CHAPTER 7

Optoelectronic Devices

Learning Objectives

After completing this chapter, you will learn the following:

- Classification of optoelectronic devices.
- Photometric and radiometric terms.
- Characteristic parameters of photosensors.
- Principle of operation and application circuits of different types of photosensors, namely, photoconductors, photodiodes, solar cells, phototransistors, photoFETs, photoSCRs, photoTRIACs, vacuum photodiodes, photomultiplier tubes and image intensifier tubes.
- Different types of displays including light-emitting diodes (LEDs), liquid-crystal displays (LCDs) and cathode-ray tube (CRT) displays.
- Emerging trends in display technology.
- Optocoupler basics.

Optoelectronics is the field related to the study of electronic devices that emit, detect and control light. These devices are collectively referred to as the optoelectronic devices. Photoemitters, photosensors, displays and optocouplers are the popular optoelectronic devices. Photoemitters are electrical-to-optical transducers that are used to convert the electrical energy into output light. Some of the common photoemitters include light-emitting diodes (LEDs) and different types of displays. Photosensors are optical-to-electrical transducers that are used for converting the incident light energy into electrical output. Photoconductors, photodiodes, phototransistors, photomultiplier tubes and image intensifiers are some of the commonly used photosensors. Optocouplers are devices that use short optical transmission path to transfer signals between elements of a circuit. Optoelectronic devices constitute the heart of a variety of systems ranging from the simple gadgets like light meters to the most complex of military systems like precision guided munitions, laser range finders, target trackers, etc.; from instrumentation, measurement and diagnostic systems to space-based weather forecasting and remote sensing systems; from fiber-optic and laser-based communication applications to spectrophotometry and photometry applications and so on.

This chapter discusses in detail the fundamentals and application circuits of different types of optoelectronic devices. The chapter begins with classification of optoelectronic devices, followed by the definition of various radiometric and photometric terms commonly used in the field of optoelectronics. Discussion on photosensors, their characteristic parameters and principle of operation of different types of photosensors including photoconductors, photodiodes, phototransistors, photoSCRs and photoemissive devices follows next. After that different types of photoemitting devices and displays are discussed. The chapter concludes with a brief description on optocouplers. The text is adequately illustrated with practical circuits and a large number of solved examples.

7.1 Optoelectronic Devices

Optoelectronics is the field that deals with the study of devices that emit, detect and control light in the wavelength spectrum ranging from ultraviolet to far infrared. Optoelectronic devices include electrical-to-optical and optical-to-electrical transducers that covert electrical energy into light energy and light energy into electrical energy, respectively. Optocouplers also come in the broad category of optoelectronic devices.

Classification

As mentioned in the introductory section of the chapter, optoelectronic devices can be classified into photoemitters, photosensors and optocouplers. Figure 7.1 lists the different types of optoelectronic devices. Photosensors, their characteristic parameters, types and their application circuits are discussed in Sections 7.2–7.8. Different types of photoemitters are covered in Sections 7.9–7.13. Optocouplers are discussed in Section 7.14.

Radiometric and Photometric Units

Optoelectronics is the study of devices and systems emitting, sensing or controlling radiation in the infrared, visible and ultraviolet bands in the wavelength spectrum of 1 nm to 1 mm. There are two approaches used to define the units and quantities related to the filed of optoelectronics, namely, *radiometry* and *photometry*.

Radiometry is the study of properties and characteristics of electromagnetic radiation and the sources and receivers of electromagnetic radiation. Radiometry covers a wide frequency spectrum; however for the present chapter we will limit our discussion to frequencies from ultraviolet to infrared.

Photometry is the science that deals with visible light and its perception by human vision. The most important difference between radiometry and photometry is that in radiometry, the measurements are made with objective electronic instruments whereas in case of photometry, measurements are done with reference to the response of human eye.

In this section, we define the commonly used radiometric and photometric quantities.

Radiometric and Photometric Flux

Flux is defined as a flow phenomenon or a field condition occurring in space. It is a measure of the total power emitted from a source or incident on a particular surface. The symbol for radiometric flux is ϕ_R and for photometric flux it is ϕ_P. Radiometric flux is measured in watts (W) while photometric flux is measured in lumens (lm). Lumen is defined as the amount of photometric flux generated by 1/683 W of radiometric flux at 555 nm where the photopic vision sensitivity of eye is maximum.

Efficacy of a radiation source is defined as the ratio of photometric or luminous flux to the total radiometric flux from the source. It is given by

$$K = \frac{\phi_P}{\phi_R} \tag{7.1}$$

where K is the efficacy (lm/W), ϕ_P the photometric flux (lm), ϕ_R the radiometric flux (W).

Radiometric and Photometric Intensity

Intensity function describes the flux distribution in space. Radiometric intensity (I_R) is defined as the radiometric flux density per steradian. It is given by the following equation and is expressed in watts per steradian (W/sr):

$$I_R = \frac{\phi_R}{\Omega} \tag{7.2}$$

where ϕ_R is the radiometric flux (W) and Ω is the solid angle (sr).

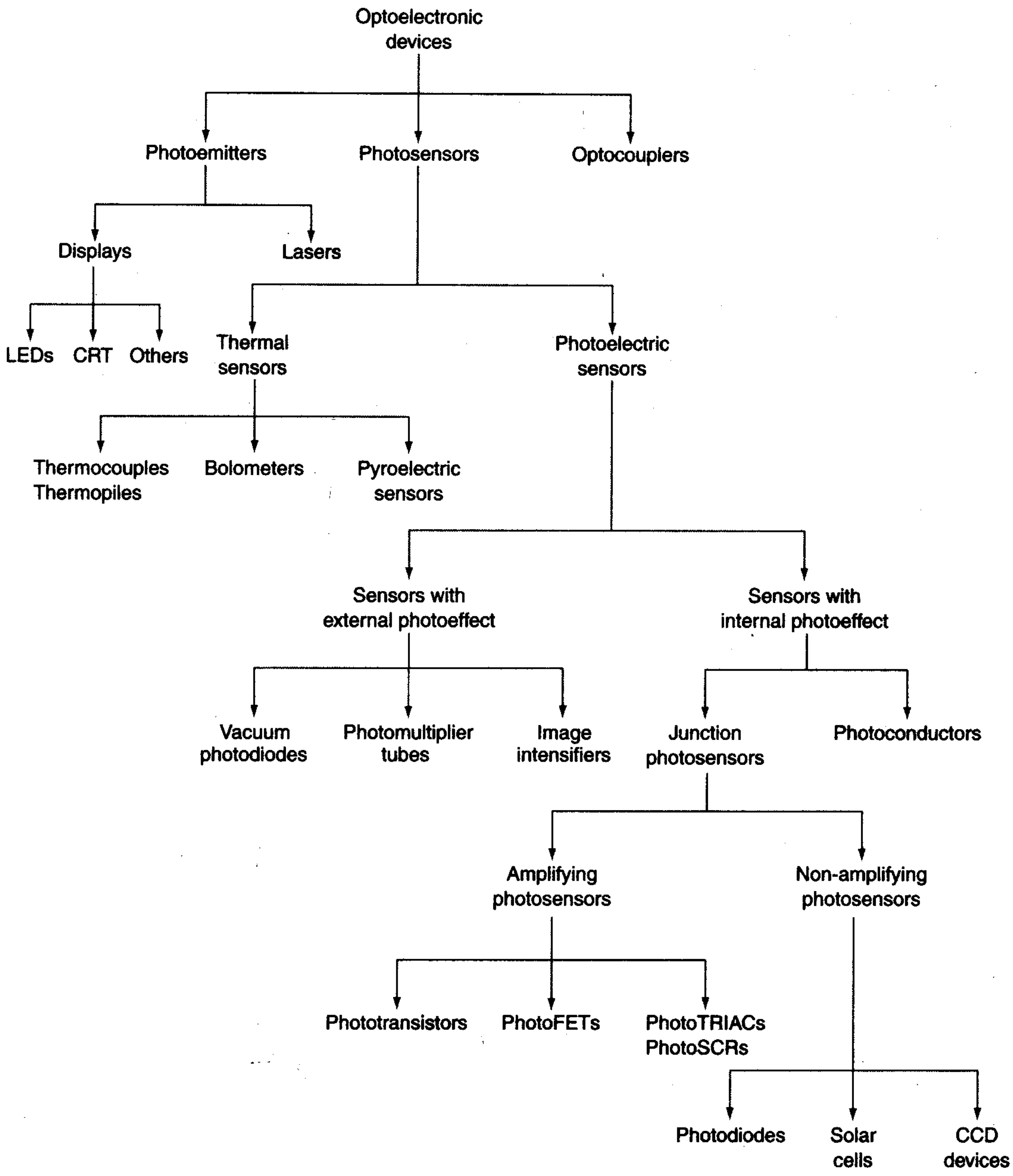


Figure 7.1 | Classification of optoelectronic devices.

Photometric or luminous intensity (I_P) is defined as the ratio of photometric flux density per steradian. It is given by

$$I_P = \frac{\phi_P}{\Omega} \tag{7.3}$$

where ϕ_P is the photometric flux (lm) and Ω the solid angle (sr).

The unit of photometric luminous intensity is Candela (Cd) and is equal to photometric flux density of one lumen per steradian (lm/sr).

Radiant Incidence and Illuminance

Radiant incidence (E_R) defines the radiometric flux distribution on a surface. It is expressed as

$$E_R = \frac{\phi_R}{A} \tag{7.4}$$

where ϕ_R is the radiometric flux (W) and A the area of flux distribution (m^2).

Illuminance (E_P) defines the photometric flux distribution on a surface and is expressed as

$$E_P = \frac{\phi_P}{A} \tag{7.5}$$

where ϕ_P is the luminous flux (lu) and A the area of flux distribution (m^2).

Two very commonly used units to define illuminance are lux and foot-candle. Lux is defined as the illumination of one lumen of luminous flux evenly distributed over an area of one square meter. Foot-candle is an old English unit and is defined as an illumination of one lumen of luminous flux evenly distributed over an area of one square foot.

1 foot-candle = 10.764 lux

Radiant Sterance and Luminance

Radiant sterance is defined as the ratio of radiometric flux per unit solid angle per unit area. Its units are W/sr/m^2. Luminance is defined as the ratio of photometric flux per unit solid angle per unit area. It is expressed in lm/sr/m^2.

7.2 Photosensors

Photosensors are electronic devices that detect the presence of light energy in the spectral band ranging from the ultraviolet to the far infrared band. As is shown in Figure 7.1, photosensors are broadly classified as thermal sensors and photoelectric sensors. *Thermal sensors* absorb radiation and react to the resulting temperature rise of the device. Their response depends only on the absorption characteristics of the device surface. Predominant thermal sensors include thermocouples, thermopiles, bolometers and pyroelectric sensors. In *photoelectric sensors*, the device response is caused by the direct interaction of the photons with the atoms. Photoelectric sensors are further classified as sensors with external photoeffect and sensors with internal photoeffect. In case of sensors with external photoeffect, the electrons are ejected from a photocathode surface placed in vacuum and are collected by a positively charged anode. Vacuum photodiodes, photomultiplier tubes and image intensifiers are examples of such sensors. Internal effect photosensors are semiconductor devices where the released electrons increase the conductivity of the sensor or result in increase in the current flowing through the device. Photoconductors, photodiodes, phototransistors, photoFETs, photoSCRs and photoTRIACs are some of the commonly used photoelectric sensors with internal photoeffect.

Photoelectric sensors can also be classified as imaging sensors and non-imaging sensors. Non-imaging sensors simply measure the intensity and/or spectral distribution of an incoming beam of radiation whereas imaging sensors also preserve the intensity versus position information in a two-dimensional field of view. Photodiodes, photomuliplier tubes (PMTs), photoconductors are all examples of non-imaging sensors. Imaging sensors include image intensifier tubes, CCDs and so on.

Characteristic Parameters

Major characteristic parameters used to characterize the performance of photosensors include responsivity, noise equivalent power (NEP), sensitivity (detectivity and dee-star), quantum efficiency, response time, noise and spectral response.

1. **Responsivity (R):** It is defined as the ratio of electrical output to radiant light input and is measured in A/W or V/W. Reponsivity is a function of wavelength of incident radiation and bandgap energy of the photosensor material. For most sensors it is specified at a particular wavelength. However in the case of some sensors like for measuring black-body radiation, it is integrated over a given wavelength range. It is also referred to as the figure of merit for the sensor system as the design of the signal processing stages depends on the amount of signal voltage or current generated by the photosensor.

   Responsivity figures for silicon PIN photodiodes are in the range of 0.4 to 0.6 A/W whereas for avalanche photodiodes, they are in the range of 40 to 80 A/W. Thermal sensors have poorer responsivity as compared to photoelectric sensors. As an example, the responsivity figure for pyroelectric sensors is in the range of 0.5 to 5 μA/W.
2. **Noise Equivalent Power (NEP):** NEP is the radiant power applied to the sensor that produces an output signal equal to the root mean square (RMS) noise output from the sensor, that is, the signal-to-noise ratio equals one. In other words, it is the minimum detectable radiation level of the sensor. The value of NEP is computed using the ratio of noise current to responsivity. For detection of weak signals, responsivity and NEP parameters are of utmost importance.
3. **Detectivity and Dee-Star:** Detectivity of a sensor is the reciprocal of its NEP. A sensor with higher detectivity value is more sensitive than a sensor with lower detectivity value. Detectivity, like NEP depends upon noise bandwidth and sensor area. To eliminate these factors, a normalized figure of detectivity referred to as "Dee-star" is used. It is defined as the detectivity normalized to an area of 1 cm^2 and a noise bandwidth of 1 Hz. The value of Dee-star (D^*) can be calculated using

$$D^* = D\sqrt{A\Delta f} \tag{7.6}$$

   where D^* is the Dee-star (W^{-1} cm Hz$^{1/2}$); D the detectivity (W^{-1}); A the detector area (cm^2); Δf the bandwidth (Hz).
4. **Quantum Efficiency or Quantum Yield:** An ideal photosensor should produce 1 photoelectron per incident photon of light. This is not true for practical sensors. The ratio of the number of photoelectrons released to the number of photons of incident light absorbed is referred to as the quantum efficiency of the sensor. It is the intrinsic efficiency of the sensor. The value of quantum efficiency (η) is computed using the formula

$$\eta = \frac{1240 \times R}{\lambda} \tag{7.7}$$

   where R is the responsivity in A/W and λ is the wavelength in nm.
5. **Response Time:** It is expressed as *rise time* parameter in photoelectric sensors and as *time constant* parameter in thermal sensors. Rise time is the time required by the output to reach from 10% to 90% of the final response and it determines the highest signal frequency to which a sensor can respond. Time constant is defined as the time required by the output to reach to 63% of the final response from zero initial value. Bandwidth of photoelectric sensors is related to its rise time by the following formula:

$$BW = \frac{0.35}{t_r} \tag{7.8}$$

   where BW is the bandwidth in MHz and t_r is the rise time is in μs.
6. **Sensor Noise:** Noise is the most critical factor in designing sensitive radiation detection systems. Noise in these systems is generated in photosensors, radiation sources and post-detection circuitry. Sensor noise includes Johnson noise, shot noise, generation-recombination noise and flicker noise.
   - **Johnson noise also known as Nyquist or thermal noise** is caused by the thermal motion of charged particles in a resistive element. The RMS value of the noise voltage depends on the resistance value, temperature and the system bandwidth and is given by

$$V_{\text{RMS}} = \sqrt{4kRT\Delta f} \tag{7.9}$$

where V_{RMS} is the RMS noise voltage (V); R the resistance value in Ω; k the Boltzmann constant (1.38×10^{-23} J/K); T the absolute temperature (K); Δf the system bandwidth (Hz).

