3–4 OPTICAL DIODES

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

After completing this section, you should be able to

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

The Light-Emitting Diode (LED)

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

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

▲ FIGURE 3–28

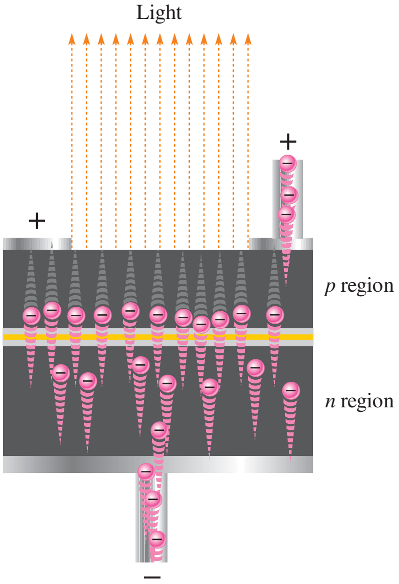
Symbol for an LED. When forward-biased, it emits light.

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

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

▶ FIGURE 3–29

Electroluminescence in a forward-biased LED.



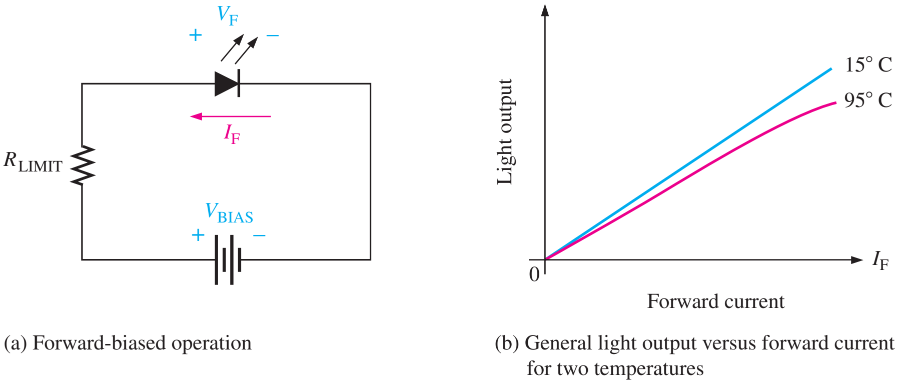
F Y I

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

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

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

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



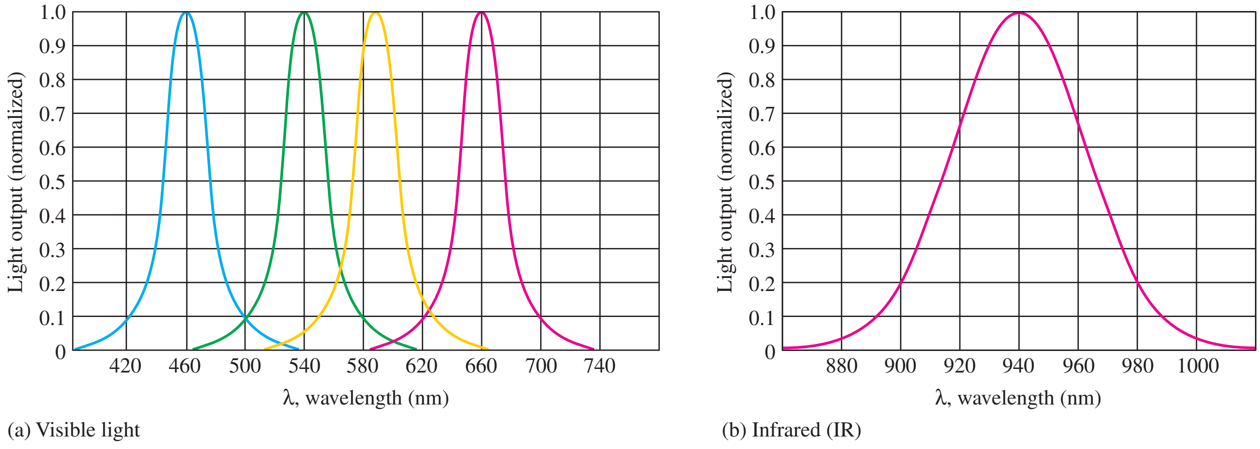
(a) Forward-biased operation

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

▲ FIGURE 3–30

Basic operation of an LED.

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



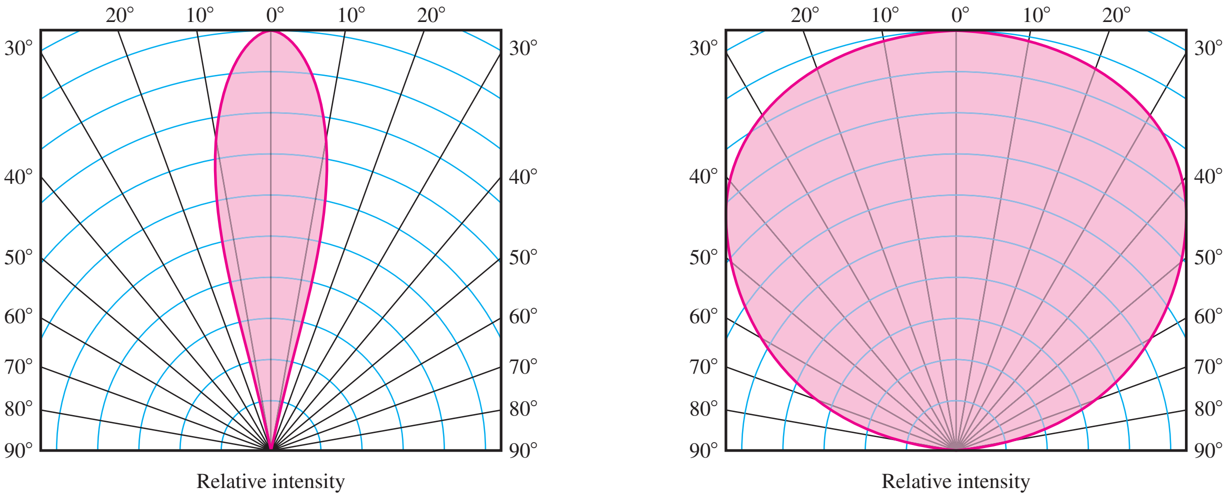
(a) Visible light

(b) Infrared (IR)

▲ FIGURE 3–31

Examples of typical spectral output curves for LEDs.

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



(a) A narrow viewing angle LED

(b) A wide viewing angle LED

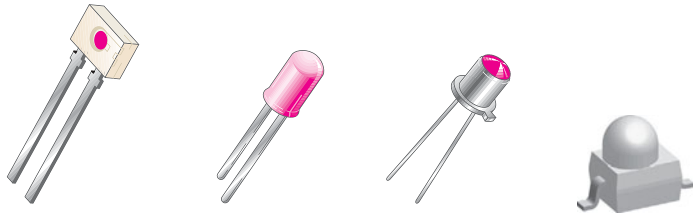
▲ FIGURE 3–32

Radiation patterns for two different LEDs.

