5-2 produce ambiguous voltages. This means that two or more troubles can produce the same set of voltages. If you measure a set of ambiguous voltages, you will need to break into the circuit and measure the resistance of the suspected components. For instance, suppose you measure 18 V at A, 0 V at B, and 0 V at C. The troubles that can produce these voltages are R_{SO}, D_{1S}, and R_{LS}.

Zener diodes can be tested in a variety of ways. A DMM set to the diode range will enable the diode to be tested for being open or shorted. A normal reading will be approximately 0.7 V in the forward-biased direction and an open (overrange) indication in the reverse-biased direction. This test, though, will not indicate if the zener diode has the proper breakdown voltage V_Z.

A semiconductor curve tracer, shown in Fig. 5-17, will accurately display the zener's forward-/reverse-biased characteristics. If a curve tracer is not

Figure 5-17 Curve tracer.

Figure 5-18 (*a*) Zener regulator circuit; (*b*) load lines.



available, a simple test is to measure the voltage drop across the zener diode while connected in a circuit. The voltage drop should be close to its rated value.

5-7 Load Lines

The current through the zener diode of Fig. 5-18*a* is given by:

$$I_Z = \frac{V_S - V_Z}{R_S}$$

Suppose $V_S = 20$ V and $R_S = 1$ kΩ. Then, the foregoing equation reduces to:

$$I_Z = \frac{20 - V_Z}{1000}$$

We get the saturation point (vertical intercept) by setting V_Z equal to zero and solving for I_Z to get 20 mA. Similarly, to get the cutoff point (horizontal intercept), we set I_Z equal to zero and solve for V_Z to get 20 V.

Alternatively, you can get the ends of the load line as follows. Visualize Fig. 5-18*a* with $V_S = 20$ V and $R_S = 1$ kΩ. With the zener diode shorted, the maximum diode current is 20 mA. With the diode open, the maximum diode voltage is 20 V.

Suppose the zener diode has a breakdown voltage of 12 V. Then its graph appears as shown in Fig. 5-18*b*. When we plot the load line for $V_S = 20$ V and $R_S =$ 1 kΩ, we get the upper load line with an intersection point of Q_1. The voltage across the zener diode will be slightly more than the knee voltage at breakdown because the curve slopes slightly.

To understand how voltage regulation works, assume that the source voltage changes to 30 V. Then, the zener current changes to:

$$I_Z = \frac{30 - V_Z}{1000}$$

This implies that the ends of the load line are 30 mA and 30 V, as shown in Fig. 5-18*b*. The new intersection is at Q_2. Compare Q_2 with Q_1, and you can see that there is more current through the zener diode, but approximately the same zener voltage. Therefore, even though the source voltage has changed from 20 to 30 V, the zener voltage is still approximately equal to 12 V. This is the basic idea of voltage regulation; the output voltage has remained almost constant even though the input voltage has changed by a large amount.

5-8 Light-Emitting Diodes (LEDs)

Optoelectronics is the technology that combines optics and electronics. This field includes many devices based on the action of a *pn* junction. Examples of optoelectronic devices are **light-emitting diodes** (**LEDs**), photodiodes, optocouplers, and laser diodes. Our discussion begins with the LED.

Light-Emitting Diode

LEDs have replaced incandescent lamps in many applications because of the LED's lower energy consumption, smaller size, faster switching and longer lifetime. Figure 5-19 shows the parts of a standard low-power LED. Just as in an ordinary diode, the LED has an anode and a cathode that must be properly biased. The outside of the plastic case typically has a flat spot on one side which indicates

Figure 5-19 Parts of an LED.

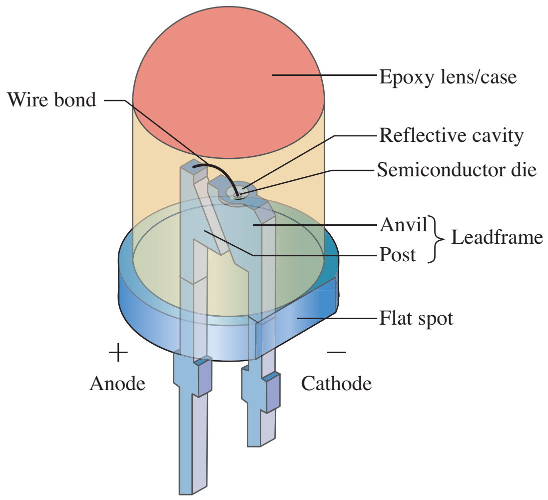
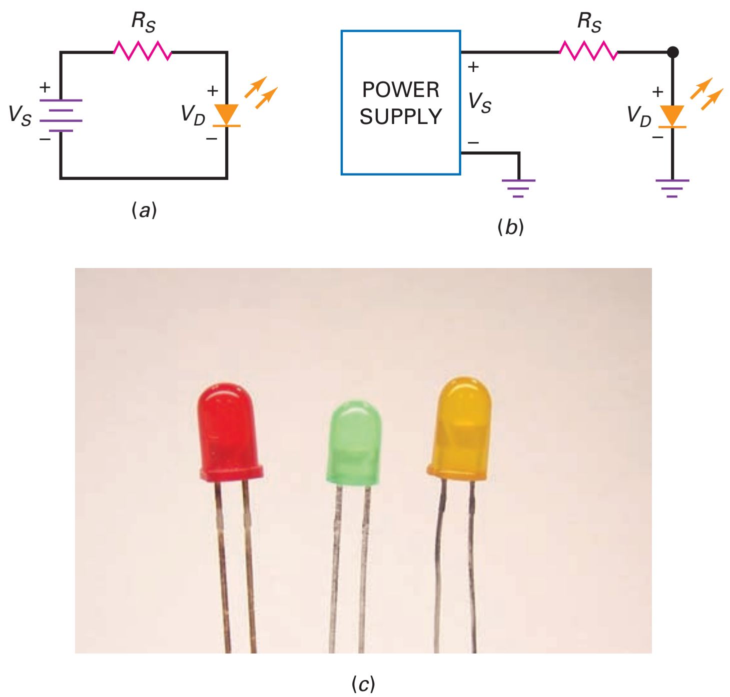


Figure 5-20 LED indicator. (*a*) Basic circuit; (*b*) practical circuit; (*c*) typical LEDs.



the cathode side of the LED. The material used for the semiconductor die will determine the LED's characteristics.

Figure 5-20*a* shows a source connected to a resistor and an LED. The outward arrows symbolize the radiated light. In a forward-biased LED, free electrons cross the *pn* junction and fall into holes. As these electrons fall from a higher to a lower energy level, they radiate energy in the form of photons. In ordinary diodes, this energy is radiated in the form of heat. But in an LED, the energy is radiated as light. This effect is referred to as **electroluminescence.**

The color of the light, which corresponds to the wavelength energy of the photons, is primarily determined by the energy band gap of the semiconductor materials that are used. By using elements like gallium, arsenic, and phosphorus, a manufacturer can produce LEDs that radiate red, green, yellow, blue, orange, white or infrared (invisible) light. LEDs that produce visible radiation are useful as indicators in applications such as instrumentation panels, internet routers, and so on. The infrared LED finds applications in security systems, remote controls, industrial control systems, and other areas requiring invisible radiation.