- **Shot noise** in a photosensor is caused by the discrete nature of the photoelectrons generated. It depends on the average current through the photosensor and system bandwidth and is expressed by

$$I_{\mathrm{SRMS}} = \sqrt{2eI_{\mathrm{av}}\Delta f} \tag{7.10}$$

where I_{SRMS} is the RMS shot noise current (A); I_{av} the average current through the photosensor (A); e the charge of an electron (1.60×10^{-19} C); Δf the system bandwidth (Hz). In the case of a photodiode, the shot noise is generated both due to the dark current and the photocurrent.

- **Generation-recombination noise** is caused by the fluctuation in current generation and the recombination rates in a photosensor. This type of noise is predominant in photoconductive sensors operating at infrared wavelengths. The generation-recombination noise can be calculated using

$$I_{\mathrm{GRMS}} = 2eG\sqrt{\eta EA\Delta f} \tag{7.11}$$

where I_{GRMS} is the RMS generation-recombination noise current (A); e the charge of an electron (1.60×10^{-19} C); Δf the system bandwidth (Hz); E the radiant incidence (W/cm^2); A the sensor-receiving area (cm^2); G the photoconductive gain; η the quantum efficiency.

- **Flicker noise or 1/f noise** occurs in all conductors where the conducting medium is not a metal and exists in all semiconductor devices that require bias current for their operation. Its amplitude is inversely proportional to the frequency and usually the flicker noise is predominant at frequencies below 100 Hz. The total equivalent noise (I_{NEQ}) is calculated by adding the noise voltages or currents in the RMS manner as given in the following equation:

$$I_{\mathrm{NEQ}} = \sqrt{I_{\mathrm{JRMS}}^{2} + I_{\mathrm{SRMS}}^{2} + I_{\mathrm{GRMS}}^{2} + I_{\mathrm{FRMS}}^{2}} \tag{7.12}$$

where I_{JRMS} is the RMS Johnson noise current (A); I_{SRMS} is the RMS shot noise current (A); I_{GRMS} is the RMS generation–recombination noise current (A) and I_{FRMS} is the RMS flicker noise current (A).

7. **Spectral Response:** It describes the wavelength range over which a sensor responds. Most photoelectric materials have narrow spectral response whereas most thermal sensors have wide spectral response. As an example, the spectral response of silicon, germanium, indium gallium arsenide (InGaAs) photodiodes are in the range of 200–1100 nm, 500–1900 nm and 700–1700 nm, respectively, whereas that of thermistors is from 0.5 to 10 µm.

EXAMPLE 7.1

A photodiode has a noise current of 1 fA, responsivity figure of 0.5 A/W, active area of 1 mm^2 and rise time of 3.5 ns. Determine its (a) NEP, (b) detectivity, (c) D, (d) quantum efficiency at 850 nm.*

Solution

1. NEP = Noise current/Responsivity = $1 \times 10^{-15}/0.5 = 2 \times 10^{-15}$ W = 2 fW.
2. Detectivity = 1/NEP = $1/\ 2 \times 10^{-15} = 0.5 \times 10^{15}$ W^{-1}.
3. $D^{*} = D \times \sqrt{A \times \Delta f}$

   $A = 1\ \mathrm{mm}^2 = 1 \times 10^{-2}\ \mathrm{cm}^2$

   Δf(in MHz) = $0.35/t_{\mathrm{r}}$ (in µs) = $0.35/3.5 \times 10^{-3}$ = 100 MHz = 1×10^{8} Hz

   Therefore, $D^{*} = 0.5 \times 10^{15} \times \sqrt{(1 \times 10^{-2} \times 1 \times 10^{8})} = 5 \times 10^{17}$ W^{-1} cm Hz$^{1/2}$.
4. Quantum efficiency, $\eta = \left[\dfrac{1240 \times R}{\lambda}\right]$

   $\eta = [(1240 \times 0.5)/850] = 0.729$

EXAMPLE 7.2 *An oscilloscope is used to measure the output of a photodiode. Determine the rise time of the pulse as seen on the oscilloscope, given that the rise time of the photodiode is 1 ns, rise time of the light pulse is 5 ns and the bandwidth of the oscilloscope is 350 MHz.*

Solution

1. Given that the rise time of the light pulse is 5 ns and the rise time of the photodiode is 1 ns.
2. Bandwidth of the oscilloscope = 350 MHz. Therefore, rise time of the oscilloscope is t_r (in μs) = 0.35/BW (in MHz) = 0.35/350 = 1×10^{-3} μs = 1 ns.
3. Therefore, overall rise time = $\sqrt{(5\times10^{-9})^2 + (1\times10^{-9})^2 + (1\times10^{-9})^2}$
   $= 5.20 \times 10^{-9}\ \text{s} = 5.20\ \text{ns}$

7.3 Photoconductors

Photoconductors, also referred to as photoresistors, light-dependent resistors (LDRs) and photocells, are semiconductor photosensors whose resistance decreases with increasing incident light intensity. They are bulk semiconductor devices with no PN junction and having a structure as shown in Figure 7.2(a). When light is incident on the photoconductor, electrons jump from the valence band to the conduction band. Hence, the resistance of the semiconductor material decreases. The resistance change in a photoconductor is of the order of 6 decades, ranging from few tens of megaohms under dark conditions to few tens or hundreds of ohms under bright light conditions. Other features include wide dynamic response, spectral coverage from ultraviolet to far infrared and low cost. However, they are sluggish devices having response time of the order of hundreds of milliseconds.

The resistance–illuminance relation in photoconductors is described by

$$R_a = R_b \times \left(\frac{E_a}{E_b}\right)^{-\alpha} \tag{7.13}$$

where R_a and R_b are the resistances at illuminance levels of E_a and E_b, respectively. E_a and E_b are the illuminance levels in lux or foot-candles. α is the characteristic slope of the resistance–illuminance curve.

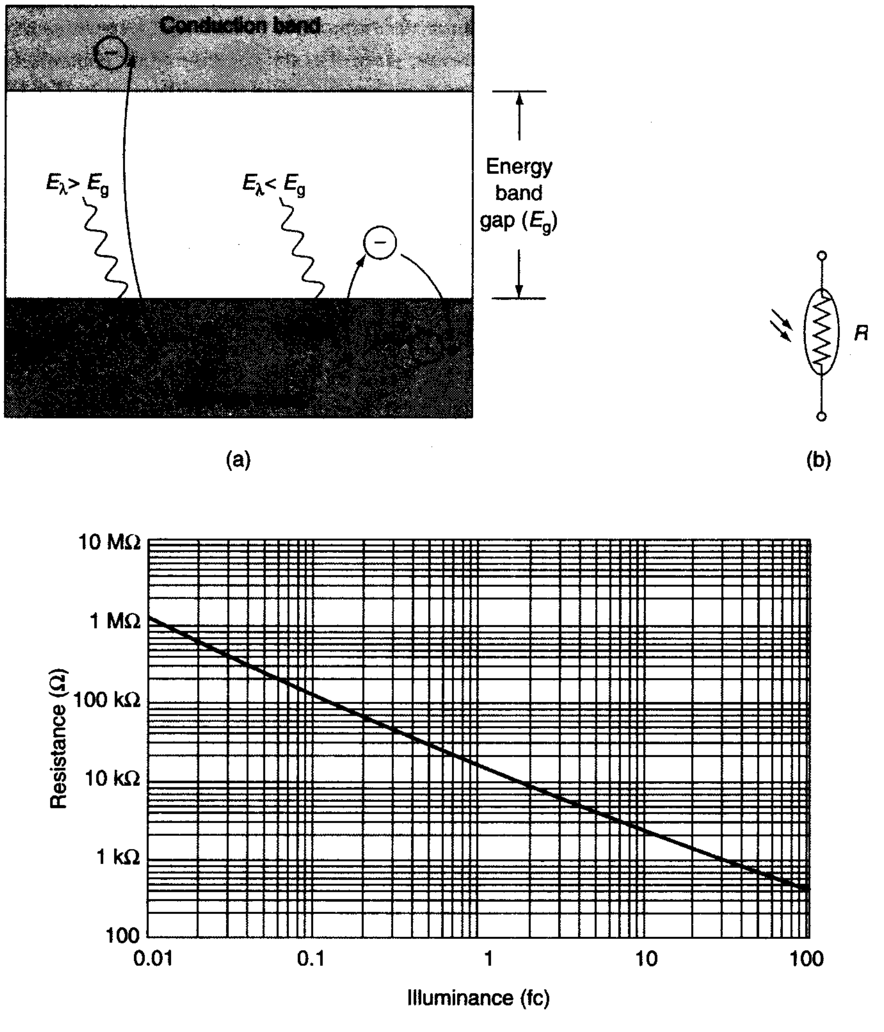
The value of α is in the range of 0.55 to 0.9. Figure 7.2(b) shows the circuit symbol of a photoconductor and Figure 7.2(c) shows the typical resistance–illuminance curve of a photoconductor.

Commonly used materials in photoconductors are cadmium sulphide (CdS), lead sulphide (PbS), lead selenide (PbSe), mercury cadmium telluride (HgCdTe) and germanium copper (Ge:Cu). Spectral response of some of these photoconductor materials is shown in Figure 7.3. Inexpensive CdS photoconductors are used in many consumer items like camera light meters, clock radios, security alarms, street lights and so on. On the other hand, Ge:Cu cells are used for infrared astronomy and infrared spectroscopy applications.

Photoconductors are further classified as intrinsic or extrinsic photoconductors depending upon whether an external dopant has been added or not to the semiconductor material. Intrinsic photoconductors operate at shorter wavelengths as the electrons have to jump from the valence to the conduction band. Extrinsic photoconductors have spectral response covering longer wavelengths.

Application Circuits

Photoconductors are usually used for detection of infrared radiation. When a bias is applied to the photoconductor in the absence of radiation, a current is generated that can be referred to as the dark current. When light is incident on the photoconductor, its resistance decreases and the current flowing through it increases. Photosignal is the increase in the current caused by radiation. Generally this photosignal is much smaller (of the order of few parts in thousand) than the dark current. Extracting this small signal from the dark current is the primary task of the front-end circuit.



(a) (b)

(c)

Figure 7.2 (a) Cross-section of a photoconductor; (b) circuit symbol of a photoconductor; (c) typical resistance–illuminance curve of a photoconductor.

Figures 7.4(a) and (b) show the simplest possible circuits using photoconductors. However, using photoconductors in these configurations reduces the responsivity of the conductor as the relative change in the circuit resistance is smaller because of the load resistance *R*. The choice of *R* and R_{sen} also affects the output voltage from the circuit. For Figure 7.4(a), higher the value of *R*, higher is the output voltage but the relative responsivity is poorer. Similarly, in case of circuit in Figure 7:4(b), higher the value of *R*, lower is the output voltage but the relative responsivity is better.

To overcome these problems, photoconductors are used in conjunction with operational amplifiers (also referred to as opamps) to obtain both better responsivity and high output voltage. There are two possible circuit configurations, namely, voltage mode amplifiers and current mode or transimpedance amplifiers. The basic transimpedance amplifier is shown in Figure 7.4(c). The non-inverting input of the opamp is connected to ground through resistance R_{com} to minimize the DC offset voltage.

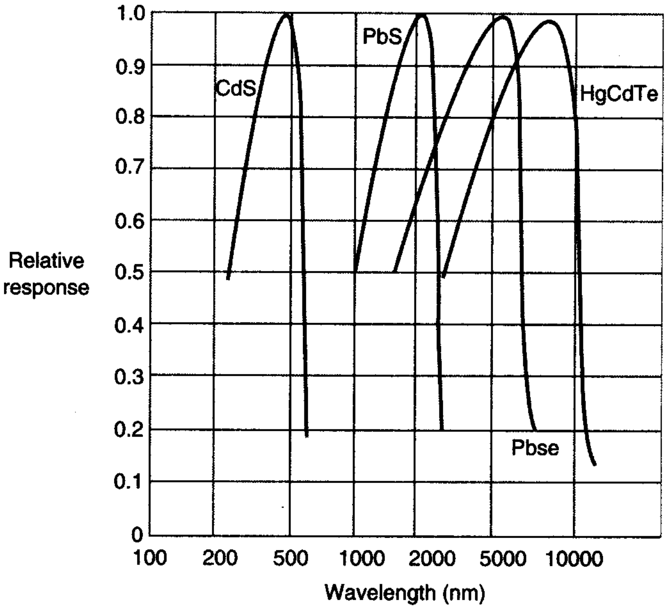


Figure 7.3 Spectral response of commonly used photoconductor materials.

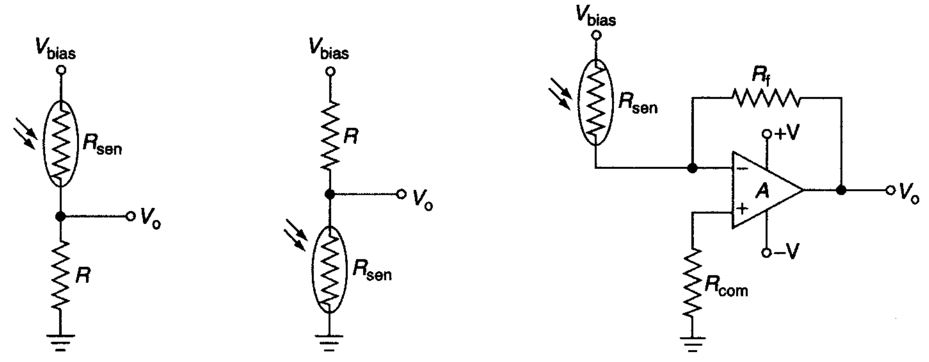
The output voltage V_o is given by

$$V_o = -(R_f/R_{sen}) \times V_{bias} \tag{7.14}$$

The gain of the transimpedance amplifier should be so set that the amplifier does not saturate at the maximum expected radiation intensity. Also, if the bias voltage of the photoconductor is more than the maximum rated input voltage of the opamp then a Zener diode should be connected between the inverting input of the opamp and the ground terminal.

Theoretically, the signal voltage can be obtained by subtracting the output voltage in dark condition from the voltage signal in Eq. (7.14) and is given by

$$V_o = -[R_f/R_{sen} - R_f/R_{dark}] \times V_{bias} \tag{7.15}$$



(a) (b) (c)

Figure 7.4 (a) and (b) Simplest application circuits using photoconductors; (c) application circuit of photoconductor using opamp in the transimpedance mode.

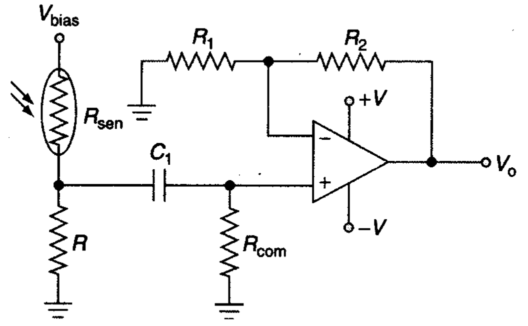


Figure 7.5 Application circuit of photoconductor using voltage mode amplifier with AC coupling.

where R_{dark} is the resistance value of the photoconductor in the absence of radiation.

However, practically it is not a feasible solution as the dark resistance of the photoconductor is a strong function of temperature and even a slight increase in temperature decreases the value of dark resistance by a large amount and vice-versa. So, the detector temperature has to be controlled to the order of 0.01°C or better, which is often not feasible.

The most common method used to extract the signal is to modulate the incident radiation at a specific frequency, either by placing a mechanical chopper in front of the detector or by electrically modulating the radiation source. The signal generated due to radiation is now an AC signal while the dark current is a DC signal. The AC signal can be separated from the DC background signal using an AC coupled amplifier. A voltage mode amplifier using AC coupling is shown in Figure 7.5.