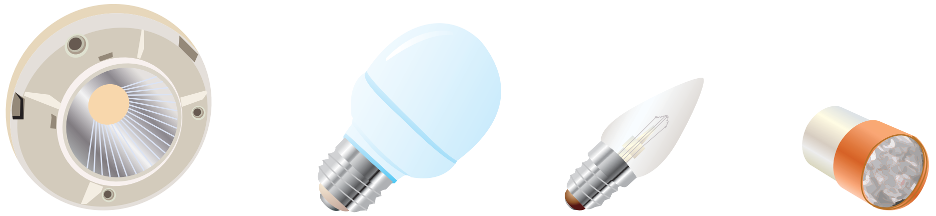
Typical small LEDs for indicators are shown in Figure 3–33(a). In addition to small LEDs for indicators, bright LEDs are becoming popular for lighting because of their superior efficiency and long life. A typical LED for lighting can deliver 50–60 lumens per watt, which is approximately five times greater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

FIGURE 3–33

Typical LEDs.



(a) Typical small LEDs for indicators



Helion 12 V overhead light with socket and module

120 V, 3.5 W screw base for low-level illumination

120 V, 1 W small screw base candelabra style

6 V, bayonet base for flashlights, etc.

(b) Typical LEDs for lighting applications

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

LED Datasheet Information

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

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

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

EXAMPLE 3–10

From the LED datasheet in Figure 3–34 determine the following:

(a) The radiant power at 910 nm if the maximum output is 35 mW.

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

(c) The radiant intensity for $I_F = 40$ mA.

Solution

(a) From the graph in Figure 3–34(c), the relative radiant power at 910 nm is approximately 0.25 and the peak radiant power is 35 mW. Therefore, the radiant power at 910 nm is

$$\phi_e = 0.25(35\text{ mW}) = \mathbf{8.75\text{ mW}}$$

(b) From the graph in part (b), $V_F \cong$ **1.25 V** for $I_F = 20$ mA.

(c) From the graph in part (e), $I_e \cong$ **10 mW/sr** for $I_F = 40$ mA.

Related Problem Determine the relative radiant power at 850 nm.

Absolute Maximum Ratings

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

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

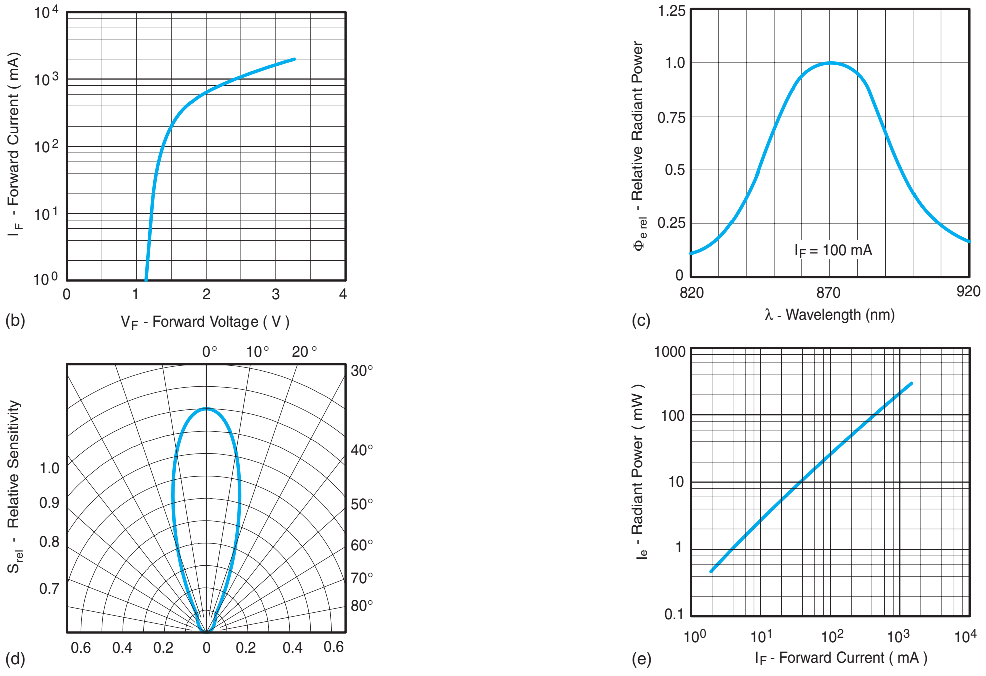
Basic Characteristics

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

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

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

(a)

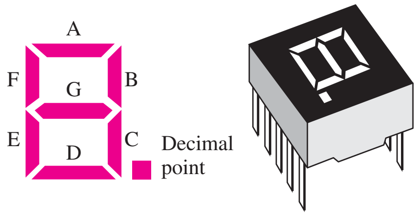


▲ **FIGURE 3–34**

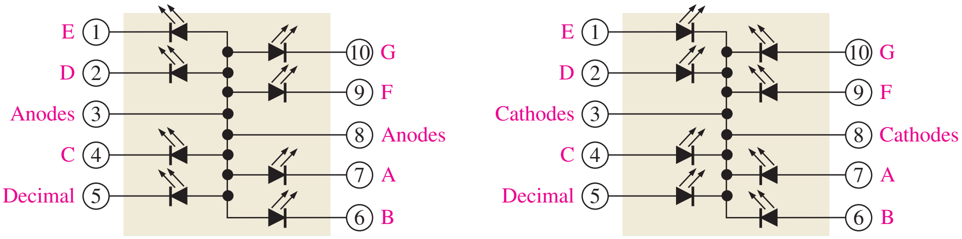
Partial datasheet for an TSMF1000 IR light-emitting diode. Datasheet courtesy of Vishay Intertechnology, Inc. Datasheets are available at www.vishay.com.

Applications

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



(a) LED segment arrangement and typical device



(b) Common anode

(c) Common cathode

▲ **FIGURE 3–35**

The 7-segment LED display.

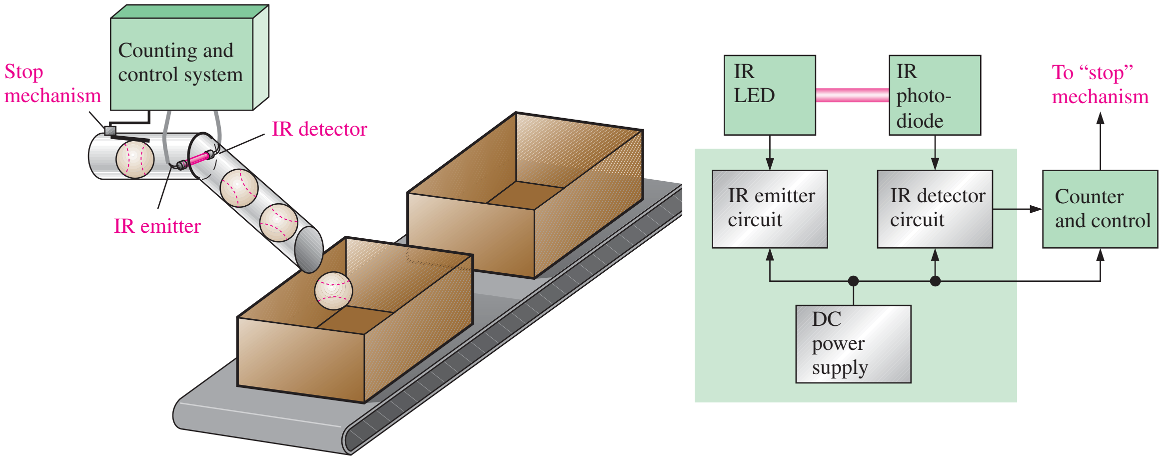
One common application of an infrared LED is in remote control units for TV, DVD, gate openers, etc. The IR LED sends out a beam of invisible light that is sensed by the receiver in your TV, for example. For each button on the remote control unit, there is a unique code. When a specific button is pressed,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