LED Voltage and Current

The resistor of Fig. 5-20*b* is the usual current-limiting resistor that prevents the current from exceeding the maximum current rating of the diode. Since the resistor has a node voltage of V_S on the left and a node voltage of V_D on the right, the voltage across the resistor is the difference between the two voltages. With Ohm's law, the series current is:

$$I_S = \frac{V_S - V_D}{R_S} \tag{5-13}$$

For most commercially available low-power LEDs, the typical voltage drop is from 1.5 to 2.5 V for currents between 10 and 50 mA. The exact voltage drop depends on the LED current, color, tolerance, along with other factors. Unless otherwise specified, we will use a nominal drop of 2 V when troubleshooting or analyzing low-power LED circuits in this book. Figure 5-20*c* shows typical low-power LEDs with housings made to help radiate the respective color.

LED Brightness

The brightness of an LED depends on the current. The amount of light emitted is often specified as its **luminous intensity** I_V and is rated in candelas (cd). Low-power LEDs generally have their ratings given in millicandelas (mcd). For instance, a TLDR5400 is a red LED with a forward voltage drop of 1.8 V and an I_V rating of 70 mcd at 20 mA. The luminous intensity drops to 3 mcd at a current of 1 mA. When V_S is much greater than V_D in Eq. (5-13), the brightness of the LED is approximately constant. If a circuit like Fig. 5-20*b* is mass-produced using a TLDR5400, the brightness of the LED will be almost constant if V_S is much greater than V_D. If V_S is only slightly more than V_D, the LED brightness will vary noticeably from one circuit to the next.

The best way to control the brightness is by driving the LED with a current source. This way, the brightness is constant because the current is constant. When we discuss transistors (they act like current sources), we will show how to use a transistor to drive an LED.

LED Specifications and Characteristics

A partial datasheet of a standard TLDR5400 5 mm T-1¾ red LED is shown in Figure 5-21. This type of LED has thru-hole leads and can be used in many applications.

The Absolute Maximum Rating table specifies that the LED's maximum forward current I_F is 50 mA and its maximum reverse voltage is only 6 V. To extend the life of this device, be sure to use an appropriate safety factor. The LED's maximum power rating is 100 mW at an ambient temperature of 25˚C and must be derated at higher temperatures.

The Optical and Electrical Characteristics table indicates that this LED has a typical luminous intensity I_V of 70 mcd at 20 mA and drops to 3 mcd at 1 mA. Also specified in this table, the dominant wavelength of the red LED is 648 nanometers and the light intensity drops off to approximately 50 percent when viewed at a 30° angle. The Relative Luminous Intensity versus Forward Current graph displays how the light intensity is effected by the LED's forward current. The graph of Relative Luminous Intensity versus Wavelength visually displays how the luminous intensity reaches a peak at a wavelength of approximately 650 nanometers.

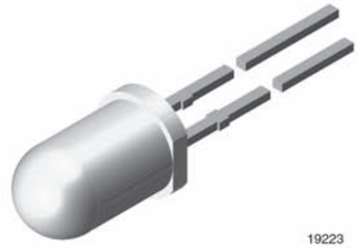
Figure 5-21 TLDR5400 Partial Datasheet. Datasheets courtesy of Vishay Intertechnology.

VISHAY.
www.vishay.com

TLDR5400

Vishay Semiconductors

High Intensity LED, Ø 5 mm Tinted Diffused Package



APPLICATIONS

- Bright ambient lighting conditions
- Battery powered equipment
- Indoor and outdoor information displays
- Portable equipment
- Telecommunication indicators
- General use

ABSOLUTE MAXIMUM RATINGS (T_{amb} = 25 °C, unless otherwise specified)
TLDR5400

PARAMETER	TEST CONDITION	SYMBOL	VALUE	UNIT
Reverse voltage (1)		V_R	6	V
DC forward current		I_F	50	mA
Surge forward current	$t_p \leq 10$ μs	I_{FSM}	1	A
Power dissipation		P_V	100	mW
Junction temperature		T_j	100	°C
Operating temperature range		T_{amb}	- 40 to + 100	°C

Note
(1) Driving the LED in reverse direction is suitable for a short term application

OPTICAL AND ELECTRICAL CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified)
TLDR5400, RED

PARAMETER	TEST CONDITION	SYMBOL	MIN.	TYP.	MAX.	UNIT
Luminous intensity	I_F = 20 mA	I_V	35	70	-	mcd
Luminous intensity	I_F = 1 mA	I_V	-	3	-	mcd
Dominant wavelength	I_F = 20 mA	λ_d	-	648	-	nm
Peak wavelength	I_F = 20 mA	λ_p	-	650	-	nm
Spectral line half width		$\Delta\lambda$	-	20	-	nm
Angle of half intensity	I_F = 20 mA	φ	-	± 30	-	deg
Forward voltage	I_F = 20 mA	V_F	-	1.8	2.2	V
Reverse current	V_R = 6 V	I_R	-	-	10	μA
Junction capacitance	V_R = 0 V, f = 1 MHz	C_j	-	30	-	pF

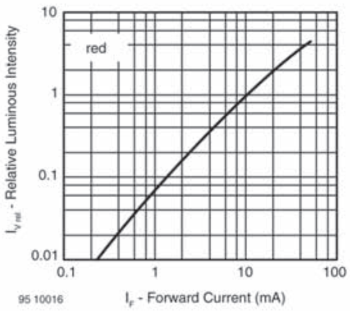


Fig. 6 - Relative Luminous Intensity vs. Forward Current

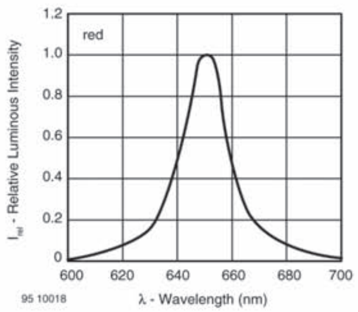


Fig. 4 - Relative Intensity vs. Wavelength

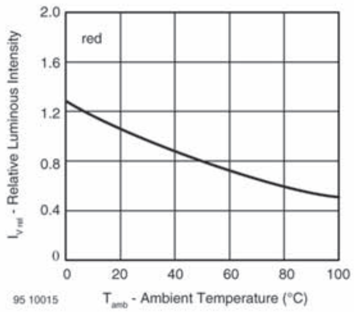


Fig. 8 - Relative Luminous Intensity vs. Ambient Temperature

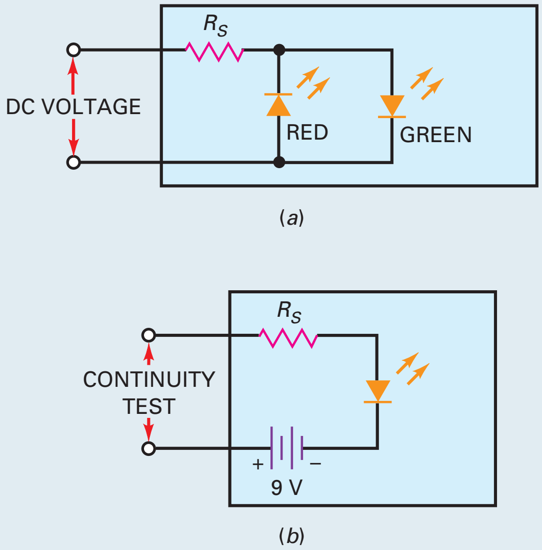
Rev. 1.8, 29-Apr-13 Document Number: 83003

What happens when the ambient temperature of the LED increases or decreases? The graph of Relative Luminous Intensity versus Ambient Temperature shows that an increase in ambient temperature has a substantial negative effect on the LED's light output. This becomes important when LEDs are used in applications with large temperature variations.

Application Example 5-12

Figure 5-22*a* shows a voltage-polarity tester. It can be used to test a dc voltage of unknown polarity. When the dc voltage is positive, the green LED lights up. When the dc voltage is negative, the red LED lights up. What is the approximate LED current if the dc input voltage is 50 V and the series resistance is 2.2 kΩ?