EXAMPLE 7.3 *Design a circuit using a photoconductor that generates a logic HIGH voltage when the light incident on it is above 200 lux, given that the photoconductor has a resistance of 10 kΩ at light level of 100 lux, $\alpha = 0.5$, power supply voltage (V_{CC}) = 10 V and the reference voltage of the Zener diode is 2.5 V.*

Solution

1. The resistance of the photoconductor at 200 lux can be calculated using the expression
$$R_a = R_b \times \left(\frac{E_a}{E_b}\right)^{-\alpha}$$
Here $R_b = 10$ kΩ, $E_b = 100$ lux, $E_a = 200$ lux, $\alpha = 0.5$. Therefore,
$$R_a = 10 \times 10^3 \times (200/100)^{-0.5} = 10 \times 10^3 \times (2)^{-0.5} = 7.07 \text{ k}\Omega$$
2. Figure 7.6 shows one of the possible circuit configurations that can be used for the given application.
3. The comparator output will go high when the voltage at positive terminal exceeds 2.5 V.
4. The value of resistance R_L can be calculated using $[(V_{CC} \times R_L)/(R_L + R_{sen})] = 2.5$ V.
5. As $V_{CC} = 10$ V and R_{sen} at 200 lux is 7.07 kΩ.
$$(10 \times R_L)/(7.07 \times 10^3 + R_L) = 2.5$$
$$4R_L = 7.07 \times 10^3 + R_L$$
$$R_L = 2.36 \text{ k}\Omega$$

6. For a 10 mA current through the Zener diode, value of resistor R can be calculated using the expression $R = [(V_{CC} - V_Z)/I_Z] = (10 - 2.5)/(10 \times 10^{-3}) = 750\ \Omega$.

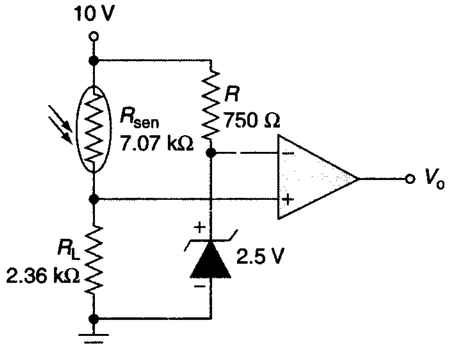


Figure 7.6 | Solution to Example 7. 3.

7.4 Photodiodes

Photodiodes are junction semiconductor light sensors that generate current or voltage when the PN junction in the semiconductor is illuminated by light of sufficient energy. The spectral response of the photodiode is a function of the bandgap energy of the material used in its construction. The upper cut-off wavelength of a photodiode is given by

$$\lambda_c = \frac{1240}{E_g} \tag{7.16}$$

where λ_c is the cut-off wavelength (nm) and E_g the bandgap energy (eV).

Photodiodes are mostly constructed using silicon, germanium, indium gallium arsenide (InGaAs), lead sulphide (PbS) and mercury cadmium telluride (HgCdTe). Figure 7.7 shows the spectral characteristics of these photodiodes.

Photodiode Types

Depending upon their construction there are several types of photodiodes. These include PN photodiodes, PIN photodiodes, Schottky-type photodiodes and avalanche photodiodes (APDs).

PN Photodiodes

PN photodiodes comprise a PN junction as shown in Figure 7.8(a). When light with sufficient energy strikes the diode, photoinduced carriers are generated which include electrons in the conduction band of the P-type material and holes in the valence band of the N-type material. When the photodiode is reverse-biased, the photoinduced electrons will move down the potential hill from the P-side to the N-side. Similarly, the photoinduced holes will add to the current flow by moving across the junction to the P-side from the N-side. Shorter wavelengths are absorbed at the surface while the longer wavelengths penetrate deep into the diode. Figure 7.8(b) shows the mechanism of conversion of incident light photons into electric current in a PN photodiode. PN photodiodes are used for precision photometry applications like medical instrumentation, analytical instruments, semiconductor tools and industrial measurement systems.

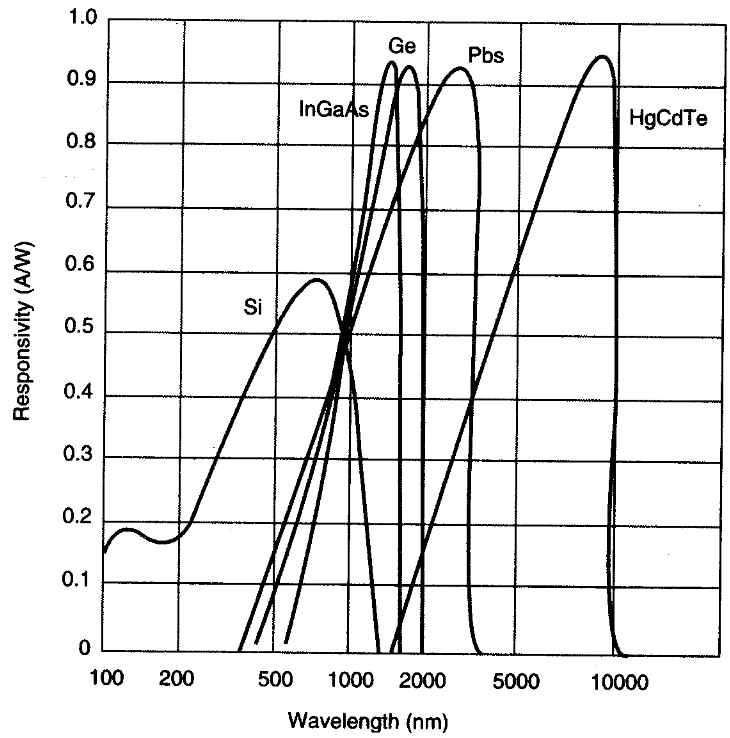
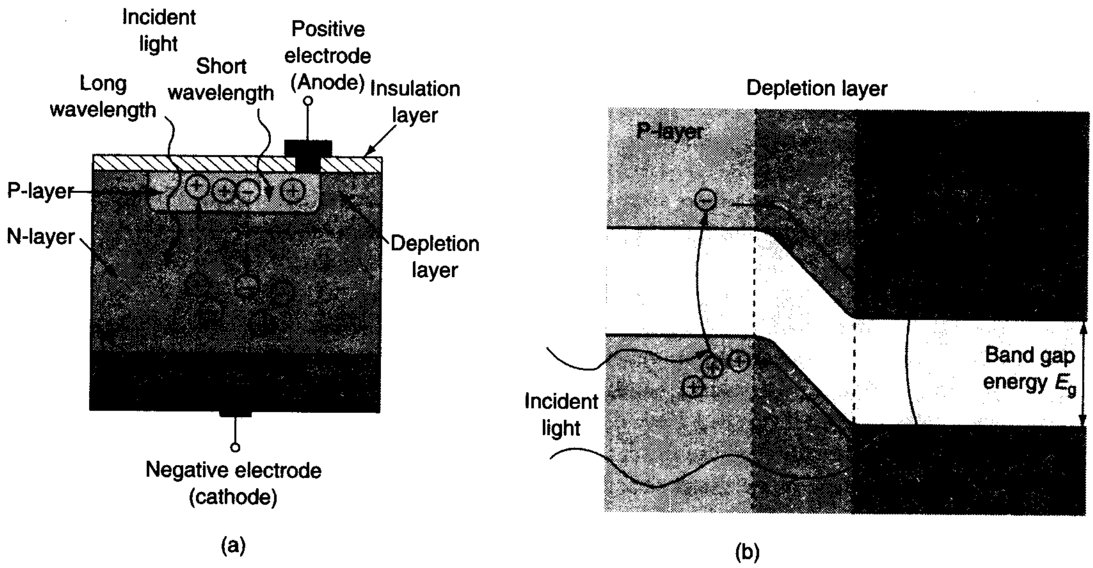


Figure 7.7 Spectral characteristics of photodiodes.



(a)

(b)

Figure 7.8 (a) Cross-section of a PN photodiode; (b) generation of current in a PN photodiode.

PIN Photodiodes

In PIN photodiodes, an extra high resistance intrinsic layer is added between the P and the N layers (Figure 7.9). This has the effect of reducing the transit or diffusion time of the photoinduced electron-hole pairs which in turn results in improved response time. PIN photodiodes feature low capacitance, thereby offering high bandwidth making them suitable for high-speed photometry as well as optical communication applications.

Schottky Photodiodes

In Schottky-type photodiodes, a thin gold coating is sputtered onto the N material to form a Schottky effect PN junction. Schottky photodiodes have enhanced ultraviolet (UV) response.

Avalanche Photodiodes (APD)

APDs are high-speed, high-sensitivity photodiodes utilizing an internal gain mechanism that functions by applying a relatively higher reverse-bias voltage than that is applied in the case of PIN photodiodes.

Figure 7.10 shows the cross-section of an APD. APDs are so constructed as to provide a very uniform junction that exhibits the avalanche effect at reverse-bias voltages between 30 V and 200 V. The electron-hole pairs that are generated by incident photons are accelerated by the high electric field to force the new electrons to move from the valence band to the conduction band. In this way, the multiplication of the order of 50–100 is achieved. APDs have fast response times similar to that of PIN photodiodes. Responsivity figures for silicon PIN photodiodes are in the range of 0.4–0.6 A/W whereas for APDs they are between 40 and 80 A/W, around

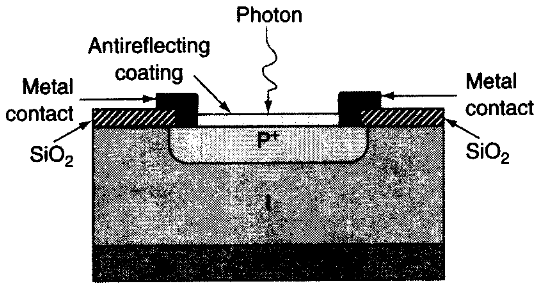


Figure 7.9 | PIN photodiode.

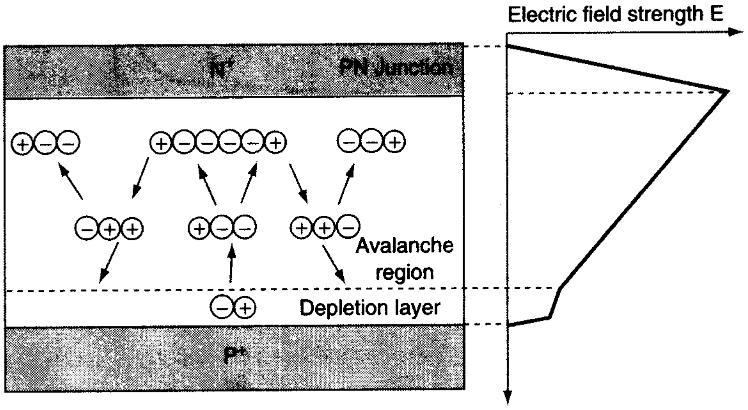


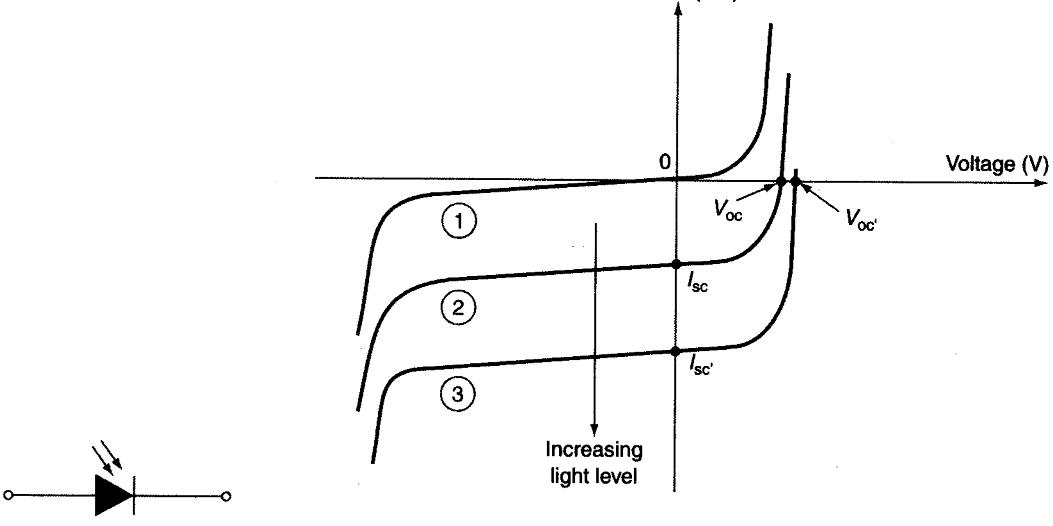
Figure 7.10 | Avalanche photodiode.

100 times more than that of PIN photodiodes. Moreover, they offer excellent signal-to-noise ratio similar to that offered by photomultiplier tubes. Hence, they are used in a variety of applications requiring high sensitivity such as long distance optical communication and optical distance measurement.

V–I Characteristics of a Photodiode

Figures 7. 11(a) and (b) show the circuit symbol and V–I characteristics of a photodiode. As we can see from Figure 7.11(b), the V–I characteristic curve of the photodiode in the dark state curve ① is similar to that of a conventional rectifier diode. However, when light strikes, curve shifts downwards with increasing intensity of light. If the photodiode terminals are shorted, a photocurrent proportional to the light intensity will flow in a direction from anode to cathode. If the circuit is open, then an open circuit voltage will be generated with the positive polarity at the anode. It may be mentioned here that the short circuit current is linearly proportional to light intensity while the open circuit voltage has a logarithmic relationship with the light intensity.

Photodiodes can be operated in two modes namely the *photovoltaic* mode and *photoconductive* mode. In the photovoltaic mode of operation, no bias voltage is applied and due to the incident light, a forward voltage is produced across the photodiode. In photoconductive operational mode, a reverse-bias voltage is applied across the photodiode. This widens the depletion region, resulting in higher speed of response. As a thumb rule, all applications requiring bandwidth less than 10 kHz can use photodiodes in photovoltaic mode. For all other applications, photodiodes are operated in photoconductive mode. Moreover, the linearity of a photodiode is also improved when it is operated in the photoconductive mode. However, there is an increase in the noise current of the photodiode when it is operated in the photoconductive mode. This is due to the reverse saturation current flowing through the photodiode. The current that flows through the photodiode when no light is incident on it is referred to as the dark current. The value of dark current is typically in the range of 1–10 nA for photoconductive operational mode. When the photodiode is operated in the photovoltaic mode, the value of dark current is zero.

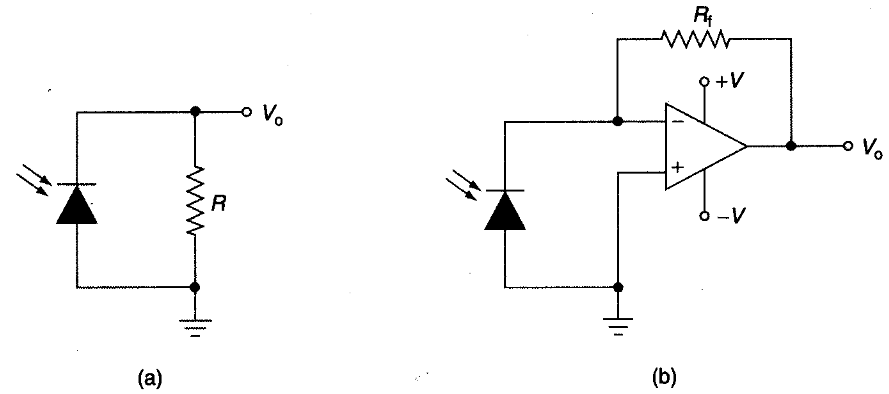


(a) (b)

Figure 7.11 (a) Circuit symbol of a photodiode; (b) V–I characteristics of a photodiode.