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

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

High-Intensity LEDs

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



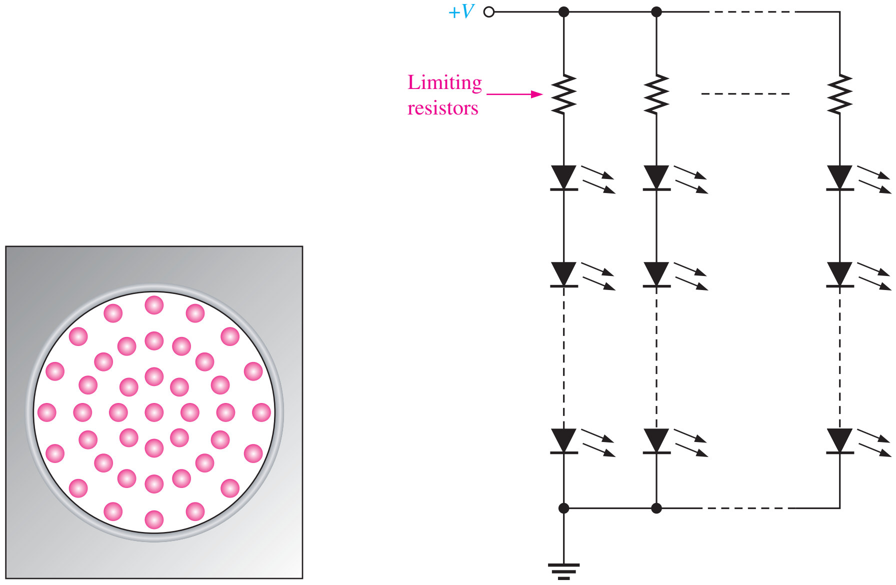
▲ FIGURE 3–36

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

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

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

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



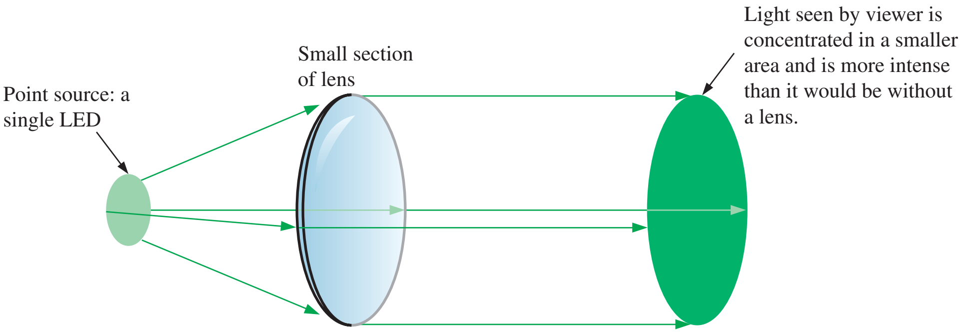
(a) LED array (b) Circuit

▲ FIGURE 3–37

LED traffic light.

FIGURE 3–38

The lens directs the light emitted from the LED to optimize visibility.

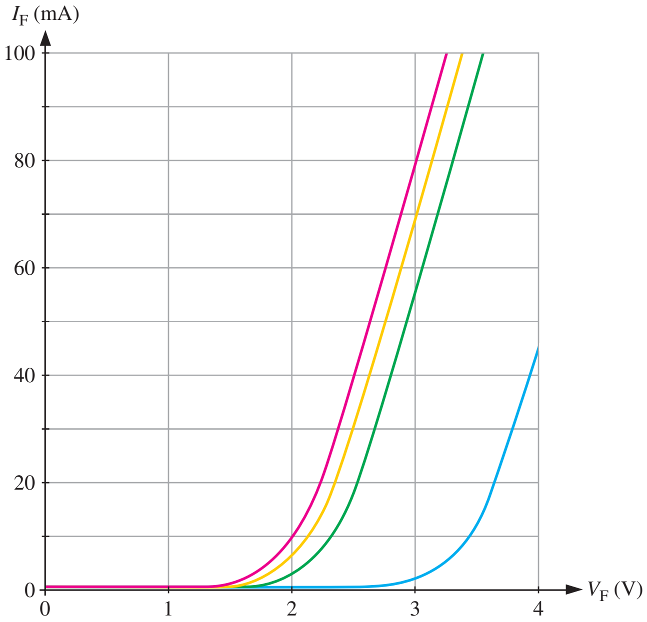


Some LED traffic arrays use small reflectors for each LED to help maximize the effect of the light output. Also, an optical lens covers the front of the array to direct the light from each individual diode to prevent improper dispersion of light and to optimize the visibility. Figure 3–38 illustrates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

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

FIGURE 3–39

V-I characteristic curves for visible-light LEDs.



EXAMPLE 3–11

Using the graph in Figure 3–39, determine the green LED forward voltage for a current of 20 mA. Design a 12 V LED circuit to minimize the number of limiting resistors for an array of 60 diodes.

Solution From the graph, a green LED has a forward voltage of approximately 2.5 V for a forward current of 20 mA. The maximum number of series LEDs is 3. The total voltage across three LEDs is

$$V = 3 \times 2.5\text{ V} = 7.5\text{ V}$$

The voltage drop across the series-limiting resistor is

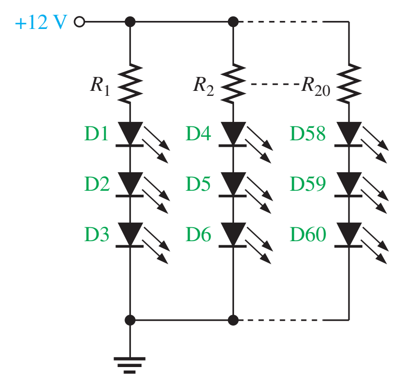
$$V = 12\text{ V} - 7.5\text{ V} = 4.5\text{ V}$$

The value of the limiting resistor is

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

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

▶ FIGURE 3–40



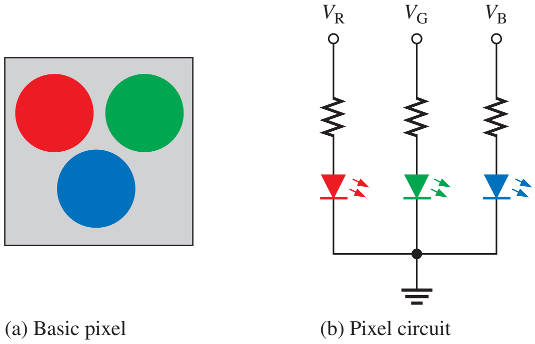
Related Problem Design a 12 V red LED array with minimum limiting resistors, a forward current of 30 mA, and containing 64 diodes.