Figure 5-22 (*a*) Polarity indicator; (*b*) continuity tester.



SOLUTION We will use a forward voltage of approximately 2 V for either LED. With Eq. (5-13):

$$I_S = \frac{50\text{ V} - 2\text{ V}}{2.2\text{ k}\Omega} = 21.8\text{ mA}$$

Application Example 5-13

Multisim

Figure 5-22*b* is a continuity tester. After you turn off all the power in a circuit under test, you can use this circuit to check for the continuity of cables, connectors, and switches. How much LED current is there if the series resistance is 470 Ω?

SOLUTION When the input terminals are shorted (continuity), the internal 9-V battery produces an LED current of:

$$I_S = \frac{9\text{ V} - 2\text{ V}}{470\ \Omega} = 14.9\text{ mA}$$

PRACTICE PROBLEM 5-13 Using Fig. 5-22*b*, what value series resistor should be used to produce 21 mA of LED current?

Application Example 5-14

LEDs are often used to indicate the existence of ac voltages. Figure 5-23 shows an ac voltage source driving an LED indicator. When there is ac voltage, there is LED current on the positive half-cycles. On the negative half-cycles, the rectifier diode turns on and protects the LED from too much reverse voltage. If the ac source voltage is 20 V_{rms} and the series resistance is 680 Ω, what is the average LED current? Also, calculate the approximate power dissipation in the series resistor.

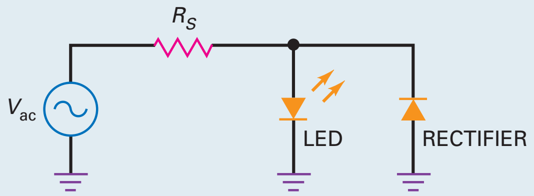


Figure 5-23 Low ac voltage indicator.

SOLUTION The LED current is a rectified half-wave signal. The peak source voltage is 1.414 × 20 V, which is approximately 28 V. Ignoring the LED voltage drop, the approximate peak current is:

$$I_S = \frac{28\ \text{V}}{680\ \Omega} = 41.2\ \text{mA}$$

The average of the half-wave current through the LED is:

$$I_S = \frac{41.2\ \text{mA}}{\pi} = 13.1\ \text{mA}$$

Ignore the diode drops in Fig. 5-23; this is equivalent to saying that there is a short to ground on the right end of the series resistor. Then the power dissipation in the series resistor equals the square of the source voltage divided by the resistance:

$$P = \frac{(20\ \text{V})^2}{680\ \Omega} = 0.588\ \text{W}$$

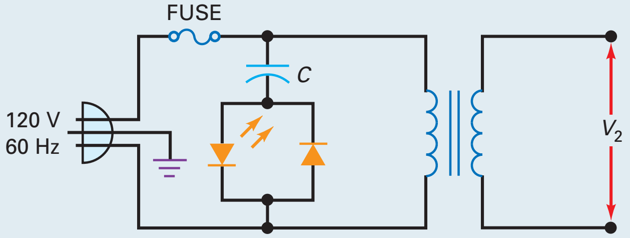
As the source voltage in Fig. 5-23 increases, the power dissipation in the series resistor may increase to several watts. This is a disadvantage because a high-wattage resistor is too bulky and wasteful for most applications.

PRACTICE PROBLEM 5-14 If the ac input voltage of Fig. 5-23 is 120 V and the series resistance is 2 kΩ, find the average LED current and approximate series resistor power dissipation.

Application Example 5-15

The circuit of Fig. 5-24 shows an LED indicator for the ac power line. The idea is basically the same as in Fig. 5-23, except that we use a capacitor instead of a resistor. If the capacitance is 0.68 μF, what is the average LED current?

Figure 5-24 High ac voltage indicator.



SOLUTION Calculate the capacitive reactance:

$$X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi(60\text{ Hz})(0.68\ \mu\text{F})} = 3.9\text{ k}\Omega$$

Ignoring the LED voltage drop, the approximate peak LED current is:

$$I_S = \frac{170\text{ V}}{3.9\text{ k}\Omega} = 43.6\text{ mA}$$

The average LED current is:

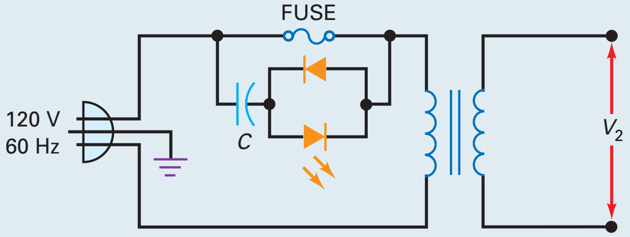
$$I_S = \frac{43.6\text{ mA}}{\pi} = 13.9\text{ mA}$$

What advantage does a series capacitor have over a series resistor? Since the voltage and current in a capacitor are 90° out of phase, there is no power dissipation in the capacitor. If a 3.9-kΩ resistor were used instead of a capacitor, it would have a power dissipation of approximately 3.69 W. Most designers would prefer to use a capacitor, since it's smaller and ideally produces no heat.

Application Example 5-16

What does the circuit of Fig. 5-25 do?

Figure 5-25 Blown-fuse indicator.



SOLUTION This is a *blown-fuse indicator.* If the fuse is OK, the LED is off because there is approximately zero voltage across the LED indicator. On the other hand, if the fuse is open, some of the line voltage appears across the LED indicator and the LED lights up.

High-Power LEDs

Typical power dissipation levels of the LEDs discussed up to this point are in the low milliwatt range. As an example, the TLDR5400 LED has a maximum power rating of 100 mW and generally operates at approximately 20 mA with a typical forward voltage drop of 1.8 V. This results in a power dissipation of 36 mW.

Figure 5-26 LUXEON TX High-Power Emitter.

Courtesy of Philips Lumileds

High-power LEDs are now available with continuous power ratings of 1 W and above. These power LEDs can operate in the hundreds of mAs to over 1 A of current. An increasing array of applications are being developed including automotive interior, exterior, and forward lighting, architectural indoor and outdoor area lighting, along with digital imaging and display backlighting.

Figure 5-26 shows an example of a high-power LED emitter that has the benefit of high luminance for directional applications such as downlights and indoor area lighting. LEDs, such as this, use much larger semiconductor die sizes to handle the large power inputs. Because this device will need to dissipate over 1 W of power, it is critical to use proper mounting techniques to a heat sink. Otherwise, the LED will fail within a short period of time.

Efficiency of a light source is an essential factor in most applications. Because an LED produces both light and heat, it is important to understand how much electrical power is used to produce the light output. A term used to describe this is called luminous efficacy. **Luminous efficacy** of a source is the ratio of output luminous flux (lm) to electrical power (W) given in lm/W. Figure 5-27 shows a partial table for LUXEON TX high-power LED emitters giving their typical performance characteristics. Notice that the performance characteristics are rated at 350 mA, 700 mA, and 1,000 mA. With a test current of 700 mA, the LIT2-3070000000000 emitter has a typical luminous flux output of 245 lm. At this forward current level, the typical forward voltage drop is 2.80 V. Therefore, the amount of power dissipated is $P_D = I_F \times V_F = 700 \text{ mA} \times 2.80 \text{ V} = 1.96 \text{ W}$. The efficacy value for this emitter would be found by:

$$\text{Efficacy} = \frac{\text{lm}}{\text{W}} = \frac{245 \text{ lm}}{1.96 \text{ W}} = 125 \text{ lm/W}$$

As a comparison, the luminous efficacy of a typical incandescent bulb is 16 lm/W and a compact fluorescent bulb has a typical rating of 60 lm/W. When looking at the overall efficiency of these types of LEDs, it is important to note that electronic circuits, called drivers, are required to control the LED's current and light output. Since these drivers also use electrical power, the overall system efficiency is reduced.