Photodiode Application Circuits

As discussed above, photodiodes can be operated in two modes, namely, the photovoltaic mode and the photoconductive mode. In the photovoltaic mode, the photodiode is operated with zero external bias voltage and is generally used for low-speed applications or for detecting low light levels. Figures 7.12(a) and (b) show two commonly used application circuits employing photodiodes in the photovoltaic mode. The output voltages for these circuits are given by ($I_{\text{det}} \times R$) and ($I_{\text{det}} \times R_{\text{f}}$), respectively, where I_{det} is the current through the photodiode. The circuit in Figure 7.12(b) offers better linearity than the circuit in Figure 7.12(a) as the equivalent input resistance across the photodiode in this case is R_{f}/A, where A is the open-loop gain of the operational amplifier. It is obvious that value of R_{f}/A is much smaller as compared to that of R in the case of Figure 7.12(a). Figure 7.13 shows the load-line analysis of a photodiode operating in the photovoltaic mode. The load line corresponding to the smaller load is closer to the current axis and the one corresponding to a larger load is close to the voltage axis. As is evident from the figure, for a better linear response the equivalent resistance across the photodiode should be as small as possible.



(a) (b)

Figure 7.12 | Application circuits of photodiodes in photovoltaic mode.

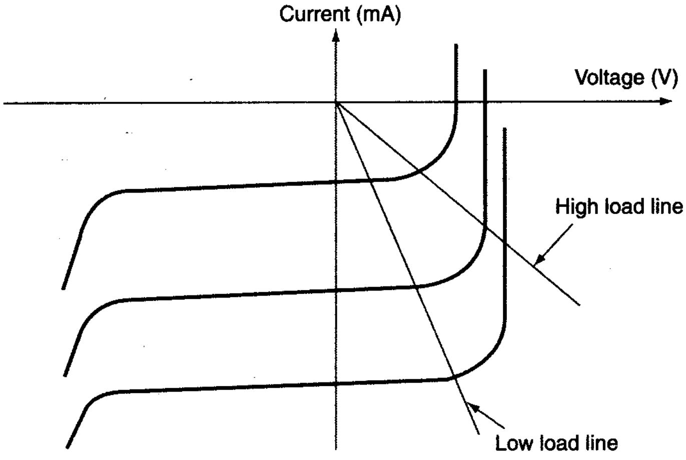


Figure 7.13 | Load-line analysis of photodiode in photovoltaic mode.

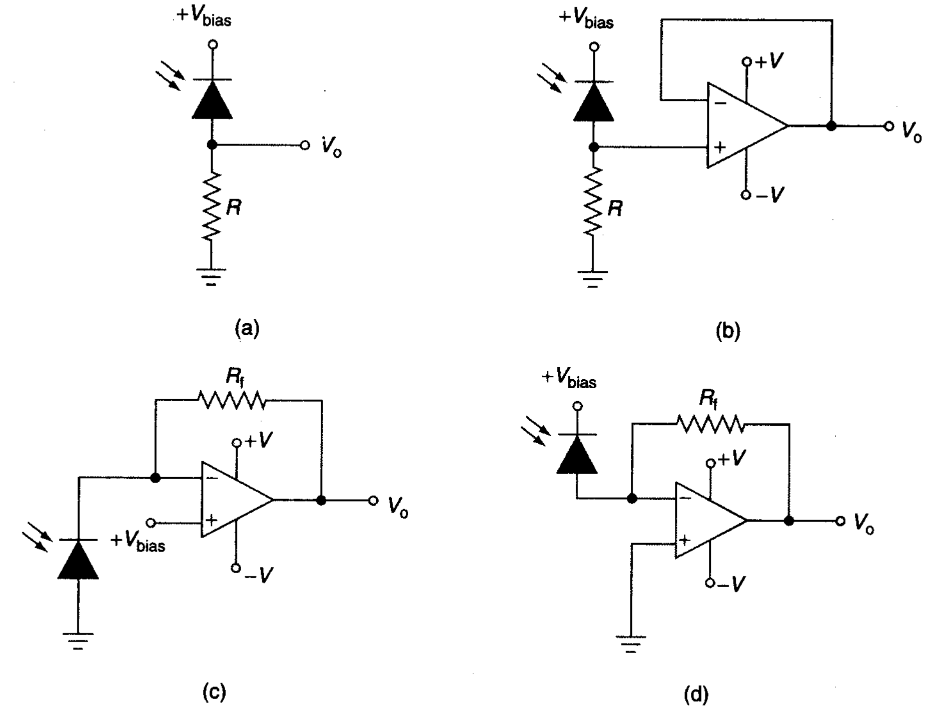


Figure 7.14 | Application circuits of photodiodes operating in photoconductive mode.

Figures 7.14(a)–(d) show four possible circuits using photodiodes in the photoconductive mode. In Figure 7.14(b), the operational amplifier is used as a voltage amplifier whereas in Figures 7.14(c) and (d) the operational amplifier is used in the transimpedance mode. For the circuit in Figure 7.14(b), the output voltage and the effective resistance across the photodiode are ($I_{det} \times R$) and R, respectively. I_{det} is the current flowing through the photodiode. The output voltage and the effective resistance across the photodiode in Figures 7.14(c) and (d) are ($I_{det} \times R_f$) and R_f/A, respectively, where I_{det} is the photodiode current and A is the open-loop gain of the operational amplifier. The response of the photodiode for different loads operating in photoconductive mode is shown in Figure 7.15. As we can see, circuits with lower value of load resistance offer better linearity.

Avalanche photodiodes (*APDs*) are also connected in a similar manner as discussed above except that a much higher reverse-bias voltage is required. Also, the power consumption of APDs during operation is much higher than that of PIN photodiodes and is given by the product of input signal, sensitivity and reverse-bias voltage. Hence a protective resistor is added to the bias circuit as shown in Figure 7.16 or a current-limiting circuit is used.

As the gain of APDs changes with temperature, so if they are operated over a wide temperature range, some temperature offset circuit has to be added which changes the reverse-bias voltage with temperature so as to compensate for the change in gain with temperature. As an alternative, a temperature controller can be added to keep the temperature of APD constant. For detecting low signal levels, shot noise from the background light should be limited by using optical filters, by source modulation or by restricting the field-of-view.

Solar Cells

Solar cell is a device whose operation is very similar to that of a photodiode operating in the photovoltaic mode. The operational principle of the basic solar cell is based on the photovoltaic effect. As mentioned above, due to the photovoltaic effect, there is a generation of an open circuit voltage across a PN junction

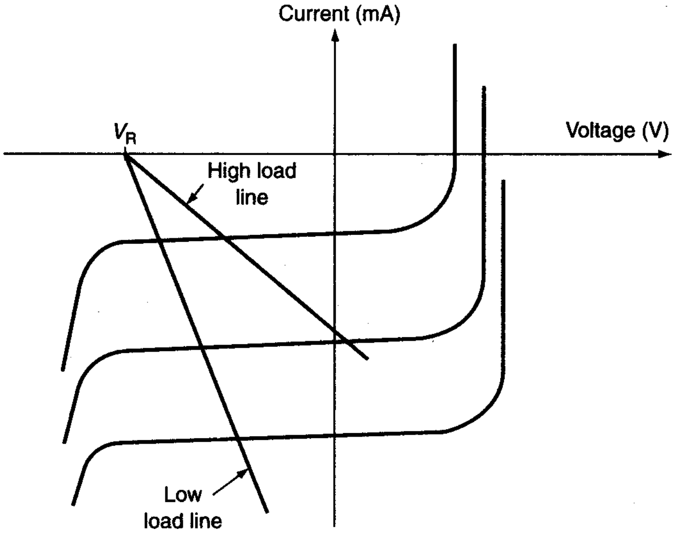


Figure 7.15 | Load-line analysis of photodiodes operating in photoconductive mode.

when it is exposed to light, which is the solar radiation in case of a solar cell. This open circuit voltage leads to the flow of electric current through a load resistance connected across it as shown in Figure 7.17.

As is evident from the figure, the impinging photon energy leads to generation of electron-hole pairs. The electron-hole pairs either recombine and vanish or start drifting in the opposite directions with electrons moving towards the N-region and holes moving towards the P-region. This accumulation of positive and negative charge carriers constitutes the open circuit voltage. This voltage can cause a current to flow through an external load or when the junction is shorted, the result is a short circuit current whose magnitude is proportional to input light intensity. The output voltage and the current-delivering capability of an individual solar cell are very small for it to be of any use as an electrical power input to any system. As an example, a typical solar cell would produce 500 mV output with a load current capability of about 150 mA. The series-parallel arrangement of solar cells is done to get

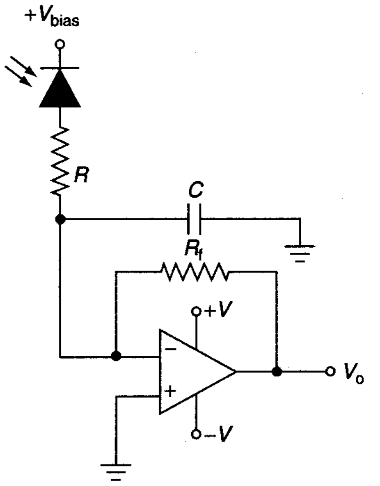


Figure 7.16 | Application circuit using avalanche photodiode.

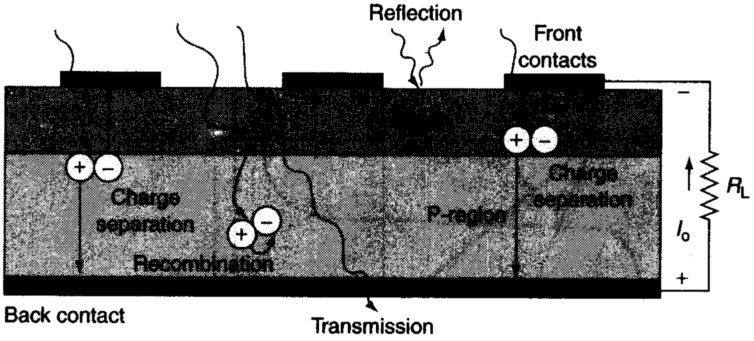


Figure 7.17 | Principle of operation of a solar cell.

the desired output voltage with required power delivery capability. The series combination is used to enhance the output voltage while the parallel combination is used to enhance the current rating.

Figure 7.18 shows the current–voltage and power–voltage characteristics of a solar cell. As is evident from the figure, solar cell generates its maximum power at a certain voltage. The point of maximum power is called maximum power point (MPP). The cell voltage and the corresponding current are less than the open circuit voltage (V_{OC}) and the short circuit current (I_{SC}), respectively, at the maximum power point.

Solar cell efficiency is the ratio of maximum electrical power produced by the solar cell to the radiant power incident on the solar cell area. The efficiency figure for some crystalline solar cells is in excess of 20%. The most commonly used semiconductor material for making solar cells is silicon. Both crystalline and amorphous forms of silicon are used for the purpose. Another promising material for making solar cells is gallium arsenide (GaAs). Gallium arsenide solar cells when perfected will be light weight and more efficient.

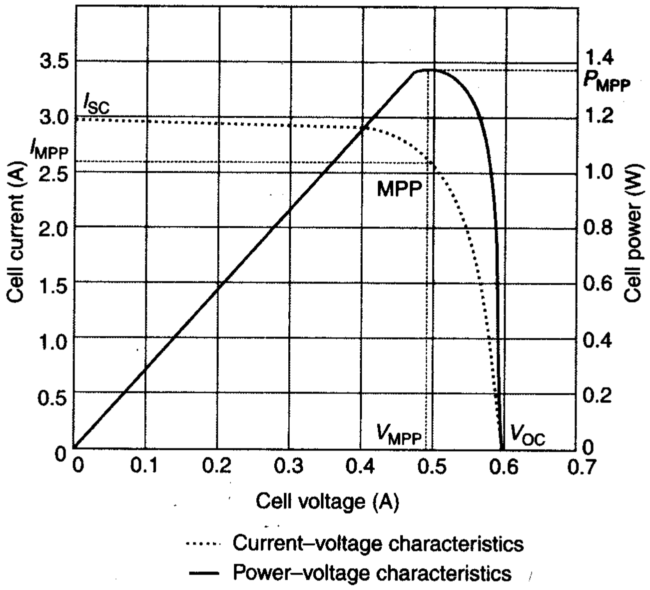


Figure 7.18 | Current–voltage and power–voltage characteristics of a solar cell.

EXAMPLE 7.4

Determine the cut-off wavelengths for silicon and germanium photodiodes, given that their bandgap energies are 1.1 eV and 0.72 eV, respectively, at 25°C. How will the cut-off wavelength change when the operating temperature changes from 25°C to 200°C?

Solution

1. The cut-off wavelength is given by the formula
$$\lambda_c = \frac{1240}{E_g}$$
2. At 25°C, for silicon photodiode, $E_g = 1.1$ eV, therefore $\lambda_c = 1240/1.1 = 1127.27$ nm.
3. The temperature variation of the bandgap energy of silicon semiconductor, as discussed in Chapter 1, is given by $E_g(T) = 1.21 - 3.60 \times 10^{-4} T$, where T is the temperature in Kelvin.
4. Therefore, bandgap energy of silicon photodiodes at 200°C is given by
$$E_g = 1.21 - 3.60 \times 10^{-4} \times 473 = 1.21 - 0.17 = 1.04 \text{ eV}$$
5. The cut-off wavelength of silicon photodiodes at 200°C is given by
$$\lambda_c = 1240/1.04 = 1192.31 \text{ nm}$$
6. At 25°C, for germanium photodiode, $E_g = 0.72$ eV, therefore $\lambda_c = 1240/0.72 = 1722.22$ nm.
7. The temperature variation of the bandgap energy of germanium semiconductor, as discussed in Chapter 1, is given by $E_g(T) = 0.785 - 2.23 \times 10^{-4} T$, where T is the temperature in Kelvin.
8. Therefore, bandgap energy of germanium photodiodes at 200°C is given by
$$E_g = 0.785 - 2.23 \times 10^{-4} \times 473 = 0.785 - 0.105 = 0.68 \text{ eV}$$
9. The cut-off wavelength of germanium photodiodes at 200°C is given by $\lambda_c = 1240/0.68 = 1823.53$ nm.

EXAMPLE 7.5

For the circuit shown in Figure 7.19, determine the amplitude of the output voltage pulse when the light pulse having wavelength of 1000 nm, pulse width of 1 s and energy

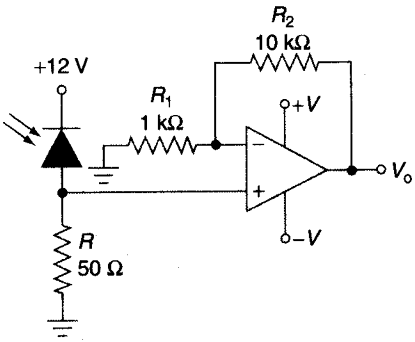


Figure 7.19 | Example 7.5.

of 10 mJ is incident on the active area of the photodiode. The responsivity of the photodiode is 0.5 A/W at 1000 nm.

Solution

1. The incident light pulse has an energy of 10 mJ and a pulse width of 1 s.
2. Therefore, the input peak power = $10 \times 10^{-3}/1 = 10$ mW.
3. Output current from the photodiode = $0.5 \times 10 \times 10^{-3} = 5$ mA.
4. Voltage across the resistance $R = 50 \times 5 \times 10^{-3} = 250$ mV.
5. Gain of the amplifier = $(1 + R_2/R_1) = [1 + (10 \times 10^3/1 \times 10^3)] = 11$.
6. Voltage amplitude of the output pulse = $250 \times 10^{-3} \times 11 = 2.75$ V.

7.5 Phototransistors

Figure 7.20 shows the construction of a phototransistor. Phototransistors are usually connected in the common-emitter configuration with base open and the radiation is concentrated on the region near the collector–base junction. Figure 7.21(a) shows the circuit symbol of the phototransistor and Figure 7.21(b) shows the typical V–I characteristics of a phototransistor. When there is no radiation incident on the phototransistor, the collector current is due to the thermally generated carriers and is given by

$$I_C = (\beta + 1) I_{CO} \tag{7.17}$$

where I_{CO} is the reverse saturation current.