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

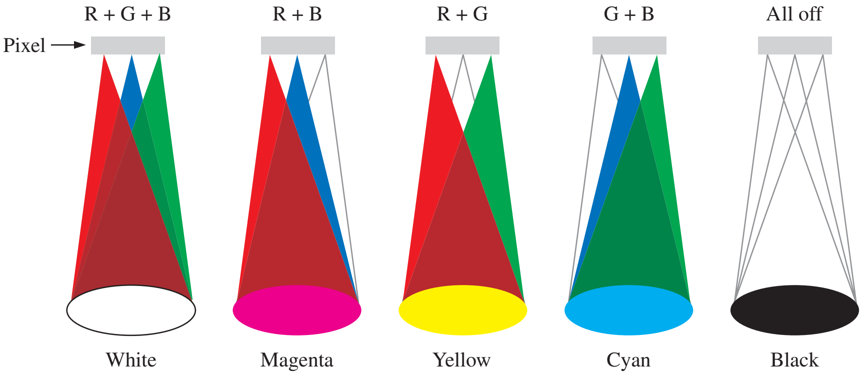
Red, green, and blue (RGB) are primary colors and when mixed together in varying amounts, can be used to produce any color in the visible spectrum. A basic pixel formed by three LEDs is shown in Figure 3–41. The light emission from each of the three diodes can be varied independently by varying the amount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

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

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



(a) Basic pixel (b) Pixel circuit



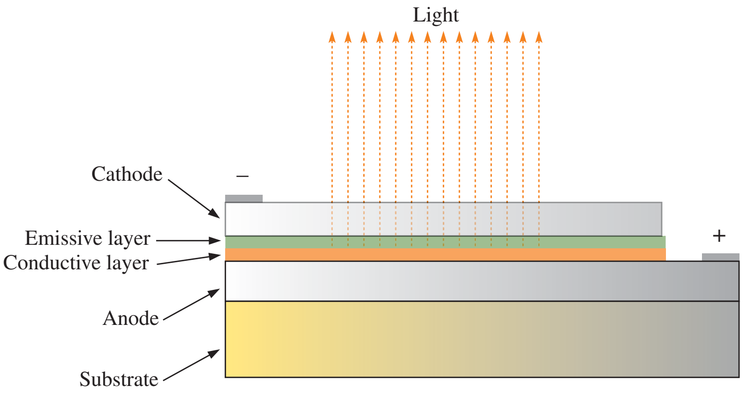
(c) Examples of different combinations of equal amounts of primary colors

▲ FIGURE 3–41

The concept of an RGB pixel used in LED display screens.

The Organic LED (OLED)

An **OLED** is a device that consists of two or three layers of materials composed of organic molecules or polymers that emit light with the application of voltage. OLEDs produce light through the process of electrophosphorescence. The color of the light depends on the type of organic molecule in the emissive layer. The basic structure of a 2-layer OLED is shown in Figure 3–42.



▲ FIGURE 3–42

Basic structure of a top-emitting 2-layer OLED.

Electrons are provided to the emissive layer and removed from the conductive layer when there is current between the cathode and anode. This removal of electrons from the conductive layer leaves holes. The electrons from the emissive layer recombine with the holes from the conductive layer near the junction of the two layers. When this recombination occurs, energy is released in the form of light that passes through the transparent cathode material. If the anode and substrate are also made from transparent materials, light is emitted in both directions, making the OLED useful in applications such as heads-up displays.

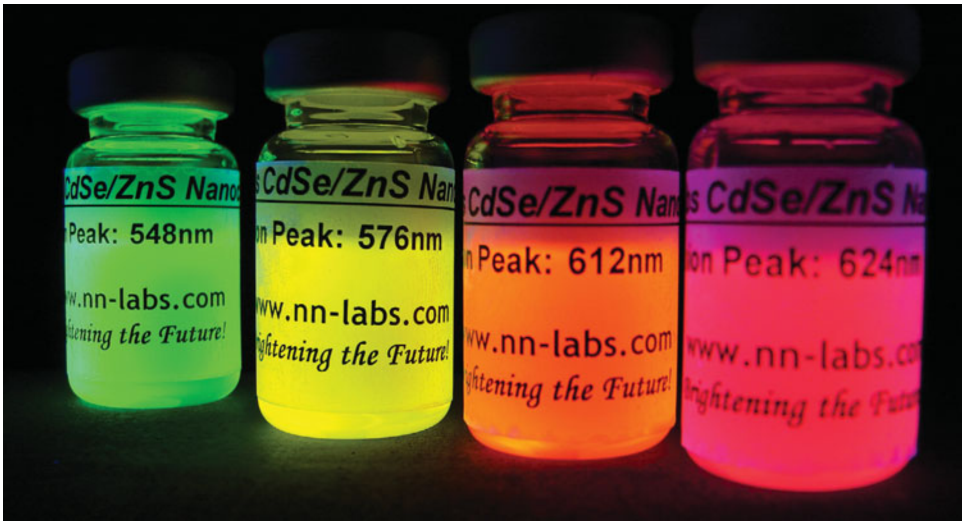
OLEDs can be sprayed onto substrates just like inks are sprayed onto paper during printing. Inkjet technology greatly reduces the cost of OLED manufacturing and allows OLEDs to be printed onto very large films for large displays like 80-inch TV screens or electronic billboards.

FYI

OLED technology was developed by Eastman Kodak. It is beginning to replace LCD (liquid crystal display) technology in handheld devices such as PDAs and cellular phones. OLEDs are brighter, thinner, faster, and lighter than conventional LEDs or LCDs. They also use less power and are cheaper to manufacture.

Quantum Dots

Quantum dots are a form of nanocrystals that are made from semiconductor material such as silicon, germanium, cadmium sulfide, cadmium selenide, and indium phosphide. Quantum dots are only 1 nm to 12 nm in diameter (a nm is one billionth of a meter). Billions of dots could fit on the head of a pin! Because of their small size, quantum effects arise due to the confinement of electrons and holes; as a result, material properties are very different than the normal material. One important property is that the band gap is dependent on the size of the dots. When excited from an external source, dots formed from semiconductors emit light in the visible range as well as infrared and ultraviolet, depending on their size. The higher-frequency blue light is emitted by smaller dots suspended in solution (larger band gap); red light is emitted from solutions with larger dots (smaller band gap). Solutions containing the quantum dots glow eerily with specific colors as shown in the photograph in Figure 3–43.



◄ FIGURE 3–43

Solutions containing quantum dots glow with specific colors that depend on the size of the dots. Courtesy of NN-Labs.