Figure 5-27 Partial data sheet for LUXEON TX emitters.

Product Selection Guide for LUXEON TX Emitters, Junction Temperature = 85°C

Table 1.

Base Part Number	Nominal ANSI CCT	Min CRI	Min Luminous Flux (lm)	Typical Luminous Flux (lm)			Typical Forward Voltage (V)			Typical Efficacy (lm/W)		
		700 mA	700 mA	350 mA	700 mA	1000 mA	350 mA	700 mA	1000 mA	350 mA	700 mA	1000 mA
LIT2-3070000000000	3000K	70	230	135	245	327	2.71	2.80	2.86	142	125	114
LIT2-4070000000000	4000K	70	250	147	269	360	2.71	2.80	2.86	155	137	126
LIT2-5070000000000	5000K	70	260	151	275	369	2.71	2.80	2.86	159	140	129
LIT2-5770000000000	5700K	70	260	151	275	369	2.71	2.80	2.86	159	140	129
LIT2-6570000000000	6500K	70	260	151	275	369	2.71	2.80	2.86	159	140	129
LIT2-2780000000000	2700K	80	200	118	216	289	2.71	2.80	2.86	124	110	101
LIT2-3080000000000	3000K	80	210	124	227	304	2.71	2.80	2.86	131	116	106
LIT2-3580000000000	3500K	80	220	130	238	319	2.71	2.80	2.86	137	121	112
LIT2-4080000000000	4000K	80	230	136	247	331	2.71	2.80	2.86	143	126	116
LIT2-5080000000000	5000K	80	230	135	247	332	2.71	2.80	2.86	142	126	116

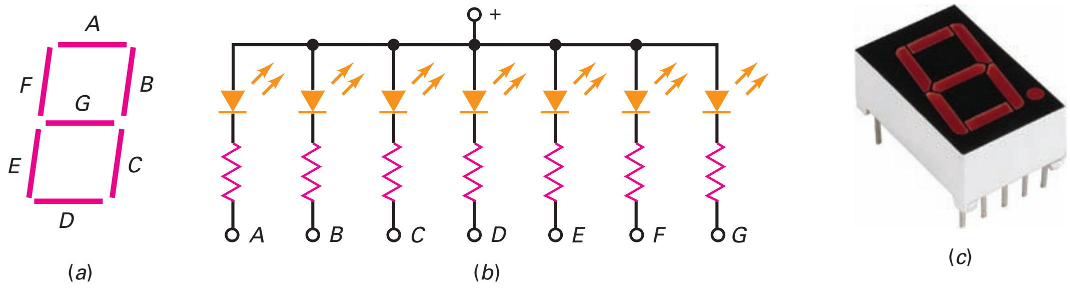
Typical Performance Characteristics

Notes for Table 1:

1. Philips Lumileds maintains a tolerance of ± 6.5% on luminous flux and ± 2 on CRI measurements.

Courtesy of Philips Lumileds

Figure 5-28 Seven-segment indicator. (*a*) Physical layout of segments; (*b*) schematic diagram; (*c*) Actual display with decimal point. Courtesy of Fairchild Semiconductor.



5-9 Other Optoelectronic Devices

Besides standard low-power through high-power LEDs, there are many other optoelectronic devices which are based on the photonic action of a *pn* junction. These devices are used to source, detect and control light in an enormous variety of electronic applications.

Seven-Segment Display

Figure 5-28*a* shows a **seven-segment display.** It contains seven rectangular LEDs (*A* through *G*). Each LED is called a *segment* because it forms part of the character being displayed. Figure 5-28*b* is a schematic diagram of the seven-segment display. External series resistors are included to limit the currents to safe levels. By grounding one or more resistors, we can form any digit from 0 through 9. For instance, by grounding *A*, *B*, and *C*, we get a 7. Grounding *A*, *B*, *C*, *D*, and *G* produces a 3.

A seven-segment display can also display capital letters *A*, *C*, *E*, and *F*, plus lowercase letters *b* and *d*. Microprocessor trainers often use seven-segment displays that show all digits from 0 through 9, plus *A*, *b*, *C*, *d*, *E*, and *F*.

The seven-segment indicator of Fig. 5-28*b* is referred to as the **common-anode** type because all anodes are connected together. Also available is the **common-cathode** type, in which all cathodes are connected together. Figure 5-28*c* shows an actual seven-segment display with pins for fitting into a socket or for soldering to a printed-circuit board. Notice the extra dot segment used for a decimal point.

GOOD TO KNOW

The principal disadvantage of LEDs is that they draw considerable current in comparison to other types of visual displays. In many cases, LEDs are pulsed on and off at a rapid rate, rather than being supplied with a steady drive current. LEDs appear to the eye to be on continuously, but they consume less power than if they were on continuously.

Photodiode

As previously discussed, one component of reverse current in a diode is the flow of minority carriers. These carriers exist because thermal energy keeps dislodging valence electrons from their orbits, producing free electrons and holes in the process. The lifetime of the minority carriers is short, but while they exist, they can contribute to the reverse current.

When light energy bombards a *pn* junction, it can dislodge valence electrons. The more light striking the junction, the larger the reverse current in a diode. A **photodiode** has been optimized for its sensitivity to light. In this diode, a window lets light pass through the package to the junction. The incoming light produces free electrons and holes. The stronger the light, the greater the number of minority carriers and the larger the reverse current.

Figure 5-29 shows the schematic symbol of a photodiode. The arrows represent the incoming light. Especially important, the source and the series resistor reverse-bias the photodiode. As the light becomes brighter, the reverse current increases. With typical photodiodes, the reverse current is in the tens of microamperes.

Figure 5-29 Incoming light increases reverse current in photodiode.

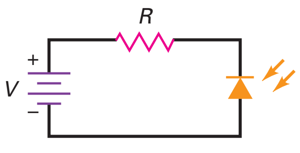
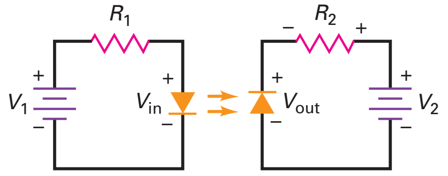


Figure 5-30 Optocoupler combines an LED and a photodiode.



Optocoupler

An optocoupler (also called an *optoisolator*) combines an LED and a photodiode in a single package. Figure 5-30 shows an optocoupler. It has an LED on the input side and a photodiode on the output side. The left source voltage and the series resistor set up a current through the LED. Then the light from the LED hits the photodiode, and this sets up a reverse current in the output circuit. This reverse current produces a voltage across the output resistor. The output voltage then equals the output supply voltage minus the voltage across the resistor.

When the input voltage is varying, the amount of light is fluctuating. This means that the output voltage is varying in step with the input voltage. This is why the combination of an LED and a photodiode is called an **optocoupler.** The device can couple an input signal to the output circuit. Other types of optocouplers use phototransistors, photothyristors, and other photo devices in their output circuit side. These devices will be discussed in later chapters.

The key advantage of an optocoupler is the electrical isolation between the input and output circuits. With an optocoupler, the only contact between the input and the output is a beam of light. Because of this, it is possible to have an insulation resistance between the two circuits in the thousands of megohms. Isolation like this is useful in high-voltage applications in which the potentials of the two circuits may differ by several thousand volts.

GOOD TO KNOW

An important specification for the optocoupler is its current/transfer ratio, which is the ratio of the device's output (photodiode or phototransistor) current to its input (LED) current.