In phototransistors, this current is referred to as the dark current. When light is incident on the phototransistor, photocurrent is generated and the magnitude of the collector current increases. The expression for the collector current is given by

$$I_C = (\beta + 1)(I_{CO} + I_\lambda) \tag{7.18}$$

where I_λ is the current generated due to incident light photons.

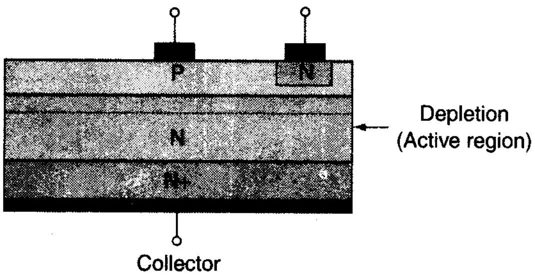


Figure 7.20 | Cross-section of a phototransistor.

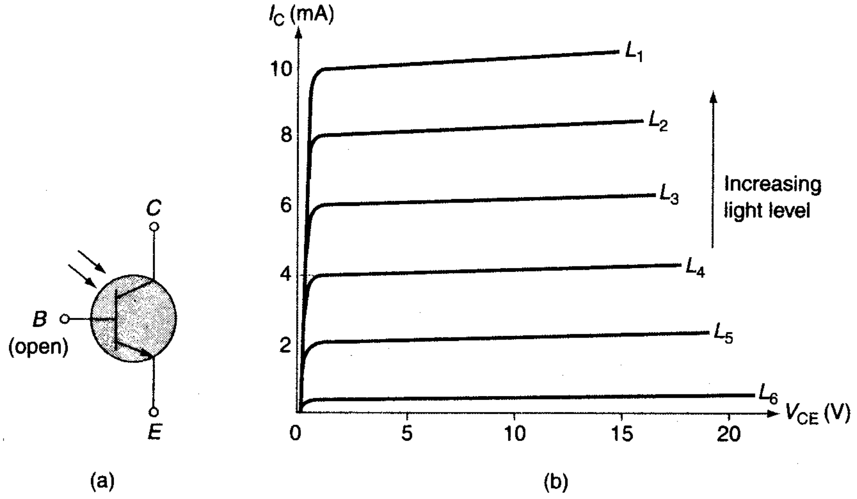


Figure 7.21 | (a) Circuit symbol of a phototransistor; (b) V–I characteristics of a phototransistor.

Phototransistor Application Circuits

Phototransistors can be used in two configurations, namely, the common-emitter configuration [Figure 7.22(a)] and the common-collector configuration [Figure 7.22(b)]. In the common-emitter configuration, the output is high and goes low when light is incident on the phototransistor, whereas in common-collector configuration, the output goes from low to high when light is incident on the phototransistor. The transistor in both the configurations can act in two modes, namely, the active mode and the switched mode. In the active mode, the transistor operates in the active region of its characteristics and the output voltage is proportional to input light intensity. In the switched mode, phototransistor is switched between cut-off and saturation and the output is either in the HIGH state or the LOW state. The modes are controlled by the value of the resistor *R*. The output of the phototransistor can be amplified using an opamp or a transistor-based amplifier circuit.

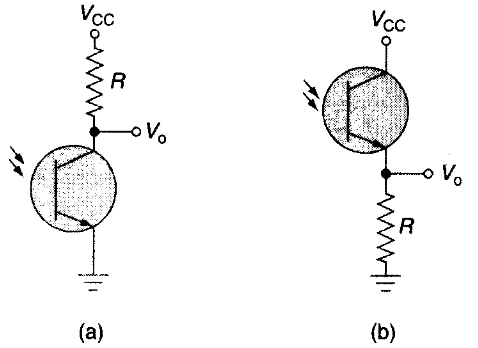


Figure 7.22 | Application circuits of phototransistors.

EXAMPLE 7.6

Determine the output voltage of the phototransistor circuit shown in Figure 7.23(a) when a CW light radiation of 1 mW is incident on the active area of the phototransistor. The active area of the transistor is 10 mm² and its output characteristics are shown in Figure 7.23(b). The base–emitter voltage of the transistor $Q_2 = 0.7$ *V, values of resistors* R_1, R_C *and* R_E *are 1 kΩ, 2.2 kΩ and 1 kΩ, respectively, and the supply voltage (*V_{CC}*) is 12 V.*

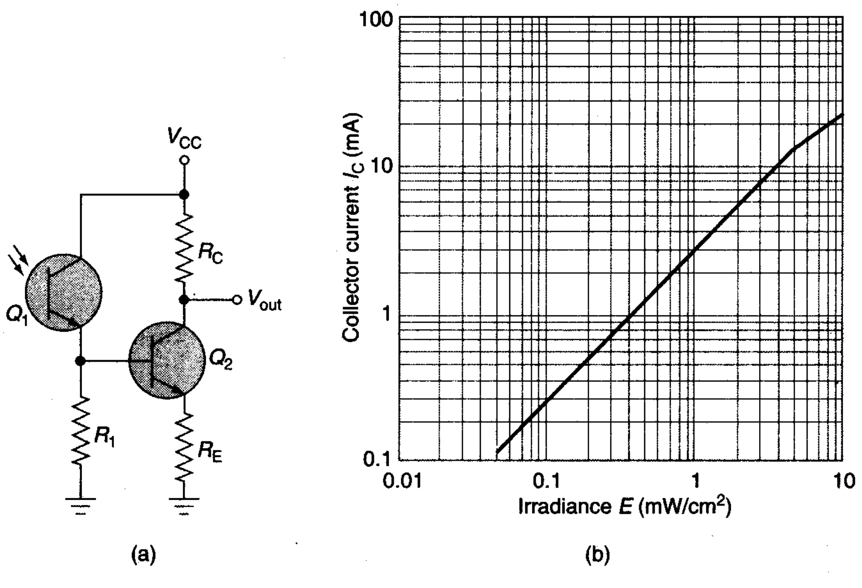


Figure 7.23 | Example 7.6.

Solution

1. The incident irradiance on the phototransistor = $1 \times 10^{-3} / (10 \times 10^{-1})^2$ W/cm² = 1 mW/cm².
2. From output characteristics of the transistor, collector current generated is 3 mA.
3. The voltage generated across the resistor R_1 is $3 \times 10^{-3} \times 1 \times 10^3 = 3$ V.
4. Therefore, the voltage applied to the base of the transistor Q_2 is 3 V. So the transistor Q_2 goes into the conducting mode.
5. The voltage across resistor $R_E = 3 - 0.7$ V $= 2.3$ V.
6. The value of emitter current (I_E) is given by $I_E = 2.3/(1 \times 10^3) = 2.3$ mA.
7. As the collector current (I_C) is approximately equal to the emitter current, therefore $I_C = 2.3$ mA.
8. The output voltage $V_{out} = V_{CC} - I_C \times R_C = 12 - 2.3 \times 10^{-3} \times 2.2 \times 10^3 = 12 - 5.06 =$ 6.94 V.

7.6 PhotoFET, PhotoSCR and PhotoTRIAC

In this section we will discuss the three other important photosensors, namely, the photoFETs, photoSCRs and the photoTRIACs. While photoSCRs and photoTRIACs are latching type of photosensors, photoFETs are non-latching photosensors like photodiodes and phototransistors.

PhotoFET

PhotoFETs are light-sensitive FET devices wherein the diode formed by the reverse-biased gate-channel junction acts as a photodiode. Incident light generates additional photocarriers resulting in increased conductivity level. Gate current flows if the gate is connected to an external resistor. Figure 7.24(a) shows the circuit symbol of a photoFET. When no light is incident on the photoFET, the value of gate impedance is very high. When light is incident on the photoFET, the value of gate impedance decreases. Figure 7.24(b) shows the typical application circuit using a photoFET. When no light is incident, the gate voltage is approximately equal to the voltage $-V_{GG}$. When light is incident, the negative gate voltage decreases resulting in increase in the value of drain current (I_D) and the value of the output voltage (V_o) decreases.

PhotoSCR

PhotoSCRs, generally referred to as light-activated SCRs (LASCRs), are essentially the same as conventional SCRs except that they are triggered by light incident on the gate junction area. They comprise a window and lens to focus more light on the gate junction area, more specifically on the middle junction J_2 of the SCR. They conduct current in one direction when activated by light of sufficient amount and continue to conduct until the current falls below a specified value referred to as holding current. In other words, photoSCRs act as a latch that can be triggered ON by the light incident on the gate junction but it does not turn OFF when the light source is removed. They can be turned

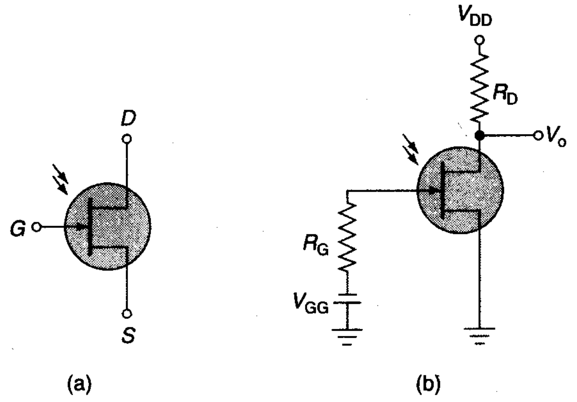


Figure 7.24 (a) Circuit symbol of photoFET; (b) a simple application circuit using photoFET.

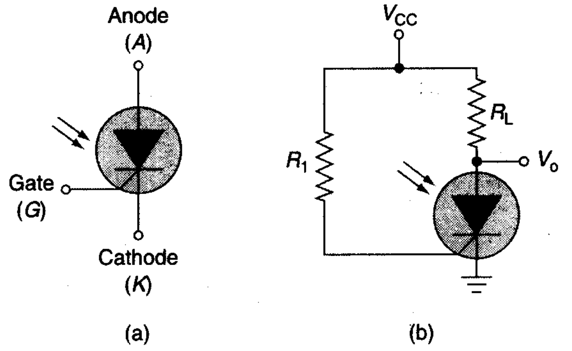


Figure 7.25 (a) Circuit symbol of photoSCR; (b) simple application circuit using photoSCR.

OFF by reducing the current below the holding current value of the SCR. PhotoSCRs can handle large amount of current as compared to a photodiode or a phototransistor. They have high value of rate of change of voltage with time, that is, high d*v*/d*t* rating which is important for triggering the SCR on application of light input. PhotoSCRs are most sensitive to light when their gate terminal is open. They are generally used in the receiving channel of optocouplers.

Figure 7.25(a) shows the circuit symbol of a photoSCR and Figure 7.25(b) shows a simple application circuit built around it. When no light is incident on the photoSCR, it is OFF and no current flows through the load resistor R_L. When the photoSCR is illuminated, it turns ON and hence allowing current to flow through the load resistor R_L.

PhotoTRIAC

PhotoTRIACs, also referred to as light-activated TRIACs, are bidirectional thyristors that are designed to conduct current in both directions when the incident light radiation exceeds a specified threshold value. PhotoTRIACs are generally used as solid-state AC switches and as photosensors in optocouplers to provide isolation from the driving source to the load. Figure 7.26 shows the circuit symbol of a photoTRIAC. The operation of photoTRIAC is similar to that of a standard TRIAC, except that the trigger current is generated indirectly in the case of a photoTRIAC by the light incident on it whereas in the case of a standard TRIAC it is supplied directly. One of the most important parameters to describe the performance of a photoTRIAC is its output d*v*/d*t* rating. Other important parameters are the break-down voltage and the power rating of the device.

There are two different types of photoTRIACs available, namely, the non-zero-crossing photoTRIACs and zero-crossing photoTRIACs. The non-zero-crossing photoTRIACs are used for applications that require fine control involving small time constants. Zero-crossing photoTRIACs are used in applications where the control time constant is fairly large.

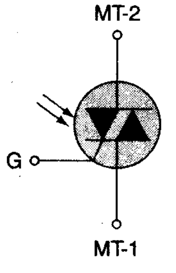


Figure 7.26 Circuit symbol of a photoTRIAC.

EXAMPLE 7.7 *The circuit shown in Figure 7.27 is kept in a dark room. Determine the output voltage (V_o). Also, determine the output voltage when a bright light is flashed on the circuit.*

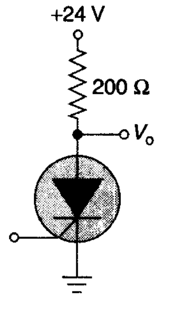


Figure 7.27 Example 7.7.

Solution

1. When the circuit is kept in the dark room with no incident light, the photo-SCR is in the non-conducting state. Therefore, the output voltage V_0 is equal to the supply voltage, that is, $V_0 = +24$ V.
2. When a bright light is incident on the photoSCR, it goes into the conducting state and ideally the output voltage is zero, that is, $V_0 = 0$ V.

7.7 Photoemissive Sensors

The photosensors discussed so far have internal photoeffect where the photoelectrons generated by the incident radiation remain within the semiconductor material. Other category of photosensors include those photosensors which have external photoeffect wherein the photogenerated electrons travel beyond the physical boundaries of the material. These sensors are also referred to as photoemissive sensors. In this section we discuss some of the commonly used photoemissive sensors including vacuum photodiodes, photomultiplier tubes and image intensifiers.

Vacuum Photodiodes

Vacuum photodiode is the oldest photosensor. It comprises an anode and a cathode placed in a vacuum envelope. Cathode, when irradiated, releases electrons that are attracted by the positively charged anode, thus producing a photocurrent proportional to the light intensity.

Photomultiplier Tubes

Photomultiplier tubes (PMT) are extremely sensitive photosensors operating in the ultraviolet, visible and near infrared spectrum. PMTs have internal gain of the order of 10^8 and can even detect single photon of light. They are constructed from a glass vacuum tube which houses a photocathode, several dynodes and an anode. When the incident photons strike the photocathode, electrons are produced as a result of the

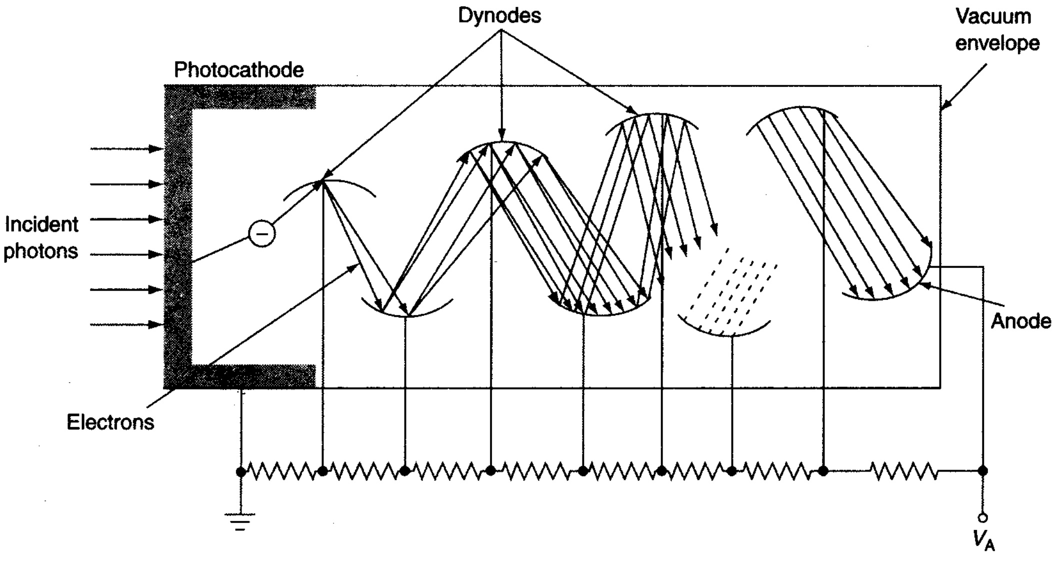


Figure 7.28 Cross-section of a photomultiplier tube.

photoelectric effect. These electrons accelerate towards the anode and in the process electron multiplication takes place due to secondary emission process from the dynodes. PMTs require few kilo-volts of biasing voltages for proper operation. Figure 7.28 shows the cross-section of a PMT. As we can see from the figure, the dynodes are given progressively increasing positive voltages with the dynode nearest to the cathode having the lowest voltage and the dynode nearest to the anode having the maximum voltage.