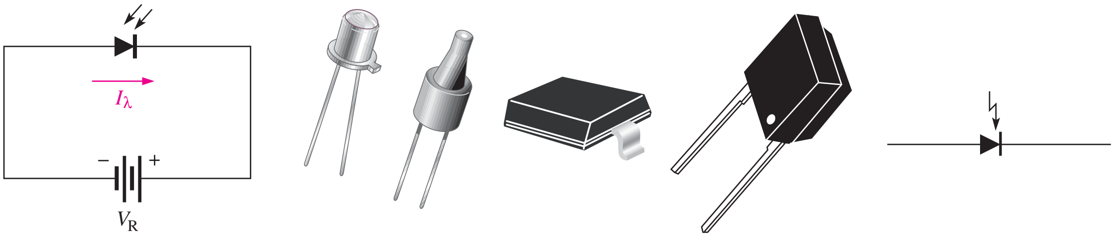
Although quantum dots are not diodes themselves, they can be used in construction of light-emitting diodes as well as display devices and a variety of other applications. As you know, LEDs work by generating a specific frequency (color) of light, which is determined by the band gap. To produce white light, blue LEDs are coated with a phosphor that adds yellow light to the blue, forming white. The result is not a pure white, but tends to be harsh and makes colors appear unnatural. While this is satisfactory for displays and signs, many people do not like it for home lighting.

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

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

The Photodiode

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



(a) Reverse-bias operation using standard symbol

(b) Typical devices

(c) Alternate symbol

▲ FIGURE 3–44

Photodiode.

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

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

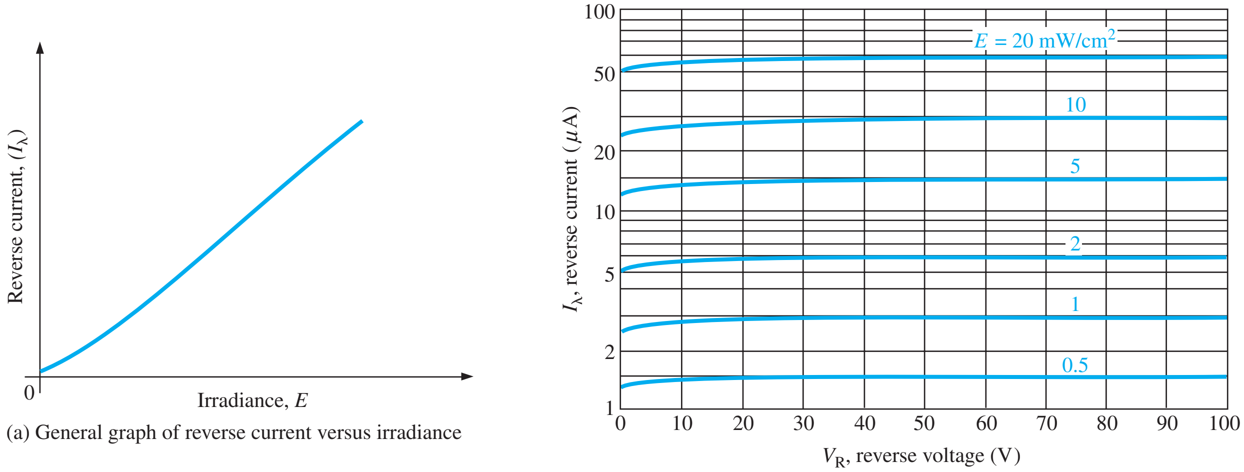
From the graph in Figure 3–45(b), you can see that the reverse current for this particular device is approximately 1.4 μA at a reverse-bias voltage of 10 V with an irradiance of 0.5 mW/cm^2. Therefore, the resistance of the device is

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

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

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

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



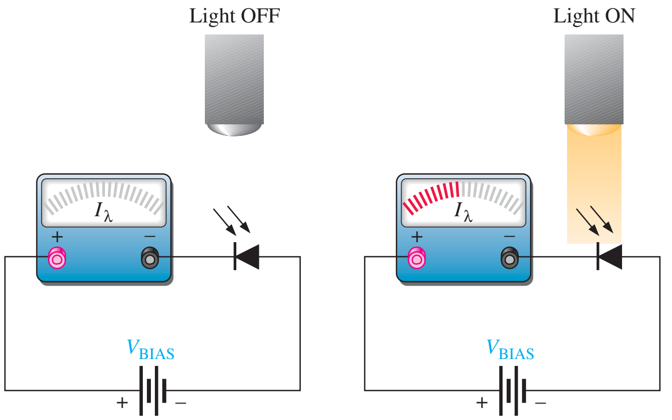
(a) General graph of reverse current versus irradiance

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

▲ **FIGURE 3–45**

Typical photodiode characteristics.

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



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

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

▲ **FIGURE 3–46**

Operation of a photodiode.

Photodiode Datasheet Information

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

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

Absolute Maximum Ratings

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

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

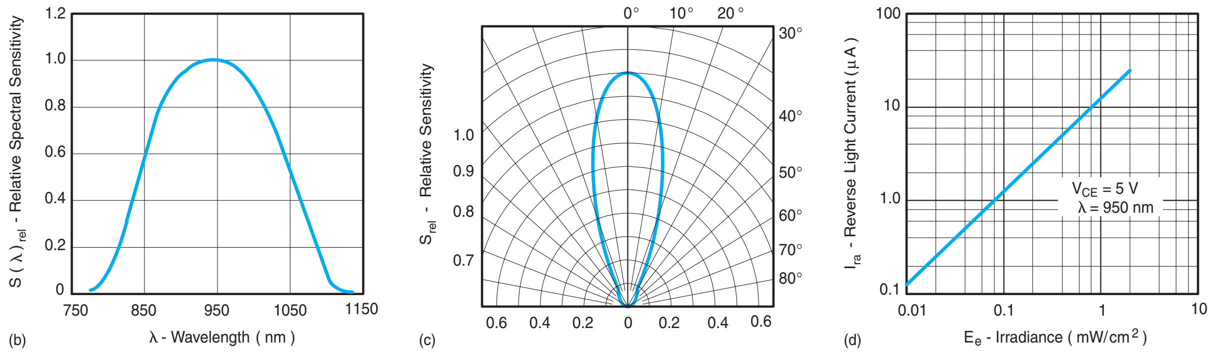
Basic Characteristics

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

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

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

(a)



(b) (c) (d)

▲ **FIGURE 3–47**

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

EXAMPLE 3–12

For a TEMD1000 photodiode,

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

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

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

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

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

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

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

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

SECTION 3–4 CHECKUP

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

3–5 OTHER TYPES OF DIODES

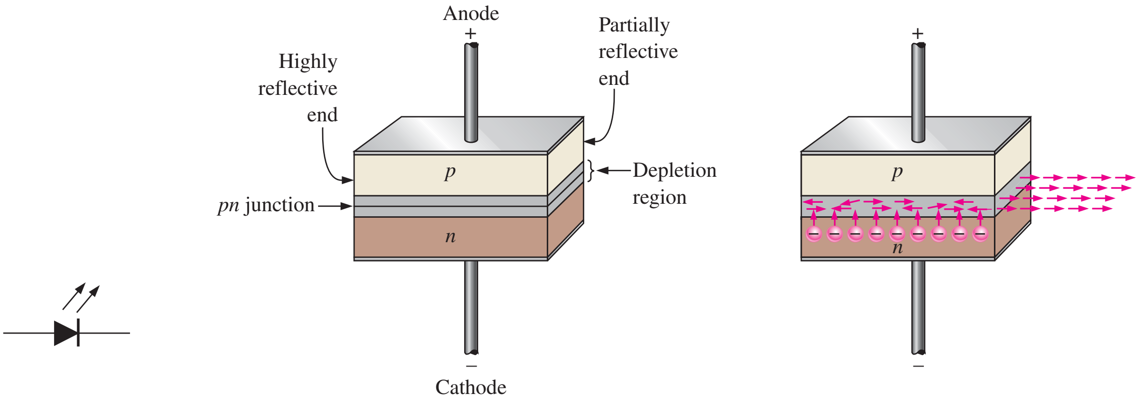
In this section, several types of diodes that you are less likely to encounter as a technician but are nevertheless important are introduced. Among these are the laser diode, the Schottky diode, the *pin* diode, the step-recovery diode, the tunnel diode, and the current regulator diode.