Laser Diode

In an LED, free electrons radiate light when falling from higher energy levels to lower ones. The free electrons fall randomly and continuously, resulting in light waves that have every phase between 0 and 360°. Light that has many different phases is called *noncoherent light.* An LED produces noncoherent light.

A **laser diode** is different. It produces a *coherent light.* This means that all the light waves are *in phase with each other.* The basic idea of a laser diode is to use a mirrored resonant chamber that reinforces the emission of light waves at a single frequency of the same phase. Because of the resonance, a laser diode produces a narrow beam of light that is very intense, focused, and pure.

Laser diodes are also known as *semiconductor lasers.* These diodes can produce visible light (red, green, or blue) and invisible light (infrared). Laser diodes are used in a large variety of applications. They are used in telecommunications, data communications, broadband access, industrial, aerospace, test and measurement, and medical and defense industries. They are also used in laser printers and consumer products requiring large-capacity optical disk systems, such as compact disk (CD) and digital video disk (DVD) players. In broadband communication, they are used with fiber-optic cables to increase the speed of the Internet.

A *fiber-optic cable* is analogous to a stranded wire cable, except that the strands are thin flexible fibers of glass or plastic that transmit light beams instead of free electrons. The advantage is that much more information can be sent through a fiber-optic cable than through a copper cable.

New applications are being found as the lasing wavelength is pushed lower into the visible spectrum with visible laser diodes (VLDs). Also, near-infrared diodes are being used in machine vision systems, sensors, and security systems.

GOOD TO KNOW

Schottky diodes are relatively high-current devices, capable of switching quickly while providing forward currents in the neighborhood of 50 A! It is also worth noting that Schottky diodes normally have lower breakdown voltage ratings as compared to conventional *pn* junction rectifier diodes.

5-10 The Schottky Diode

As frequency increases, the action of small-signal rectifier diodes begins to deteriorate. They are no longer able to switch off fast enough to produce a well-defined half-wave signal. The solution to this problem is the *Schottky diode.* Before describing this special-purpose diode, let us look at the problem that arises with ordinary small-signal diodes.

Charge Storage

Figure 5-31*a* shows a small-signal diode, and Fig. 5-31*b* illustrates its energy bands. As you can see, conduction-band electrons have diffused across the junction and traveled into the *p* region before recombining (path *A*). Similarly, holes have crossed the junction and traveled into the *n* region before recombination occurs (path *B*). The greater the lifetime, the farther the charges can travel before recombination occurs.

For instance, if the lifetime equals 1 μs, free electrons and holes exist for an average of 1 μs before recombination takes place. This allows the free electrons to penetrate deeply into the *p* region, where they remain temporarily stored at the higher energy band. Similarly, the holes penetrate deeply into the *n* region, where they are temporarily stored in the lower energy band.

The greater the forward current, the larger the number of charges that have crossed the junction. The greater the lifetime, the deeper the penetration of these charges and the longer the charges remain in the high and low energy bands. The temporary storage of free electrons in the upper energy band and holes in the lower energy band is referred to as *charge storage.*

Charge Storage Produces Reverse Current

When you try to switch a diode from on to off, charge storage creates a problem. Why? Because if you suddenly reverse-bias a diode, the stored charges will flow in the reverse direction for a while. The greater the lifetime, the longer these charges can contribute to reverse current.

For example, suppose a forward-biased diode is suddenly reverse biased, as shown in Fig. 5-32*a*. Then a large reverse current can exist for a while because

Figure 5-31 Charge storage. (*a*) Forward bias creates stored charges; (*b*) stored charges in high and low energy bands.

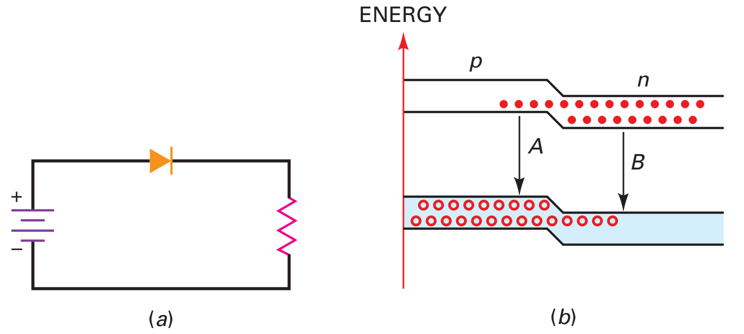
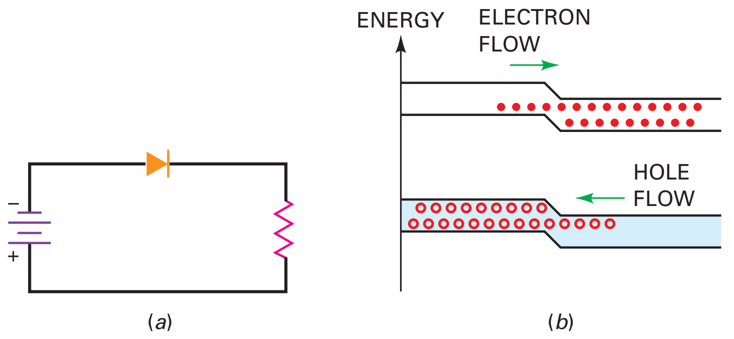


Figure 5-32 Stored charges allow a brief reverse current. (*a*) Sudden reversal of source voltage; (*b*) flow of stored charges in reverse direction.



of the flow of stored charges in Fig. 5-32*b*. Until the stored charges either cross the junction or recombine, the reverse current will continue.

Reverse Recovery Time

The time it takes to turn off a forward-biased diode is called the *reverse recovery time* t_{rr}. The conditions for measuring t_{rr} vary from one manufacturer to the next. As a guide, t_{rr} is the time it takes for the reverse current to drop to 10 percent of the forward current.

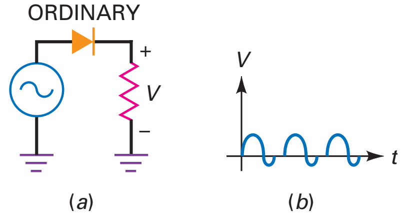
For instance, the 1N4148 has a t_{rr} of 4 ns. If this diode has a forward current of 10 mA and it is suddenly reverse biased, it will take approximately 4 ns for the reverse current to decrease to 1 mA. Reverse recovery time is so short in small-signal diodes that you don't even notice its effect at frequencies below 10 MHz or so. It's only when you get well above 10 MHz that you have to take t_{rr} into account.

Poor Rectification at High Frequencies

What effect does reverse recovery time have on rectification? Take a look at the half-wave rectifier shown in Fig. 5-33*a*. At low frequencies, the output is a half-wave rectified signal. As the frequency increases well into megahertz, however, the output signal begins to deviate from the half-wave shape, as shown in Fig. 5-33*b*. Some reverse conduction (called *tails*) is noticeable near the beginning of the reverse half-cycle.

The problem is that the reverse recovery time has become a significant part of the period, allowing conduction during the early part of the negative half-cycle. For instance, if $t_{rr} = 4$ ns and the period is 50 ns, the early part of the reverse half-cycle will have tails similar to those shown in Fig. 5-33*b*. As the frequency continues to increase, the rectifier becomes useless.

Figure 5-33 Stored charges degrade rectifier behavior at high frequencies. (*a*) Rectifier circuit with ordinary small-signal diode; (*b*) tails appear on negative half-cycles at higher frequencies.