Salient features of PMTs include low-noise, high-frequency response and large active area. By virtue of these features, PMTs are used in nuclear and particle physics, astronomy, medical imaging and motion picture film scanning. APDs have replaced PMTs in some applications, but PMTs are still used in many application areas.

Image Intensifiers

Image intensifiers are devices that amplify visible and near infrared light from an image so that a dimly lit scene can be viewed by a camera or by human eye. Contemporary image intensifiers comprise an objective lens, vacuum tube with photocathode at one end, tilted microchannel plate (MCP) and a phosphor screen (Figure 7.29). Objective lens focuses the image onto the photocathode. When the photons strike the photocathode, electrons are released due to the photoelectric effect. These photoelectrons are accelerated through around 4–5 kV into a tilted microchannel plate where secondary electron multiplication takes place. The electrons all move together due to the potential difference across the tube and for each photoelectron hundreds or even thousands of electrons are created. All these electrons hit the phosphor screen at the other end, releasing one photon for every electron. Thus the screen converts the high-energy electrons into photons, which correspond to the input image radiation but with the incident flux being amplified many times.

Image intensifiers are classified into the following categories: generation 0, generation 1, generation 2 and generation 3. Generation 0 and generation 1 devices did not have the MCP and the stream of electrons generated by the photocathode was accelerated towards the phosphor screen by the applied potential. Generation 1 devices were a tremendous improvement upon generation 0 devices and had three times the photosensitivity than that of generation 0 devices. Generation 2 devices introduced the concept of microchannel plates. Generation 3 devices are the same as generation 2 devices except that the photocathode material in these devices is gallium arsenide (GaAs) whereas it was S-25 in the case of generation 2 devices. Also, generation 3 devices had a better MCP. Generation 3 ultra and generation 4 tubes are also available which offer slight improvement over generation 3 devices. Image intensifiers are used in night vision devices (NVD) used for military applications.

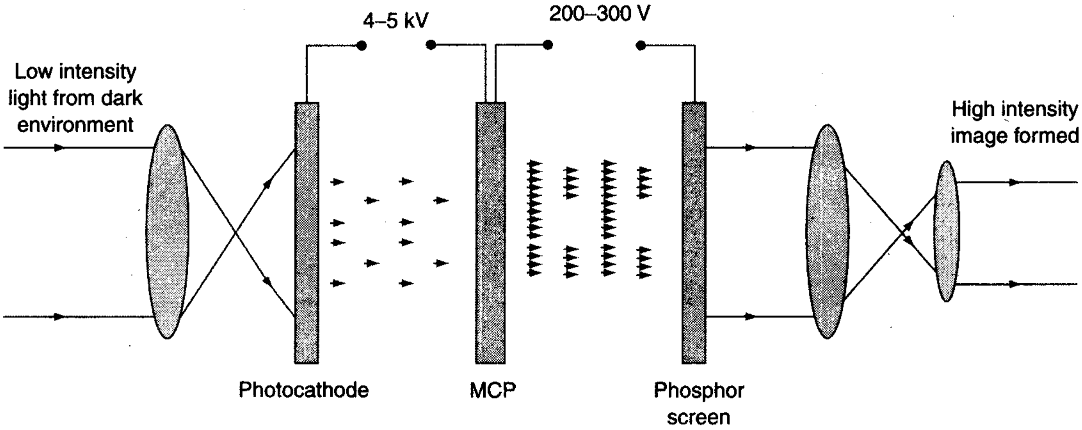


Figure 7.29 | Image intensifier tube.

7.8 Thermal Sensors

Thermal sensors absorb radiation, which produces a temperature change that in turn causes a change in the physical or the electrical property of the sensor. In other words, thermal sensors respond to change in their bulk temperature caused by the incident radiation. Thermocouples, thermopiles, bolometers and pyroelectric sensors come in the category of thermal sensors. Thermal sensors lack the sensitivity of photoelectric sensors and are generally slow in response, but have a wide spectral response. Most of these sensors are passive devices, requiring no bias. In this section, we will discuss about the different types of thermal sensors and their application circuits.

Thermocouple and Thermopile

Thermocouple sensors are based on the Seeback effect, that is, the temperature change at the junction of two dissimilar metals generates an electromagnetic force (EMF) proportional to the temperature change. The commonly used thermocouple materials are bismuth–antimony, iron–constantan and copper–constantan. Their temperature coefficients are 100 μV/°C, 54 μV/°C and 39 μV/°C, respectively. To compensate for the changes in the ambient temperature, thermocouples generally have two junctions, namely, the measuring junction and the reference junction.

The responsivity of a single thermocouple is very low and therefore to increase the responsivity, several junctions are connected in series to form a thermopile. Thermopiles are series combination of around 20–200 thermocouples. Spectral response of thermocouples and thermopiles extends into the far infrared band up to 40 μm. They are suitable for making measurements over a large temperature range up to 1800 kΩ. However, thermocouples are less suitable for applications where smaller temperature differences need to be measured with great accuracy such as 0–100°C measurement with 0.1°C accuracy. For such applications, thermistors and resistance temperature detectors (RTDs) are more suitable.

The responsivity of thermopiles is of the order of 10–100 V/W and the typical signal output varies from few tens of micro-volts to few milli-volts. Hence, they need low noise and very low offset operational amplifiers for providing the gain. The gain required varies from as small as 10 to as large as 10,000 or more. Generally, for gain less than 1000, a single-stage amplifier is used. For gain values more than 1000, two amplifier stages are used. Figure 7.30 shows the application circuit where two amplifier stages are used. As we can see from the figure, thermopiles require no bias voltage.

The thermopile signal would be positive or negative depending upon whether the temperature of the object filling the thermopile's field-of-view is greater than or less than that of the thermopile. Also, the

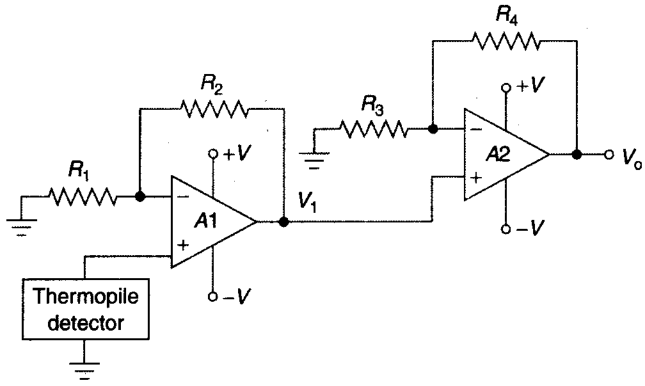


Figure 7.30 | Application circuit using thermopiles.

output of the circuit varies with change in the ambient temperature. It is therefore necessary to compensate for the ambient temperature variations. Many thermopile modules have an inbuilt thermistor to compensate for the ambient temperature variations.

Bolometers

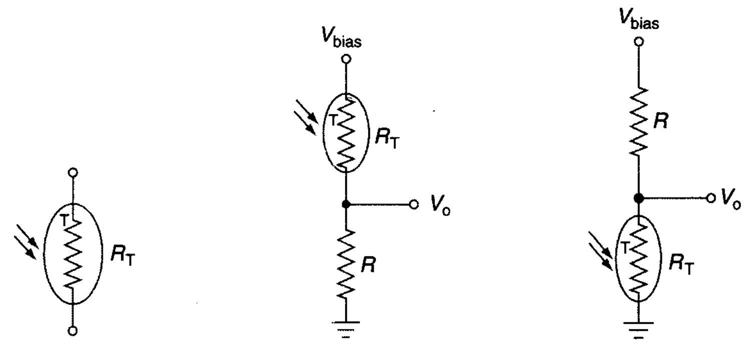
Bolometer is the most popular type of thermal sensor. The sensing element in a bolometer is a resistor with a high temperature coefficient. Bolometers are different from photoconductors, as in a photoconductor a direct photon–electron interaction causes a change in the conductivity of the material whereas in a bolometer the increased temperature and the temperature coefficient of the element causes the resistance change. Bolometers can be further categorized as metal bolometers, thermistor bolometers and low-temperature germanium bolometers.

Metal bolometers use metals such as bismuth, nickel or platinum having temperature coefficients in the range of 0.3–0.5%/°C. Thermistor bolometers are the most popular and they find applications in burglar alarms, smoke sensors and other similar devices. The sensor in this case is a thermistor, an element made of manganese, cobalt and nickel oxide. They have high temperature coefficients up to 5%/°C that varies with temperature as $1/T^2$. They are classified as negative temperature coefficient (NTC) and positive temperature coefficient (PTC) thermistors depending upon whether their temperature coefficient of resistance is negative or positive. Figure 7.31(a) shows the circuit symbol of a thermistor. Spectral response of thermistors extends from 0.5 to 10 μm. More sensitive thermistors typically have NEP and response time of the order of 10^{-10} W and 100 ms. Less sensitive thermistors have NEP and response time figures of 10^{-8} W and 5 ms, respectively. Figures 7.31(b) and (c) show the simplest possible configurations in which a thermistor can be used for measurement of light intensity. The figures are self-explanatory. The output of the circuits in Figures 7.31(b) and (c) can be fed to an operational amplifier or to a comparator for linear light control or light ON–OFF control, respectively.

Low temperature germanium bolometers are sensitive laboratory-type bolometers that use germanium as the sensor. They have the highest responsivity when operated at few degrees above the absolute zero temperature.

Pyroelectric Sensors

Pyroelectric sensors are characterized by spontaneous electric polarization, which is altered by temperature changes as light illuminates these sensors. Pyroelectric sensors are low-cost, high-sensitivity devices that are stable against temperature variations and electromagnetic interference. Pyroelectric sensors only respond to modulating light radiation and there will be no output for a CW incident radiation. Figure 7.32(a) shows the circuit symbol of pyroelectric sensors.



(a) (b) (c)

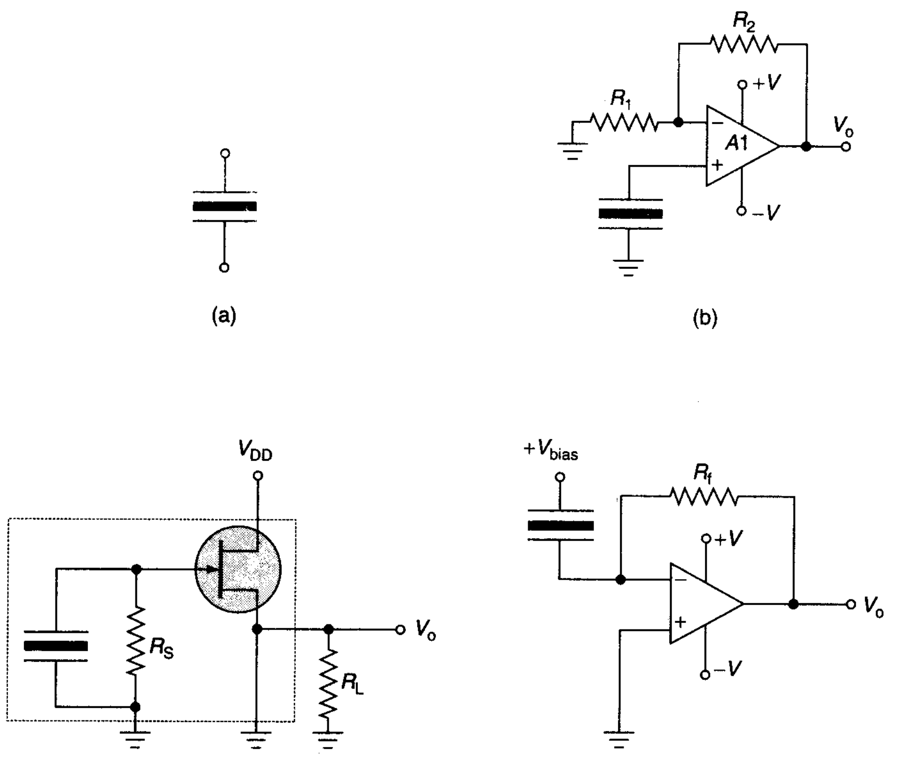
Figure 7.31 (a) Circuit symbol of a thermistor; (b) and (c) application circuits of a thermistor.

Pyroelectric sensors operate in two modes, namely, the voltage mode and the current mode. In the voltage mode, the voltage generated across the entire pyroelectric crystal is detected. In the current mode of operation, current flowing on and off the electrode on the exposed face of the crystal is detected. Voltage mode is more commonly used than the current mode.

The circuit for voltage mode is shown in Figure 7.32(b). The operational amplifier chosen should have very high input impedance of the order of 10^{12} to 10^{14} Ω. But the circuit is sensitive to ambient temperature variations. Ambient temperature variations can be compensated by employing AC coupling between the amplifier stages or by adding a compensation crystal in opposition, either in series or in parallel. One crystal is exposed to radiation and the other is shielded from radiation. As the ambient temperature changes, the surface charge generated on one crystal is cancelled by the equal and opposite charge generated on the other crystal. The incident radiation, however, generates charge only on one crystal and is not cancelled.

Voltage mode pyroelectric sensors are generally integrated with an FET. A shunt resistor (R_S) in the range of 10^{10}–10^{11} Ω is added to provide thermal stabilization. External connections include a power supply (V_{DD}) and load resistor (R_L) [Figure 7.32(c)]. The output voltage appears across R_L.

The circuit for current mode operation is shown in Figure 7.32(d). The modulation frequency can be much higher in the case of current mode operation than it is for voltage mode operation. Hence, it is much easier to separate the signal generated from the ambient temperature drift.



(a) (b)

(c) (d)

Figure 7.32 (a) Circuit symbol of pyroelectric sensors; (b) and (c) voltage mode pyroelectric sensor application circuits; (d) current mode pyroelectric sensor application circuit.

7.9 Displays

Displays are output devices that are used for visual presentation of information. Displays form an interface between the machine and the human. In this section, we will discuss different types of displays and the characteristic parameters used to define the quality of displays.

Display Characteristics

Three factors are critical for a good visual display, namely, legibility, brightness and contrast.

Legibility

Legibility is the property of a display by virtue of which the characters are easy to read with speed and accuracy. The factors which contribute to the legibility of the display are its style, size, character sharpness and shape.

Brightness

Brightness refers to the perception of luminance by the visual world.

Contrast

Contrast of a display depends on the background luminance and the source luminance. The readability of the display depends upon the contrast parameter. It is defined in different ways for passive and active displays. In the case of passive displays such as LCD, contrast is defined as

$$C = (L_O - L_B) / L_O \tag{7.19}$$

where L_O is the object or source luminance (cd/m^2) and L_B is the background luminance (cd/m^2).

Contrast can have values between 0 and 1, 0 being the case when the object and the background luminance are the same and 1 when the background has zero luminance.

For active displays such as LED displays, the contrast parameter is defined in terms of contrast ratio which is defined as

$$CR = L_O / L_B \tag{7.20}$$

The contrast ratio can have values between 1 and ∞. For contrast ratio equal to 1, the object and the background have the same luminance and the displayed characters are not visible at all. The background luminance is 0 and the display has best visibility at contrast value equal to ∞.

Types of Displays

Displays can be categorized into different types depending upon the manner in which they display information. These include bar graph displays, segmented displays, dot-matrix displays and large displays.