After completing this section, you should be able to

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

The Laser Diode

The term **laser** stands for *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation. Laser light is **monochromatic,** which means that it consists of a single color and not a mixture of colors. Laser light is also called **coherent light,** a single wavelength, as compared to incoherent light, which consists of a wide band of wavelengths. The laser diode normally emits coherent light, whereas the LED emits incoherent light. The symbols are the same as shown in Figure 3–48(a).



(a) Symbol (b) (c)

▲ FIGURE 3–48

Basic laser diode construction and operation.

The basic construction of a laser diode is shown in Figure 3–48(b). A *pn* junction is formed by two layers of doped gallium arsenide. The length of the *pn* junction bears a precise relationship with the wavelength of the light to be emitted. There is a highly reflective surface at one end of the *pn* junction and a partially reflective surface at the other end, forming a resonant cavity for the photons. External leads provide the anode and cathode connections.

The basic operation is as follows. The laser diode is forward-biased by an external voltage source. As electrons move through the junction, recombination occurs just as in an ordinary diode. As electrons fall into holes to recombine, photons are released. A released photon can strike an atom, causing another photon to be released. As the forward current is increased, more electrons enter the depletion region and cause more photons to be emitted. Eventually some of the photons that are randomly drifting within the depletion region strike the reflected surfaces perpendicularly. These reflected photons move along the depletion region, striking atoms and releasing additional photons due to the avalanche effect. This back-and-forth movement of photons increases as the generation of photons "snowballs" until a very intense beam of laser light is formed by the photons that pass through the partially reflective end of the *pn* junction.

Each photon produced in this process is identical to the other photons in energy level, phase relationship, and frequency. So a single wavelength of intense light emerges from the laser diode, as indicated in Figure 3–48(c). Laser diodes have a threshold level of current above which the laser action occurs and below which the diode behaves essentially as an LED, emitting incoherent light.

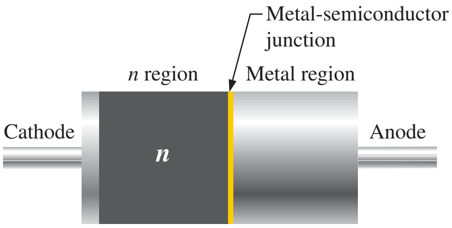
An Application Laser diodes and photodiodes are used in the pick-up system of compact disk (CD) players. Audio information (sound) is digitally recorded in stereo on the surface of a compact disk in the form of microscopic "pits" and "flats." A lens arrangement focuses the laser beam from the diode onto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

The Schottky Diode

Schottky diodes are high-current diodes used primarily in high-frequency and fast-switching applications. They are also known as *hot-carrier diodes.* The term *hot-carrier* is derived from the higher energy level of electrons in the *n* region compared to those in the metal region. A Schottky diode symbol is shown in Figure 3–49. A Schottky diode is formed by joining a doped semiconductor region (usually *n*-type) with a metal such as gold, silver, or platinum. Rather than a *pn* junction, there is a metal-to-semiconductor junction, as shown in Figure 3–50. The forward voltage drop is typically around 0.3 V because there is no depletion region as in a *pn* junction diode.

▲ **FIGURE 3–49**

Schottky diode symbol.



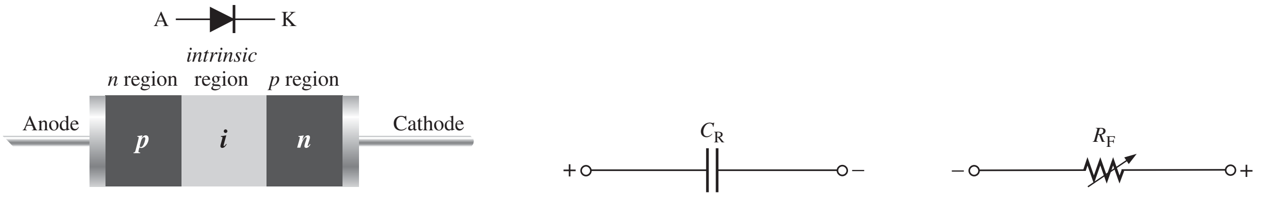
◀ **FIGURE 3–50**

Basic internal construction of a Schottky diode.

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

The *PIN* Diode

The *pin* diode consists of heavily doped *p* and *n* regions separated by an intrinsic (*i*) region, as shown in Figure 3–51(a). When reverse-biased, the *pin* diode acts like a nearly constant capacitance. When forward-biased, it acts like a current-controlled variable resistance. This is shown in Figure 3–51(b) and (c). The low forward resistance of the intrinsic region decreases with increasing current.



(a) Construction

(b) Reverse-biased

(c) Forward-biased

▲ **FIGURE 3–51**

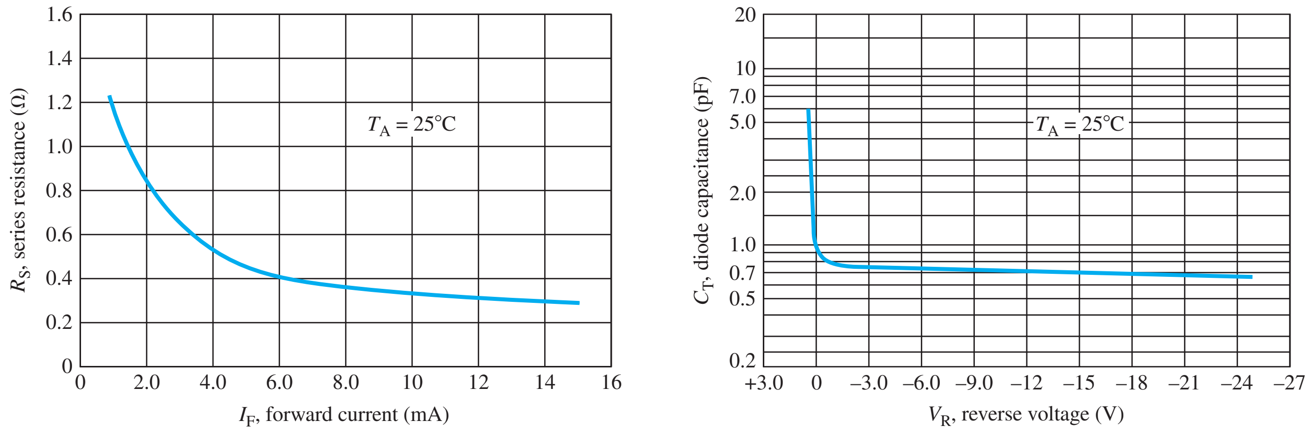
PIN diode.