Eliminating Charge Storage

The solution to the problem of tails is a special-purpose device called a **Schottky diode.** This kind of diode uses a metal such as gold, silver, or platinum on one side of the junction and doped silicon (typically *n*-type) on the other side. Because of the metal on one side of the junction, the Schottky diode has no depletion layer. The lack of a depletion layer means that there are *no stored charges at the junction.*

When a Schottky diode is unbiased, free electrons on the *n* side are in smaller orbits than are the free electrons on the metal side. This difference in orbit size is called the *Schottky barrier,* approximately 0.25 V. When the diode is forward biased, free electrons on the *n* side can gain enough energy to travel in larger orbits. Because of this, free electrons can cross the junction and enter the metal, producing a large forward current. Since the metal has no holes, there is no charge storage and no reverse recovery time.

Hot-Carrier Diode

The Schottky diode is sometimes called a *hot-carrier diode.* This name came about as follows. Forward bias increases the energy of the electrons on the *n* side to a higher level than that of the electrons on the metal side of the junction. This increase in energy inspired the name *hot carrier* for the *n*-side electrons. As soon as these high-energy electrons cross the junction, they fall into the metal, which has a lower-energy conduction band.

High-Speed Turnoff

The lack of charge storage means that the Schottky diode can switch off faster than an ordinary diode can. In fact, a Schottky diode can easily rectify frequencies above 300 MHz. When it is used in a circuit like Fig. 5-34*a*, the Schottky diode produces a perfect half-wave signal like Fig. 5-34*b* even at frequencies above 300 MHz.

Figure 5-34*a* shows the schematic symbol of a Schottky diode. Notice the cathode side. The lines look like a rectangular *S*, which stands for *Schottky.* This is how you can remember the schematic symbol.

Applications

The most important application of Schottky diodes is in digital computers. The speed of computers depends on how fast their diodes and transistors can turn on and off. This is where the Schottky diode comes in. Because it has no charge storage, the Schottky diode has become the backbone of low-power Schottky TTLs, a group of widely used digital devices.

Figure 5-34 Schottky diodes eliminate tails at high frequencies. (*a*) Circuit with Schottky diode; (*b*) half-wave signal at 300 MHz.

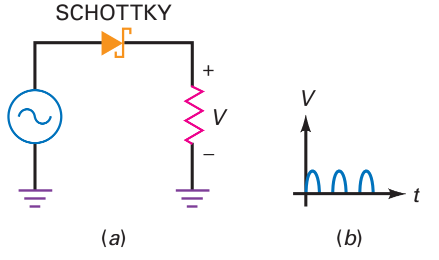
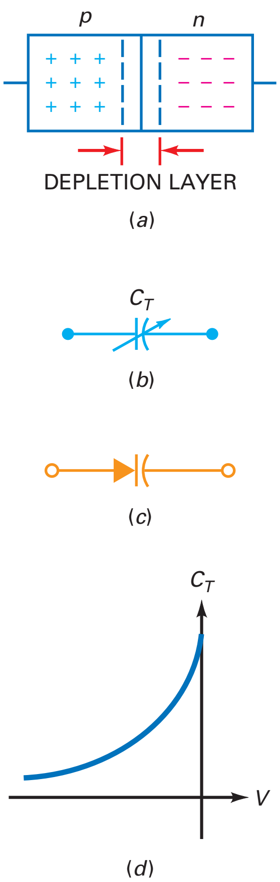


Figure 5-35 Varactor.
(*a*) Doped regions are like capacitor plates separated by a dielectric;
(*b*) ac-equivalent circuit;
(*c*) schematic symbol; (*d*) graph of capacitance versus reverse voltage.



A final point. Since a Schottky diode has a barrier potential of only 0.25 V, you may occasionally see it used in low-voltage bridge rectifiers because you subtract only 0.25 V instead of the usual 0.7 V for each diode when using the second approximation. In a low-voltage supply, this lower diode voltage drop is an advantage.

5-11 The Varactor

The **varactor** (also called the *voltage-variable capacitance, varicap, epicap,* and *tuning diode*) is widely used in television receivers, FM receivers, and other communications equipment because it can be used for electronic tuning.

Basic Idea

In Fig. 5-35*a*, the depletion layer is between the *p* region and the *n* region. The *p* and *n* regions are like the plates of a capacitor, and the depletion layer is like the dielectric. When a diode is reverse biased, the width of the depletion layer increases with the reverse voltage. Since the depletion layer gets wider with more reverse voltage, the capacitance becomes smaller. It's as though you moved apart the plates of a capacitor. The key idea is that capacitance is controlled by reverse voltage.

Equivalent Circuit and Symbol

Figure 5-35*b* shows the ac-equivalent circuit for a reverse-biased diode. In other words, as far as an ac signal is concerned, the varactor acts the same as a variable capacitance. Figure 5-35*c* shows the schematic symbol for a varactor. The inclusion of a capacitor in series with the diode is a reminder that a varactor is a device that has been optimized for its variable-capacitance properties.

Capacitance Decreases at Higher Reverse Voltages

Figure 5-35*d* shows how the capacitance varies with reverse voltage. This graph shows that the capacitance gets smaller when the reverse voltage gets larger. The really important idea here is that reverse dc voltage controls capacitance.

How is a varactor used? It is connected in parallel with an inductor to form a parallel resonant circuit. This circuit has only one frequency at which maximum impedance occurs. This frequency is called the *resonant frequency*. If the dc reverse voltage to the varactor is changed, the resonant frequency is also changed. This is the principle behind electronic tuning of a radio station, a TV channel, and so on.

Varactor Characteristics

Because the capacitance is voltage controlled, varactors have replaced mechanically tuned capacitors in many applications such as television receivers and automobile radios. Data sheets for varactors list a reference value of capacitance measured at a specific reverse voltage, typically −3 V to −4 V. Figure 5-36 shows a partial data sheet for an MV209 varactor diode. It lists a reference capacitance C_t of 29 pF at –3 V.

In addition to providing the reference value of capacitance, data sheets normally list a capacitance ratio C_R, or tuning range associated with a voltage range. For example, along with the reference value of 29 pF, the data sheet of an MV209 shows a minimum capacitance ratio of 5:1 for a voltage range of –3 V to –25 V. This means that the capacitance, or tuning range, decreases from 29 to 6 pF when the voltage varies from –3 V to –25 V.

Figure 5-36 MV209 Partial Data Sheet. (Used with permission from SCILLC dba ON Semiconductor.)

	C_t, Diode Capacitance V_R = 3.0 Vdc, f = 1.0 MHz pF			Q, Figure of Merit V_R = 3.0 Vdc f = 50 MHz	C_R, Capacitance Ratio C_3/C_{25} f = 1.0 MHz (Note 1)	
Device	**Min**	**Nom**	**Max**	**Min**	**Min**	**Max**
MMBV109LT1, MV209	26	29	32	200	5.0	6.5