Bar graph displays are composed of several bar elements as shown in Figure 7.33. Bar graph displays are replacing analog displays as indicators due to their simplicity and cost-effectiveness. Segmented displays are available in two configurations, namely, the seven-segment displays [Figure 7.34(a)] and sixteen-segment displays [Figure 7.34(b)].

Seven-segment display comprises seven bars and one or two decimal points and is an industry standard for numeric displays. These displays are used for displaying numerals and limited alphabets. Sixteen-segment displays can present the entire upper-case alphabets and numerals. Segmented displays can present only limited information. Dot-matrix displays are the simplest displays that represent the set of lower-case and upper-case alphabets and numerals at reasonable cost and complexity. The most commonly used dot-matrix display is the 5 × 7 display which comprises 35 display elements set in a pattern of 5 rows and 7 columns (Figure 7.35). Each element is addressed by selecting the proper row and column. Bar, segmented and 5 × 7 dot-matrix displays

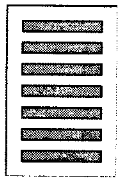
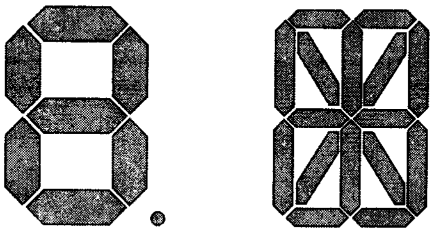


Figure 7.33 | Bar graph display.



(a) (b)

Figure 7.34 | (a) Seven-segment displays; (b) sixteen-segment displays.

can be constructed using LEDs or liquid-crystal displays (LCDs). Large-scale displays include cathode ray tube (CRT) displays, plasma displays, LCD thin film transistor (TFT) displays and so on.

LEDs and LCDs are discussed in Sections 7.10 and 7.11, respectively, followed by CRT displays and emerging trends in display technology in Sections 7.12 and 7.13, respectively.

7.10 Light-Emitting Diodes

LED is a semiconductor PN junction diode designed to emit light when forward-biased. It is one of the most popular optoelectronic source. LEDs consume very little power and are inexpensive.

We have studied in Chapter 2 that when a PN junction is forward-biased, the electrons in the N-type material and the holes in the P-type material travel towards the junction. Some of these holes and electrons recombine with each other and in the process radiate energy. The energy will be released either in the form of photons of light or in the form of heat. In silicon and germanium diodes, most of the energy is released as heat and the emitted light is insignificant. However, in some materials like gallium phosphide (GaP), gallium arsenide (GaAs) and gallium arsenide phosphide (GaAsP) substantial photons of light are emitted. Hence, these materials are used in the construction of LEDs.

In the absence of an externally applied voltage, the N-type material contains electrons while the P-type material contains holes that can act as current carriers. When the diode is forward-biased, the energy levels shift and hence there is a significant increase in the concentration of electrons in the conduction band on the N-side and that of holes in valence band on the P-side. These electrons and holes combine near the junction to release energy in the form of photons (Figure 7.36). It may be mentioned here that the process of light emission in an LED is that of spontaneous emission, that is, the photons emitted are not in phase and travel in different directions.

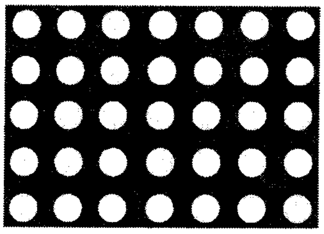


Figure 7.35 | 5 × 7 Dot-matrix display.

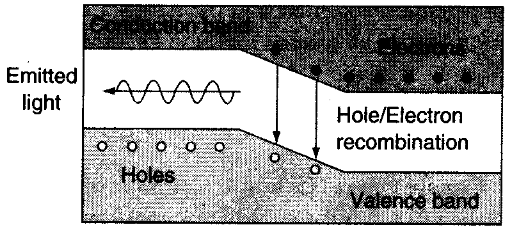


Figure 7.36 | PN junction of an LED.

Table 7.1 | Bandgap energy and the typical wavelengths of commonly used LED materials

Material	Bandgap energy (eV)	Wavelength (nm)
GaAs	1.43	910
GaP	2.24	560
$GaAs_{60}P_{40}$	1.91	650
AlSb	1.60	775
InSb	0.18	6900

The energy of the photon resulting from this recombination is equal to the bandgap energy of the semiconductor material and is expressed by the following empirical formula:

$$\lambda = \frac{1240}{\Delta E} \tag{7.21}$$

where λ is the wavelength (nm) and ΔE the bandgap energy (eV).

Some of the commonly used semiconductor materials used for fabricating LEDs are gallium arsenide (GaAs), gallium phosphide (GaP), gallium arsenic phosphide (GaAsP), aluminum antimonide (AlSb) and indium antimonide (InSb). Table 7.1 enlists the bandgap and the typical wavelengths emitted by these materials.

LED Characteristic Curves

The characteristics of interest in an LED are the V–I characteristics, spectral distribution curve, light output versus input current and the directional characteristics.

1. **V–I Characteristics:** Figure 7.37(a) shows the V–I characteristics of LEDs of different colors. As the LED is operated in the forward-biased mode, the V–I characteristics in the forward-biased region are shown. V–I characteristics of LEDs are similar to that of conventional PN junction diodes except that the cut-in voltage in the case of LEDs is in the range of 1.3–3 V as compared to 0.7 V for silicon diodes and 0.3 V for germanium diodes.
2. **Spectral Distribution Curve:** Spectral distribution curve shows the variation of light intensity with wavelength. Figure 7.37(b) shows the typical spectral curves for yellow, green and red LEDs.
3. **Light Output versus Input Current:** Figure 7.37(c) shows a typical light output versus input current curve depicting the dependence of emitted light on forward current flowing through the LED.
4. **Directional Characteristics:** Directional characteristics refer to the variation in the light output with change in the viewing angle [Figure 7.37(d)].

LED Parameters

The parameters of interest in the case of LEDs are forward voltage (V_F), candle power (*CP*), radiant power output (P_o), peak spectral emission (λ_P) and spectral bandwidth.

1. **Forward Voltage (V_F):** It is the DC voltage across the LED when it is ON. The typical values of V_F for LEDs are in the range of 1.3–3.0 V. As we can see from Figure 7.37(a), V_F is near 1.5 V for yellow, green and red LEDs.
2. **Candle Power (*CP*):** It is a measure of the luminous intensity or the brightness of the light emitted by the LED. It is the most important parameter of an LED. It is a non-linear function of LED current and the value of *CP* increases with increase in the current flowing through the LED.

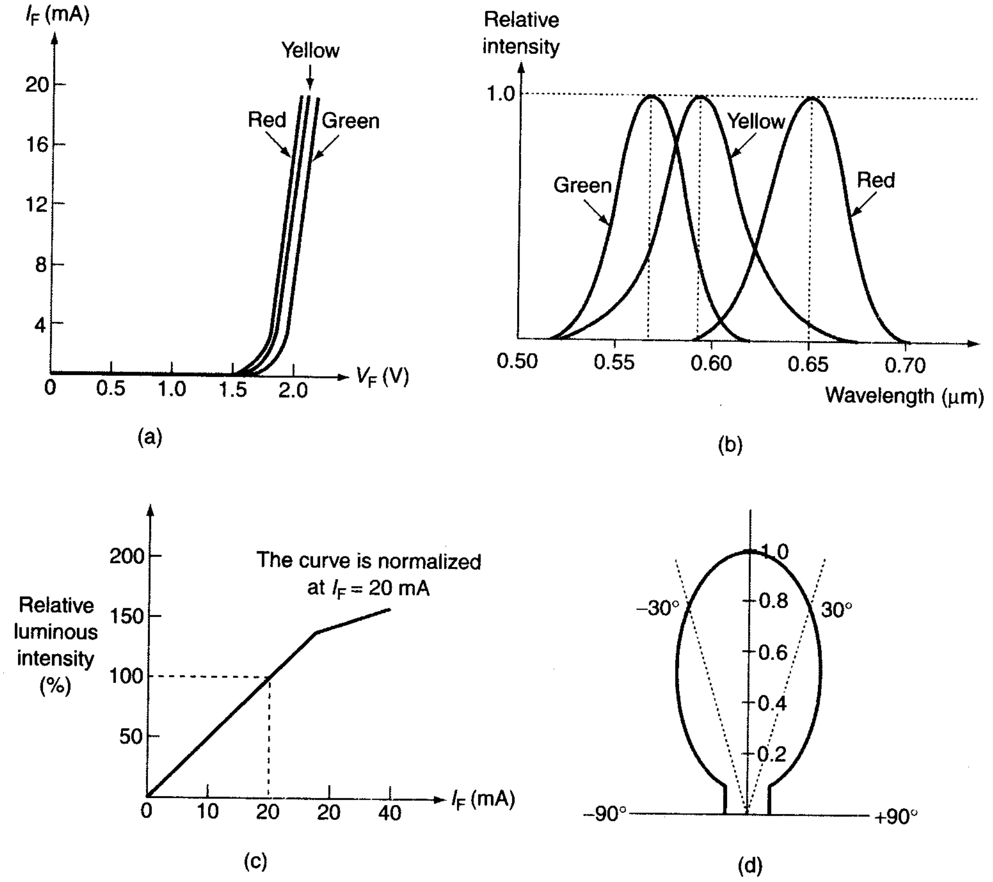


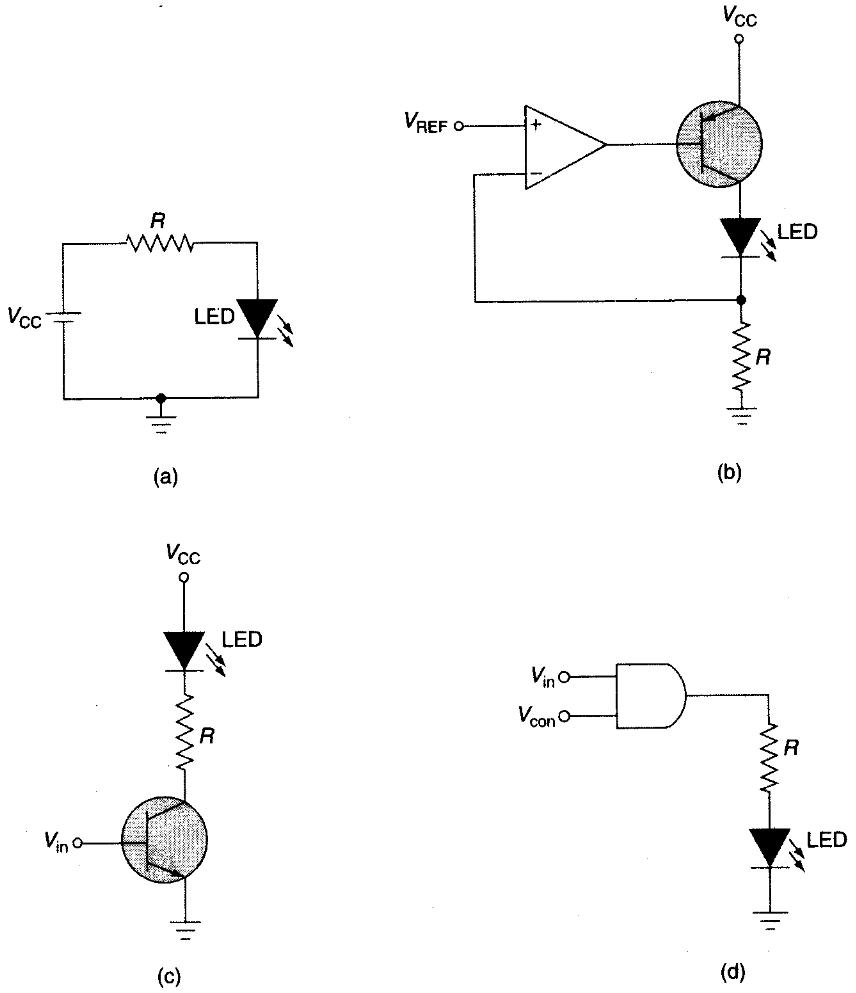
Figure 7.37 (a) V–I characteristics of an LED; (b) spectral characteristics of an LED; (c) light output versus input current characteristics of an LED; (d) directional characteristics of an LED.

3. **Radiant Power Output (P_o):** It is the light power output of the LED.
4. **Peak Spectral Emission (λ_p):** It is the wavelength where the intensity of light emitted by the LED is maximum.
5. **Spectral Bandwidth:** It gives an indication as to how concentrated the brightest color is around its nominal wavelength.

LED Drive Circuits

LEDs are operated in the forward-biased mode. As the current through the LED changes very rapidly with change in the forward voltage above the threshold voltage, LEDs are current-driven devices. Figure 7.38(a) shows a simple circuit for driving an LED. The resistor (R) is the current-limiting resistor used to limit the current flowing through the LED. In this case the V–I characteristics of the LED is used to determine the voltage that needs to be applied to the LED to generate the desired forward current. A silicon diode can be placed inversely parallel to the LED for reverse polarity voltage protection. The current that will flow through the LED is given by

$$I = (V_{CC} - V_F)/R \tag{7.22}$$



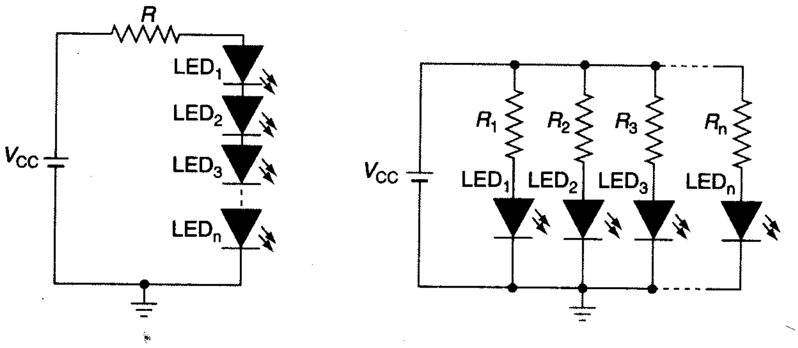
(a) (b) (c) (d)

Figure 7.38 (a) Simple LED driver circuit; (b) constant current source based LED driver circuit; (c) and (d) logic circuits for driving LEDs.

where V_{CC} is the supply voltage; V_F is the forward diode voltage; R is the current-limiting resistor. However, any change in the forward voltage of the LED due to temperature changes or variation from device to device causes a change in the LED current. Moreover, there is power dissipation across the series resistor R, resulting in reduced efficiency. A better drive circuit configuration is the one that employs a constant current source as shown in Figure 7.38(b). The current flowing through the LED is determined by the reference voltage (V_{REF}) and the resistor R.

LEDs can also be used to display the logic output states. Figures 7.38(c) and (d) show two typical logic circuits that can be used to drive LEDs. Figure 7.38(c) uses a transistor-based switch while Figure 7.38(b) employs a logic gate/buffer. In both the circuits, the LED glows when the voltage V_{in} is in the logic HIGH state.

When the light emitted by one LED is not sufficient, several LEDs can be connected in series to enhance the light level to the desired value. LEDs can be connected in series as shown in Figure 7.39(a). In a series connection, the current flowing through each LED is the same. The value of the supply voltage (V_{CC}) should be sufficiently



(a) (b)

Figure 7.39 (a) Connecting LEDs in series; (b) connecting LEDs in parallel.

large to drive the desired number of LEDs. Also, it should be checked that the series current flowing in the circuit through each LED is in their operating range. The value of the resistor (R) to be connected is given by

$$R = [V_{CC} - (V_{F1} + V_{F2} + V_{F3} + \cdots + V_{F_n})]/I \tag{7.23}$$

where V_{F1}, V_{F2}, ..., V_{F_n} are the forward voltages across LED$_1$, LED$_2$, ..., LED$_n$ respectively and I is the current flowing through the LEDs.