GREENTECH NOTE

Thin-film PV solar panels, a relatively new development, use a somewhat different concept for the diodes than a standard crystalline silicon panel uses. The thin films are based on amorphous silicon, rather than crystalline silicon, as standard PV panels are. The *p* and *n* layers are separated by an intrinsic layer forming a *p-i-n* diode. Because they are very thin, light can penetrate the entire layer and multiple layers can be added with different band gaps to capture a larger percentage of the light spectrum. This is a promising method for forming large flexible panels.

The forward series resistance characteristic and the reverse capacitance characteristic are shown graphically in Figure 3–52 for a typical *pin* diode.

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



▲ FIGURE 3–52

PIN diode characteristics.

The Step-Recovery Diode

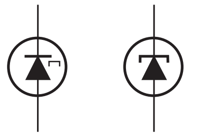
The step-recovery diode uses graded doping where the doping level of the semiconductive materials is reduced as the *pn* junction is approached. This produces an abrupt turn-off time by allowing a fast release of stored charge when switching from forward to reverse bias. It also allows a rapid re-establishment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

HISTORY NOTE

Leo Esaki won the Nobel Prize in physics in 1973 for the invention of the tunnel diode in the late 1950s. Surprisingly, in 1976 Robert Noyce, cofounder of Intel Corp., revealed in a talk before the MIT Club of New York that he had in his notebooks from 1956 a complete description of the tunnel diode. However, credit for the invention is given to Esaki and the tunnel diode is also known as the Esaki diode in his honor.

The Tunnel Diode

The tunnel diode exhibits a special characteristic known as *negative resistance.* This feature makes it useful in oscillator and microwave amplifier applications. Two alternate symbols are shown in Figure 3–53. Tunnel diodes are constructed with germanium or gallium arsenide by doping the *p* and *n* regions much more heavily than in a conventional rectifier diode. This heavy doping results in an extremely narrow depletion region. The heavy doping allows conduction for all reverse voltages so that there is no breakdown effect as with the conventional rectifier diode. This is shown in Figure 3–54.



▲ FIGURE 3–53

Tunnel diode symbols.

Also, the extremely narrow depletion region permits electrons to "tunnel" through the *pn* junction at very low forward-bias voltages, and the diode acts as a conductor. This is shown in Figure 3–54 between points *A* and *B*. At point *B*, the forward voltage begins to develop a barrier, and the current begins to decrease as the forward voltage continues to increase. This is the *negative-resistance region.*

$$R_{\mathrm{F}} = \frac{\Delta V_{\mathrm{F}}}{\Delta I_{\mathrm{F}}}$$

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

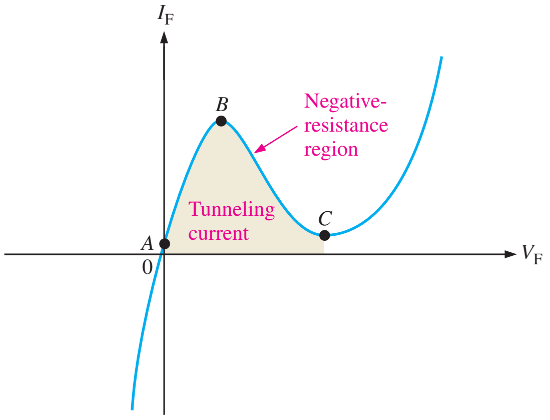


FIGURE 3–54

Tunnel diode characteristic curve.

An Application A parallel resonant circuit can be represented by a capacitance, inductance, and resistance in parallel, as in Figure 3–55(a). R_P is the parallel equivalent of the series winding resistance of the coil. When the tank circuit is "shocked" into oscillation by an application of voltage as in Figure 3–55(b), a damped sinusoidal output results. The damping is due to the resistance of the tank, which prevents a sustained oscillation because energy is lost when there is current through the resistance.

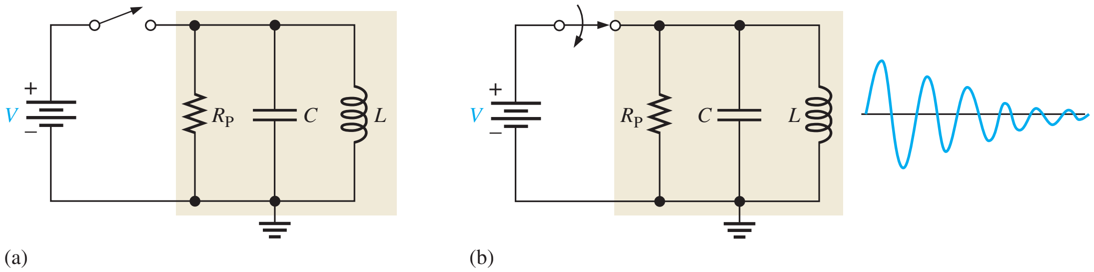


FIGURE 3–55

Parallel resonant circuit.

If a tunnel diode is placed in series with the tank circuit and biased at the center of the negative-resistance portion of its characteristic curve, as shown in Figure 3–56, a sustained oscillation (constant sinusoidal voltage) will result on the output. This is because the negative-resistance characteristic of the tunnel diode counteracts the positive-resistance characteristic of the tank resistance. The tunnel diode is only used at very high frequencies.

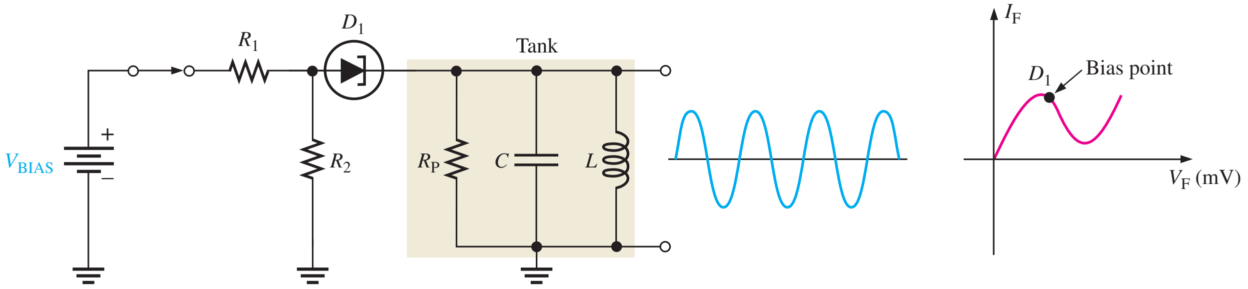


FIGURE 3–56

Basic tunnel diode oscillator.

Current Regulator Diode

The current regulator diode is often referred to as a constant-current diode. Rather than maintaining a constant voltage, as the zener diode does, this diode maintains a constant current. The symbol is shown in Figure 3–57.