1. C_R is the ratio of C_t measured at 3 Vdc divided by C_t measured at 25 Vdc.

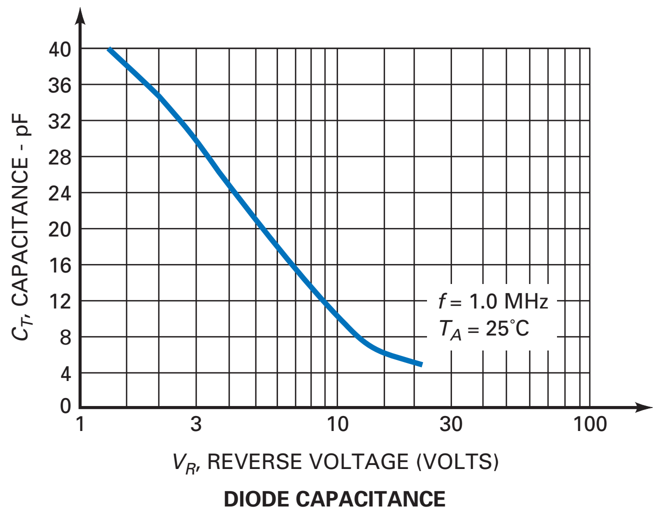
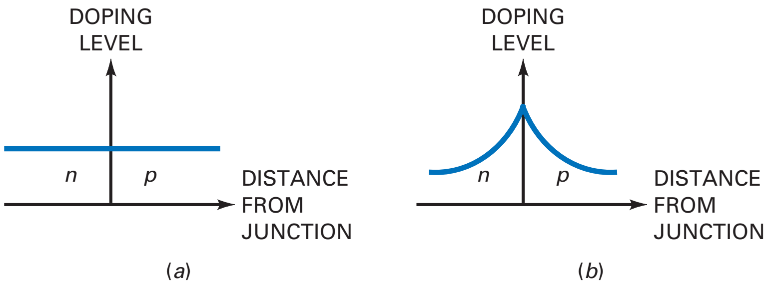


Figure 5-37 Doping profiles. (*a*) Abrupt junction; (*b*) hyperabrupt junction.



The tuning range of a varactor depends on the doping level. For instance, Fig. 5-37*a* shows the doping profile for an abrupt-junction diode (the ordinary type of diode). The profile shows that the doping is uniform on both sides of the junction. The tuning range of an abrupt-junction diode is between 3:1 and 4:1.

To get larger tuning ranges, some varactors have a *hyperabrupt junction,* one whose doping profile looks like Fig. 5-37*b*. This profile tells us that the doping level increases as we approach the junction. The heavier doping produces a narrower depletion layer and a larger capacitance. Furthermore, changes in reverse voltage have more pronounced effects on capacitance. A hyperabrupt varactor has a tuning range of about 10:1, enough to tune an AM radio through its frequency range of 535 to 1605 kHz. (Note: You need a 10:1 range because the resonant frequency is inversely proportional to the square root of capacitance.)

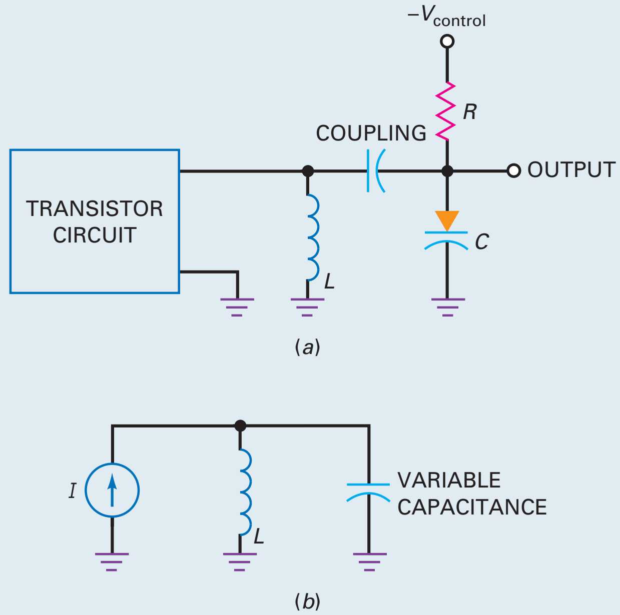
Application Example 5-17

What does the circuit of Fig. 5-38*a* do?

SOLUTION A transistor is a semiconductor device that acts like a current source. In Fig. 5-38*a*, the transistor pumps a fixed number of milliamperes into the resonant *LC* tank circuit. A negative dc voltage reverse-biases the varactor. By varying this dc control voltage, we can vary the resonant frequency of the *LC* circuit.

As far as the ac signal is concerned, we can use the equivalent circuit shown in Fig. 5-38*b*. The coupling capacitor acts like a short circuit. An ac current source drives a resonant *LC* tank circuit. The varactor acts like variable capacitance, which means that we can change the resonant frequency by changing the dc control voltage. This is the basic idea behind the tuning of some radio and television receivers.

Figure 5-38 Varactors can tune resonant circuits. (*a*) Transistor (current source) drives tuned *LC* tank; (*b*) ac-equivalent circuit.



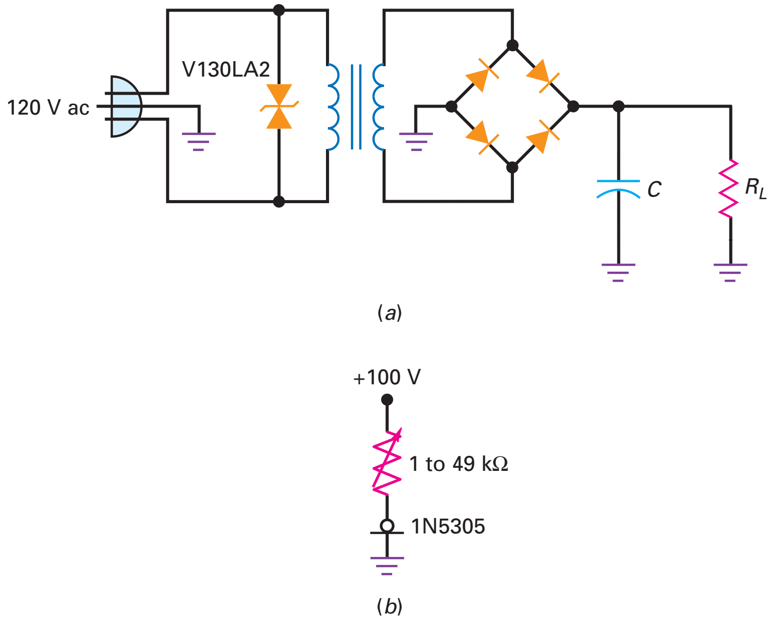
5-12 Other Diodes

Besides the special-purpose diodes discussed so far, there are others you should know about. Because they are so specialized, only a brief description follows.

Varistors

Lightning, power-line faults, and transients can pollute the ac line voltage by superimposing dips and spikes on the normal 120 V rms. *Dips* are severe voltage drops lasting microseconds or less. *Spikes* are very brief overvoltages up to 2000 V or more. In some equipment, filters are used between the power line and the primary of the transformer to eliminate the problems caused by ac line transients.

Figure 5-39 (*a*) Varistor protects primary from ac line transients; (*b*) current-regulator diode.



One of the devices used for line filtering is the **varistor** (also called a *transient suppressor*). This semiconductor device is like two back-to-back zener diodes with a high breakdown voltage in both directions. Varistors are commercially available with breakdown voltages from 10 to 1000 V. They can handle peak transient currents in the hundreds or thousands of amperes.

For instance, a V130LA2 is a varistor with a breakdown voltage of 184 V (equivalent to 130 V rms) and a peak current rating of 400 A. Connect one of these across the primary winding as shown in Fig. 5-39*a*, and you don't have to worry about spikes. The varistor will clip all spikes at the 184-V level and protect your power supply.

Current-Regulator Diodes

These are diodes that work in a way exactly opposite to the way zener diodes work. Instead of holding the voltage constant, these diodes hold the current constant. Known as **current-regulator diodes** (or *constant-current diodes*), these devices keep the current through them fixed when the voltage changes. For example, the 1N5305 is a constant-current diode with a typical current of 2 mA over a voltage range of 2 to 100 V. Figure 5-39*b* shows the schematic symbol of a current-regulator diode. In Fig. 5-39*b*, the diode will hold the load current constant at 2 mA even though the load resistance varies from 1 to 49 kΩ.

