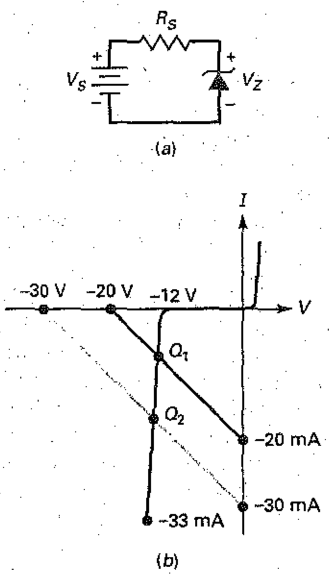


Figure 5-18 (*a*) Zener regulator circuit; (*b*) load lines.

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.

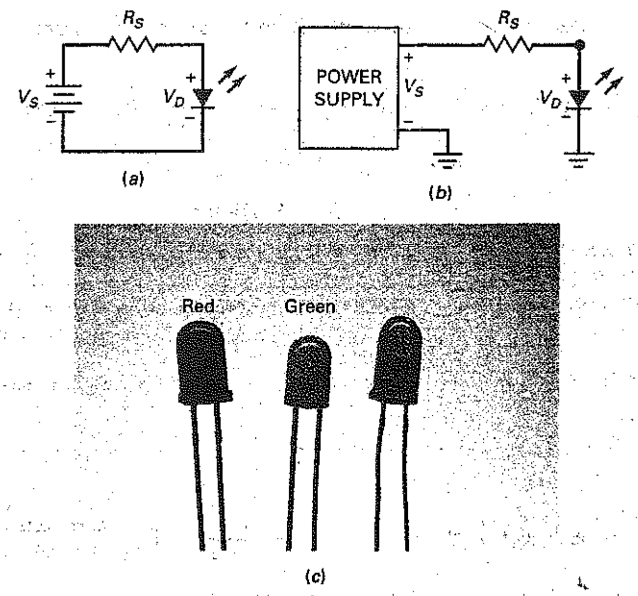
5-8 Optoelectronic Devices

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

Figure 5-19*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 junction and fall into holes. As these electrons fall from a higher to a lower energy level, they radiate energy. In ordinary diodes, this energy is radiated in the form of heat. But in an LED, the energy is radiated as light. LEDs made from different elements have the ability to radiate energy across a wide wavelength spectrum. LEDs have replaced incandescent lamps in many applications because of their low voltage, long life, and fast on-off switching.

Figure 5-19 LED indicator. (*a*) Basic circuit; (*b*) practical circuit; (*c*) typical LEDs.



By using elements like gallium, arsenic, and phosphorus, a manufacturer can produce LEDs that radiate red, green, yellow, blue, orange, or infrared (invisible). LEDs that produce visible radiation are useful with instruments, calculators, and so on. The infrared LED finds applications in burglar alarm systems, remote controls, CD players, and other devices requiring invisible radiation.

LED Voltage and Current

The resistor of Fig. 5-19*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 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, and so on. Unless otherwise specified, we will use a nominal drop of 2 V when troubleshooting or analyzing the LED circuits in this book. Fig. 5-19*c* shows typical LEDs.

LED Brightness

The brightness of an LED depends on the current. When V_S is much greater than V_D in Eq. (5-13), the brightness of the LED is approximately constant. For instance, a TIL222 is a green LED with a forward voltage of between 1.8 (minimum) and 3 V (maximum), for a current of 25 mA. If a circuit like Fig. 5-19*b* is mass-produced using a TIL222, 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.

Breakdown Voltage

LEDs have very low breakdown voltages, typically between 3 and 5 V. Because of this, they are easily destroyed if reverse biased with too much voltage. When troubleshooting an LED circuit in which the LED will not light, check the polarity of the LED connection to make sure that it is forward biased.

An LED is often used to indicate the presence of power-line voltage into equipment. In this case, a rectifier diode may be used in parallel with the LED to prevent reverse-bias destruction of the LED. An example of using a rectifier diode to protect an LED is given later.

Seven-Segment Display

Figure 5-20*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 5-20*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. 5-20*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.

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

Figure 5-20 Seven-segment indicator. (*a*) Physical layout of segments; (*b*) schematic diagram.