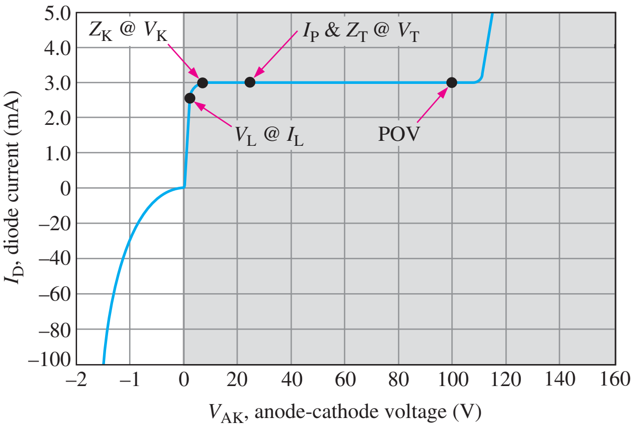
FIGURE 3–57

Symbol for a current regulator diode.

Figure 3–58 shows a typical characteristic curve. The current regulator diode operates in forward bias (shaded region), and the forward current becomes a specified constant value at forward voltages ranging from about 1.5 V to about 6 V, depending on the diode type. The constant forward current is called the *regulator current* and is designated I_P. For example, the 1N5283–1N5314 series of diodes have nominal regulator currents ranging from 220 μA to 4.7 mA. These diodes may be used in parallel to obtain higher currents. This diode does not have a sharply defined reverse breakdown, so the reverse current begins to increase for V_{AK} values of less than 0 V (unshaded region of the figure). This device should never be operated in reverse bias.

FIGURE 3–58

Typical characteristic curve for a current regulator diode.



In forward bias, the diode regulation begins at the limiting voltage, V_L, and extends up to the POV (peak operating voltage). Notice that between V_K and POV, the current is essentially constant. V_T is the test voltage at which I_P and the diode impedance, Z_T, are specified on a datasheet. The impedance Z_T has very high values ranging from 235 kΩ to 25 MΩ for the diode series mentioned before.

SECTION 3–5 CHECKUP

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

BIPOLAR JUNCTION TRANSISTORS

4

CHAPTER OUTLINE

CHAPTER OBJECTIVES

- Describe the basic structure of the BJT
- Discuss basic BJT operation
- Discuss basic BJT parameters and characteristics and analyze transistor circuits
- Discuss how a BJT is used as a voltage amplifier
- Discuss how a BJT is used as a switch
- Discuss the phototransistor and its operation
- Identify various types of transistor packages
- Troubleshoot faults in transistor circuits

KEY TERMS

- BJT
- Emitter
- Base
- Collector
- Gain
- Beta
- Saturation
- Linear
- Cutoff
- Amplification
- Phototransistor

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Study aids and Multisim files for this chapter are available at http://www.pearsonhighered.com/electronics

INTRODUCTION

The invention of the transistor was the beginning of a technological revolution that is still continuing. All of the complex electronic devices and systems today are an outgrowth of early developments in semiconductor transistors.

Two basic types of transistors are the bipolar junction transistor (BJT), which we will begin to study in this chapter, and the field-effect transistor (FET), which we will cover in later chapters. The BJT is used in two broad areas—as a linear amplifier to boost or amplify an electrical signal and as an electronic switch. Both of these applications are introduced in this chapter.

APPLICATION ACTIVITY PREVIEW

Suppose you work for a company that makes a security alarm system for protecting homes and businesses against illegal entry. You are given the responsibility for final development and for testing each system before it is shipped out. The first step is to learn all you can about transistor operation. You will then apply your knowledge to the Application Activity at the end of the chapter.

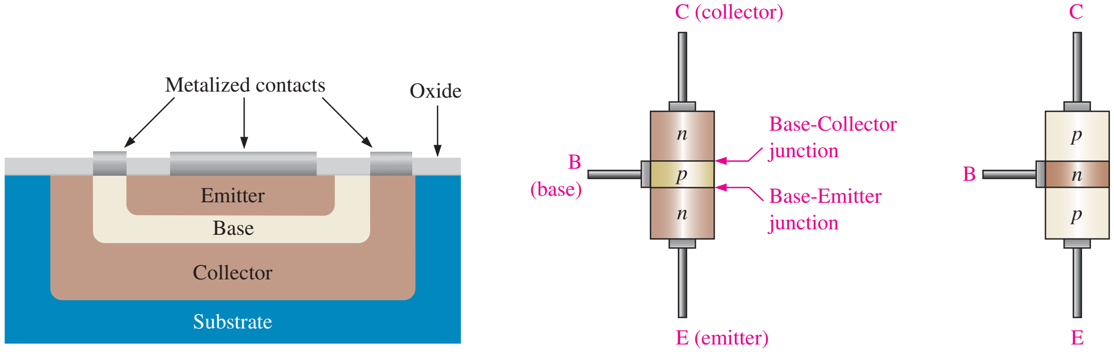
4–1 BIPOLAR JUNCTION TRANSISTOR (BJT) STRUCTURE

The basic structure of the bipolar junction transistor (BJT) determines its operating characteristics. In this section, you will see how semiconductive materials are used to form a BJT, and you will learn the standard BJT symbols.

After completing this section, you should be able to

- ❑ **Describe the basic structure of the BJT**
  - ◆ Explain the difference between the structure of an *npn* and a *pnp* transistor
  - ◆ Identify the symbols for *npn* and *pnp* transistors
  - ◆ Name the three regions of a BJT and their labels

The **BJT** is constructed with three doped semiconductor regions separated by two *pn* junctions, as shown in the epitaxial planar structure in Figure 4–1(a). The three regions are called **emitter**, **base**, and **collector**. Physical representations of the two types of BJTs are shown in Figure 4–1(b) and (c). One type consists of two *n* regions separated by a *p* region (*npn*), and the other type consists of two *p* regions separated by an *n* region (*pnp*). The term **bipolar** refers to the use of both holes and electrons as current carriers in the transistor structure.



(a) Basic epitaxial planar structure (b) *npn* (c) *pnp*

▲ FIGURE 4–1

Basic BJT construction.

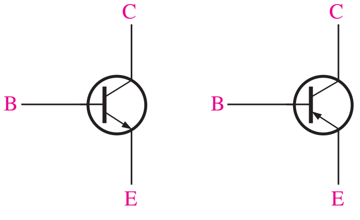
The *pn* junction joining the base region and the emitter region is called the *base-emitter junction*. The *pn* junction joining the base region and the collector region is called the *base-collector junction,* as indicated in Figure 4–1(b). A wire lead connects to each of the three regions, as shown. These leads are labeled E, B, and C for emitter, base, and collector, respectively. The base region is lightly doped and very thin compared to the heavily doped emitter and the moderately doped collector regions. ~~(The reason for this is discussed in the next section.)~~ Figure 4–2 shows the schematic symbols for the *npn* and *pnp* bipolar junction transistors.

HISTORY NOTE

The transistor was invented in 1947 by a team of scientists from Bell Laboratories. William Shockley, Walter Brattain, and John Bardeen developed the solid-state device that replaced the vacuum tube. Each received the Nobel prize in 1956. The transistor is arguably the most significant invention of the twentieth century.

▶ FIGURE 4–2

Standard BJT (bipolar junction transistor) symbols.



(a) *npn* (b) *pnp*