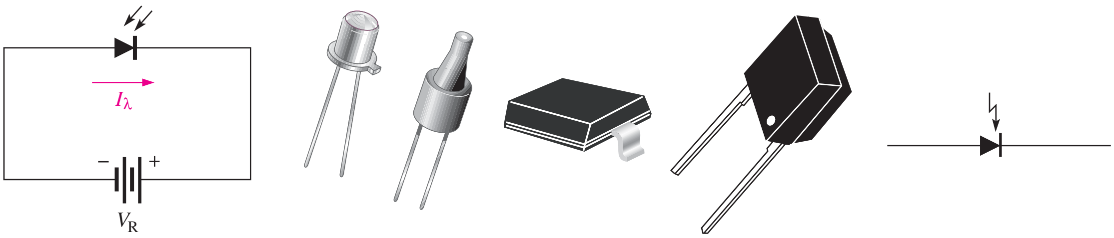
an incandescent bulb. Quantum dot filters can be designed to contain combinations of colors, giving designers control of the spectrum. The important advantage of quantum dot technology is that it does not lose the incoming light; it merely absorbs the light and reradiates it at a different frequency. 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).

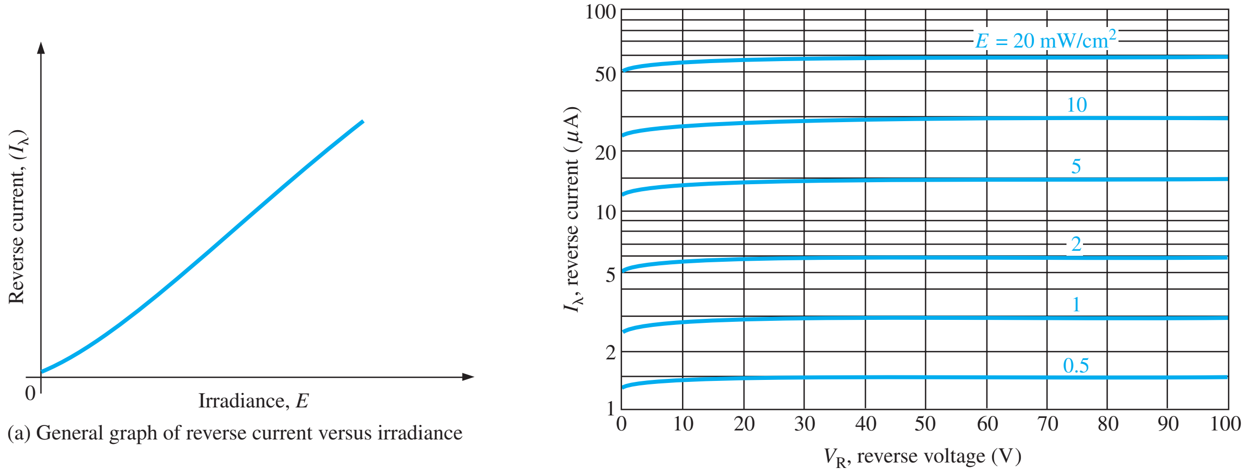
From the graph in Figure 3–45(b), you can see that the reverse current for this particular device is approximately 1.4 μA at a reverse-bias voltage of 10 V with an irradiance of 0.5 mW/cm^2. Therefore, the resistance of the device is

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

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.



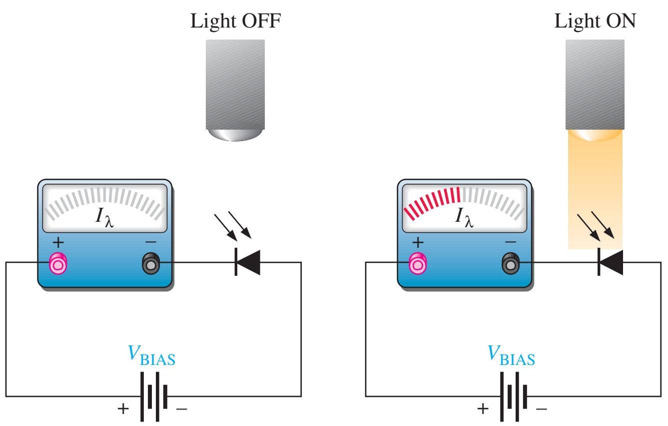
(a) General graph of reverse current versus irradiance

(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.