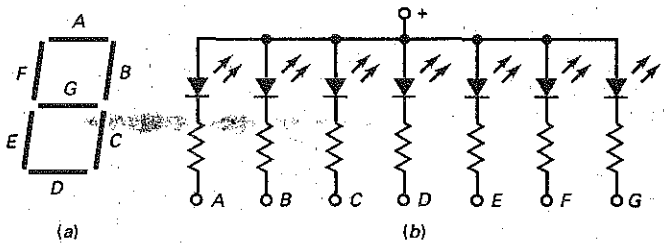


Figure 5-21 Incoming light increases reverse current in photodiode.

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.

produces free electrons and holes. The stronger the light, the greater the number of minority carriers and the larger the reverse current.

Figure 5-21 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.

Optocoupler

An optocoupler (also called an *optoisolator*) combines an LED and a photodiode in a single package. Figure 5-22 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.

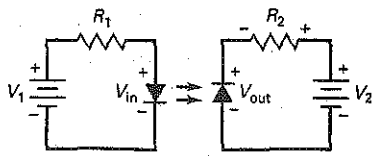
Laser Diode

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, medical and defense industries. They are also used in laser printers and consumer products requiring large-capacity optical disk systems, such as

Figure 5-22 Optocoupler combines an LED and a photodiode.



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.

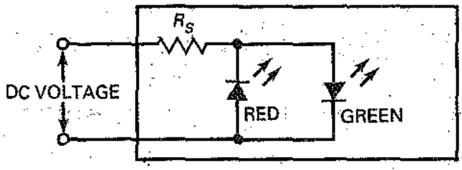
A *fiber-optic cable* is analogous to a stranded wire cable, except that the strands are thin flexible fibers of glass or plastic that transmit light beams instead of free electrons. The advantage is that much more information can be sent through a fiber-optic cable than through a copper cable.

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.

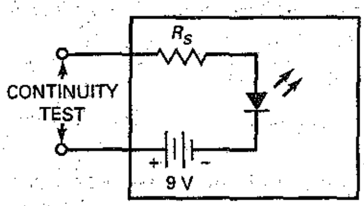
Example 5-12

Figure 5-23*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 5-23 (*a*) Polarity indicator; (*b*) continuity tester.



(*a*)



(*b*)

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

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

Example 5-13

MultiSim

Figure 5-23*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:

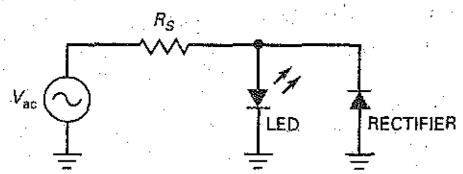
$$I_S = \frac{9\text{ V} - 2\text{ V}}{470\ \Omega} = 14.9\text{ mA}$$

PRACTICE PROBLEM 5-13 Using Fig. 5-23, what value series resistor should be used to produce 21 mA of LED current?

Example 5-14

LEDs are often used to indicate the existence of ac voltages. Figure 5-24 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 5-24 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. 5-24; 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:

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

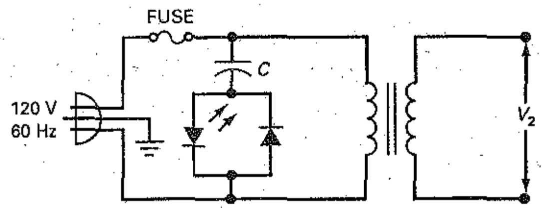
As the source voltage in Fig. 5-24 increases, the power dissipation in the series resistor may increase to several watts. This is a disadvantage because a high-wattage resistor is too bulky and wasteful for most applications.

PRACTICE PROBLEM 5-14 If the ac input voltage of Fig. 5-24 is 120 V and the series resistance is 2 kΩ, find the average LED current and approximate series resistor power dissipation.

Example 5-15

The circuit of Fig. 5-25 shows an LED indicator for the ac power line. The idea is basically the same as in Fig. 5-24, except that we use a capacitor instead of a resistor. If the capacitance is 0.68 μF, what is the average LED current?

Figure 5-25 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:

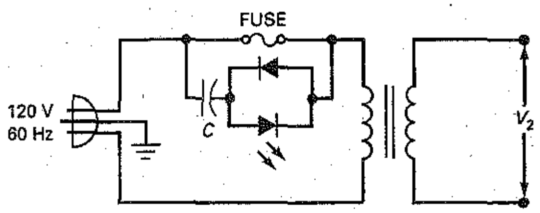
$$I_S = \frac{43.6\text{ mA}}{\pi} = 13.9\text{ mA}$$

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.

Example 5-16

What does the circuit of Fig. 5-26 do?

Figure 5-26 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.