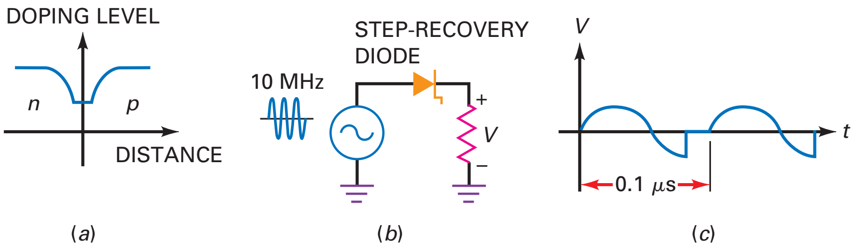
Step-Recovery Diodes

The **step-recovery diode** has the unusual doping profile shown in Fig. 5-40*a*. This graph indicates that the density of carriers decreases near the junction. This unusual distribution of carriers causes a phenomenon called *reverse snap-off.*

Figure 5-40*b* shows the schematic symbol for a step-recovery diode. During the positive half-cycle, the diode conducts like any silicon diode. But during the negative half-cycle, reverse current exists for a while because of the stored charges and then suddenly drops to zero.

Figure 5-40*c* shows the output voltage. It's as though the diode conducts reverse current for a while and then suddenly snaps open. This is why the

Figure 5-40 Step-recovery diode. (*a*) Doping profile shows less doping near junction; (*b*) circuit rectifying an ac input signal; (*c*) snap-off produces a positive voltage step rich in harmonics.



step-recovery diode is also known as a *snap diode.* The sudden step in current is rich in harmonics and can be filtered to produce a sine wave of a higher frequency. (*Harmonics* are multiples of the input frequency like $2f_{in}$, $3f_{in}$, and $4f_{in}$.) Because of this, step-recovery diodes are useful in frequency multipliers, circuits whose output frequency is a multiple of the input frequency.

Back Diodes

Zener diodes normally have breakdown voltages greater than 2 V. By increasing the doping level, we can get the zener effect to occur near zero. Forward conduction still occurs around 0.7 V, but now reverse conduction (breakdown) starts at approximately −0.1 V.

A diode with a graph like Fig. 5-41*a* is called a **back diode** because it conducts better in the reverse than in the forward direction. Figure 5-41*b* shows a sine wave with a peak of 0.5 V driving a back diode and a load resistor. (Notice that the zener symbol is used for the back diode.) The 0.5 V is not enough to turn on the diode in the forward direction, but it is enough to break down the diode in the reverse direction. For this reason, the output is a half-wave signal with a peak of 0.4 V, as shown in Fig. 5-41*b*.

Back diodes are occasionally used to rectify weak signals with peak amplitudes between 0.1 and 0.7 V.

Tunnel Diodes

By increasing the doping level of a back diode, we can get breakdown to occur at 0 V. Furthermore, the heavier doping distorts the forward curve, as shown in Fig. 5-42*a*. A diode with this graph is called a **tunnel diode.**

Figure 5-42*b* shows the schematic symbol for a tunnel diode. This type of diode exhibits a phenomenon known as **negative resistance.** This means that an increase in forward voltage produces a decrease in forward current, at least over the part of the graph between V_P and V_V. The negative resistance of tunnel

Figure 5-41 Back diode. (*a*) Breakdown occurs at −0.1 V; (*b*) circuit rectifying weak ac signal.

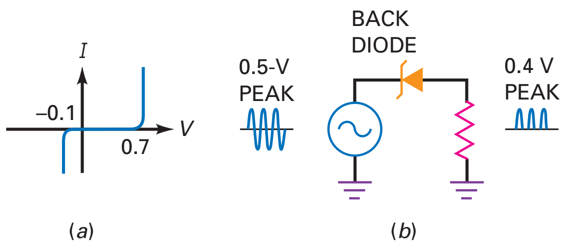


Figure 5-42 Tunnel diode. (*a*) Breakdown occurs at 0 V; (*b*) schematic symbol.

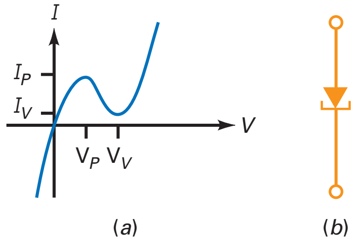
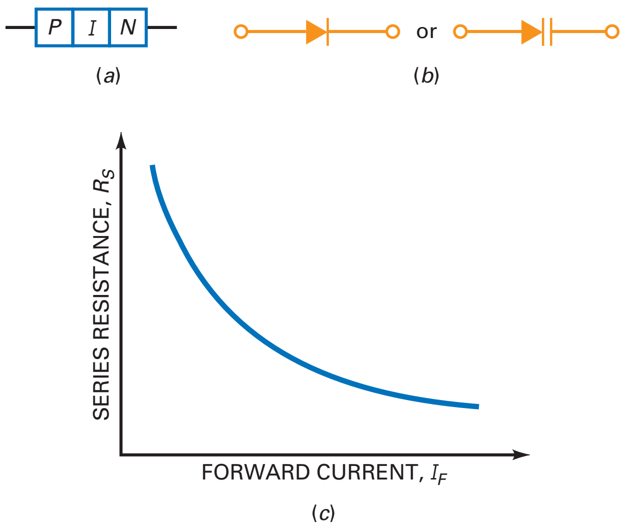


Figure 5-43 PIN diode. (*a*) Construction; (*b*) schematic symbol; (*c*) series resistance.



diodes is useful in high-frequency circuits called *oscillators.* These circuits are able to generate a sinusoidal signal, similar to that produced by an ac generator. But unlike the ac generator that converts mechanical energy to a sinusoidal signal, an oscillator converts dc energy to a sinusoidal signal. Later chapters will show you how to build oscillators.

Summary Table 5-3 Special-Purpose Devices

Device	Key Idea	Application
Zener diode	Operates in breakdown region	Voltage regulators
LED	Emits noncoherent light	DC or ac indicators, efficient light source
Seven-segment indicator	Can display numbers	Measuring instruments
Photodiode	Light produces minority carriers	Light detectors
Optocoupler	Combines LED and photodiode	Input/output isolators
Laser diode	Emits coherent light	CD/DVD players, broadband communications
Schottky diode	Has no charge storage	High-frequency rectifiers (300 MHz)
Varactor	Acts like variable capacitance	TV and receiver tuners
Varistor	Breaks down both ways	Line-spike protectors
Current-regulator diode	Holds current constant	Current regulators
Step-recovery diode	Snaps off during reverse conduction	Frequency multipliers
Back diode	Conducts better in reverse	Weak-signal rectifiers
Tunnel diode	Has a negative-resistance region	High-frequency oscillators
PIN diode	Controlled resistance	Microwave communications

PIN Diodes

A **PIN diode** is a semiconductor device that operates as a variable resistor at RF and microwave frequencies. Figure 5-43*a* shows its construction. It consists of an intrinsic (pure) semiconductor material sandwiched between *p*-type and *n*-type materials. Figure 5-43*b* shows the schematic symbol for the PIN diode.

When the diode is forward biased, it acts like a current-controlled resistance. Figure 5-43*c* shows how the PIN diode's series resistance R_S decreases as its forward current increases. When reverse biased, the PIN diode acts like a fixed capacitor. The PIN diode is widely used in modulator circuits for RF and microwave applications.

Table of Devices

Summary Table 5-3 lists all the special-purpose devices in this chapter. The zener diode is useful in voltage regulators, the LED as a dc or an ac indicator, the seven-segment indicator in measuring instruments, and so on. You should study the table and remember the ideas it contains.