LEDs can also be connected in parallel to enhance the output light level. However, in the case of parallel connection, one needs to be more careful. Figure 7.39(b) shows the parallel connection of LEDs. The resistors R_1, R_2, ..., R_n are used to protect the LEDs. If these resistors were not used, then the LED with the lowest forward voltage will draw excess current and is likely to get damaged. Then the LED with the next smallest forward voltage will get damaged and this process continues till all the LEDs get damaged. The values of these resistors determine the current flowing through individual LEDs.

EXAMPLE 7.8

For the circuit shown in Figure 7.40, determine the current through the LED when (a) $V_B = 0$ V and (b) $V_B = 10$ V. (V_{BE} of both the transistors is 0.7 V and $V_{CE(sat)}$ of both the transistors is 0.2 V.)

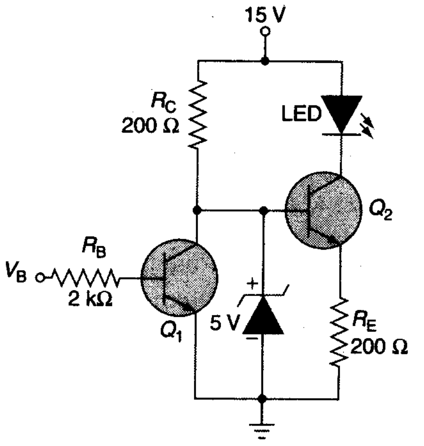


Figure 7.40 Example 7.8.

Solution

1. When $V_B = 0$ V, transistor Q_1 is in the cut-off region and there is no collector current flowing through the transistor.
2. Therefore, the base voltage of transistor Q_2 is equal to the reverse breakdown voltage of the Zener diode Z_1. Therefore, $V_{B2} = 5$ V.
3. Transistor Q_2 is in the conducting mode and the voltage at the emitter terminal of transistor Q_2 is given by $V_{E2} = V_{B2} - 0.7\text{ V} = 5 - 0.7 = 4.3$ V.
4. The emitter current flowing through transistor $Q_2 = V_{E2}/R_E = 4.3/200 =$ 21.5 mA.
5. As the collector current is approximately equal to the emitter current, the value of $I_C = 21.5$ mA.
6. The current flowing through the LED is the same as the collector current of the transistor. Therefore, the current flowing through the LED is 21.5 mA.
7. When $V_B = 10$ V, transistor Q_1 is in saturation. Therefore, the voltage $V_{CE1} =$ 0.2 V.
8. The base voltage of transistor Q_2, $V_{B2} = 0.2$ V.
9. Hence, transistor Q_2 is in cut-off and the value of collector current is nearly zero. Therefore, the current flowing through the LED is also nearly zero.

7.11 Liquid-Crystal Displays

Liquid crystals are materials that exhibit properties of both solids and liquids, that is, they are an intermediate phase of matter. They can be classified into three different groups: nematic, smectic and cholestric. Nematic liquid crystals are generally used in the fabrication of liquid-crystal displays (LCDs) with the twisted nematic material being the most common.

Construction of an LCD

Figure 7.41(a) shows the construction of a twisted nematic LCD display. As we can see from the figure, it comprises a cell of liquid-crystal fluid, conductive electrodes, a set of polarizers and a glass casing.

The outermost layers are the polarizers which are housed on the outer surface of the glass casing. Polarizers are components that polarize light in one plane. The polarizer attached to the front glass is referred to as the front polarizer, while the one attached to the rear glass is the rear polarizer. On the inner surface of the glass casing, transparent electrodes are placed in the shape of the desired image. The electrode attached to the front glass is referred to as the segment electrode while the one attached to the rear glass is the backplane or the common electrode. The patterns of the backplane and segment electrodes form the numbers, letters, symbols, etc. The liquid crystal is sandwiched between the two electrodes. The basic principle of operation of LCD is to control the transmission of light by changing the polarization of the light passing through the liquid crystal with the help of an externally applied voltage. As LCDs do not emit their own light, backlighting is used to enhance the legibility of the display in dark conditions. A variety of methods exist for backlighting LCD panels such as use of incandescent lamps, LEDs and electro luminescent lamps.

LCDs have the capability to produce both positive as well as negative images. A positive image is defined as a dark image on a light background. In a positive image display, the front and the rear polarizers are perpendicular to each other. Light entering the display is guided by the orientation of the liquid-crystal molecules that are twisted by 90° from the front glass plate to the rear glass plate. This twist allows the incoming light to pass through the second polarizer [Figure 7.41(b)]. When a voltage is applied to the display, the liquid-crystal molecules straighten out and stop redirecting the light. As a result light travels straight through and is filtered out by the second polarizer. Therefore, no light can pass through, making this region darker compared

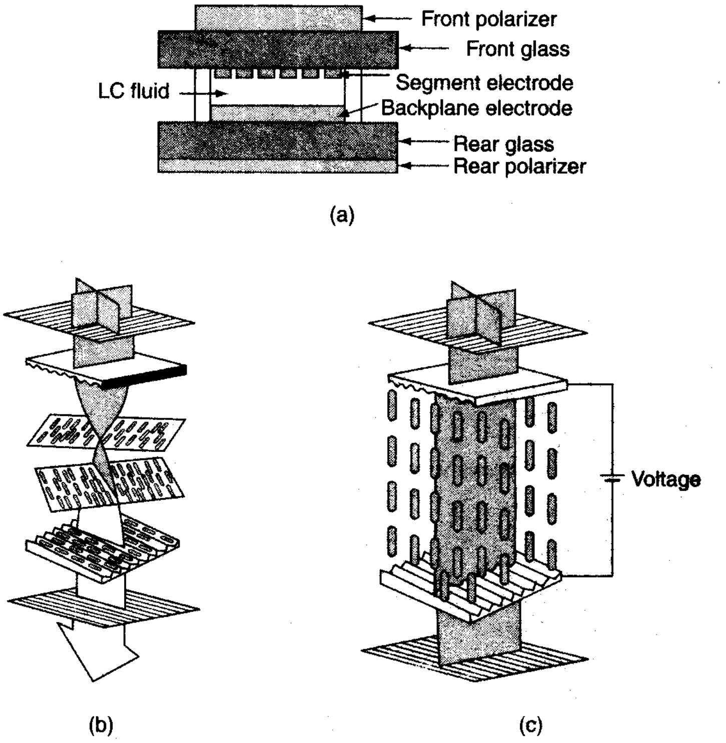


Figure 7.41 (a) Cross-section of a twisted nematic LCD display; (b) and (c) twisted nematic LCD operation.

to the rest of the screen [Figure 7.41(c)]. Hence, in order to display characters or graphics, voltage is applied to the desired regions, making them dark and visible to the eye.

A negative image is a light image on a dark background. In negative image displays, the front and the rear polarizers are aligned parallel to each other.

Driving an LCD

The LCD driver waveforms are designed to create a zero DC potential across all the pixels, as the DC voltage deteriorates the LC fluid such that it cannot be energized. LCDs are driven with symmetrical waveforms with less than 50 mV DC component. Figure 7.42 shows the brightness versus the RMS drive voltage curve for LCDs. V_{ON} is the RMS voltage applied across the liquid crystal that creates an ON pixel that is typically at the 90% contrast level. V_{OFF} or V_{TH} is the RMS voltage across the liquid crystal when the contrast voltage reaches 10% level. Another important specification is the discrimination ratio, which is defined as the ratio of V_{ON} to V_{OFF}. The discrimination ratio defines the contrast levels the LCD panel will achieve.

LCDs can be classified as direct-drive and multiplex-drive displays depending upon the technique used to drive them. Direct-drive displays, also known as static-drive displays, have an independent driver for each pixel. The drive voltage in this case is a square waveform having two voltage levels, namely, ground and V_{CC} [Figure 7.43(a)]. In the figure, segment 0 is the ON segment whereas segment 1 is the OFF segment. Direct-drive displays offer the best contrast ratios over a wide operating temperature range. However, as the display size increases the drive circuitry becomes very complex. Hence, multiplex-drive circuits are used for larger size displays. These displays reduce the total number of interconnections between the LCD and the driver. They have more than one backplane and the driver produces an amplitude-varying, time-synchronized

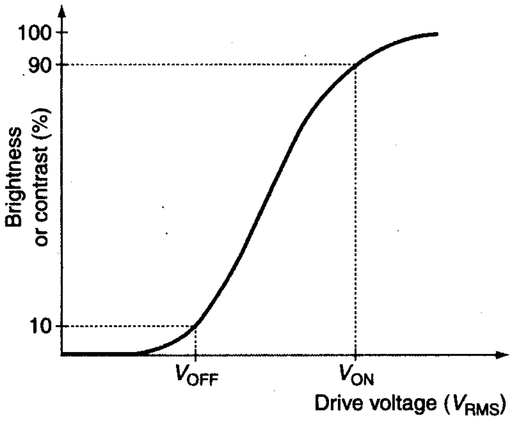


Figure 7.42 | Brightness versus drive voltage curve for LCD displays.

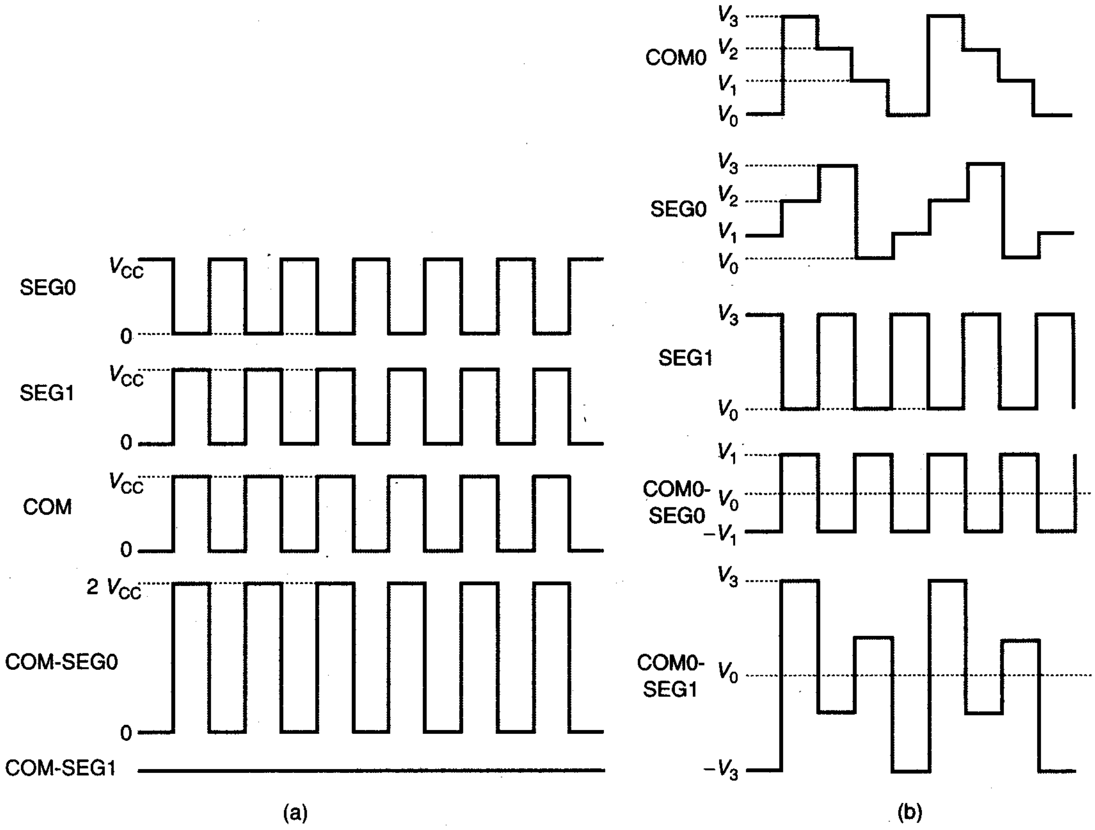


Figure 7.43 | (a) Direct-drive waveforms; (b) multiplex-drive waveforms.

waveform for both segment and backplanes. Figure 7.43(b) shows a typical multiplex-drive waveform showing the segment and the backplane waveforms. Segment 0 is inactive whereas segment 1 is active. Segment 0 is inactive as the voltage across the LCD never crosses its activation threshold voltage.

LCD Response Time

The LCD response time is defined by the ON and OFF response times. ON time refers to the time required by an OFF pixel to become visible after the application of proper drive voltage. The OFF time is defined as the time required by the ON pixel to turn OFF after the application of proper drive voltage. The response time of LCDs varies widely with temperature and increases rapidly at low operating temperatures. Hence, LCDs can only operate at low temperatures when used along with temperature controllers. At high temperatures, the liquid-crystal molecules begin to assume random orientations, resulting in the pixels on the positive image display becoming completely dark, while the pixels on the negative image display becoming completely transparent. Figure 7.44 shows the typical variation of the ON and the OFF times of an LCD display with temperature.

Liquid-Crystal Display Types

LCDs are non-emissive devices, that is, they do not generate light on their own. Depending upon the mode of transmission of light in an LCD, they are classified as reflective, transmissive and transreflective LCD displays.

Reflective LCD displays have a reflector attached to the rear polarizer which reflects incoming light evenly back into the display. Figure 7.45 shows the principle of operation of reflective LCD displays. These displays rely on the ambient light to operate and do not work in dark conditions. They produce only positive images. The front and the rear polarizers are perpendicular to each other. These types of displays are commonly used in calculators and digital wrist watches.

In **transmissive LCD displays**, back light is used as the light source. Most of these displays operate in the negative mode, that is, the text will be displayed in light color and the background is a dark color. Figure 7.46 shows the basic construction of a transmissive display. Negative transmissive displays have the front and the rear polarizers in parallel with each other whereas positive transmissive displays have the front and the rear polarizers perpendicular to each other. Transmissive displays are good for very low light level conditions. They offer very poor contrast when used in direct sunlight because sunlight swamps out the backlighting. Hence, these displays cannot be used in natural sunlight and provide good picture quality indoors. They are generally used in medical devices, electronics test and measuring equipments and in laptops.

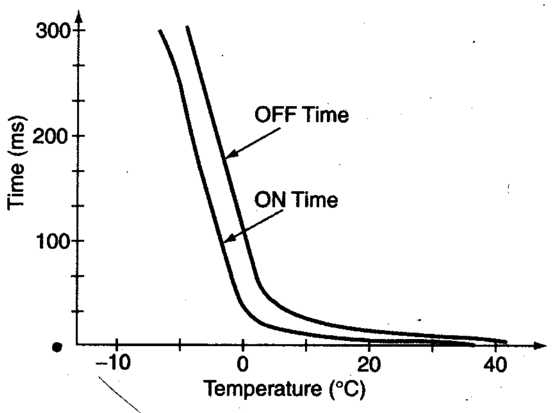


Figure 7.44 Variation of response time of LCD display with temperature.

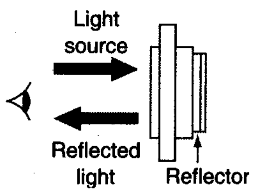


Figure 7.45 Reflective LCD display.

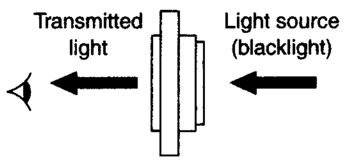


Figure 7.46 Transmissive LCD displays.

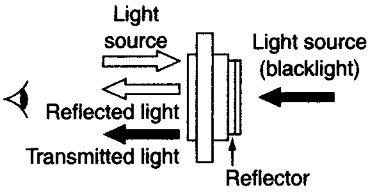


Figure 7.47 Transreflective LCD displays.

Transreflective displays are a combination of reflective and transmissive displays (Figure 7.47). A white or silver translucent material is applied to the rear of the display, which reflects some of the ambient light back to the observer. It also allows the backlight to pass through. They are good for displays operating in varying light conditions. However, they offer poorer contrast ratios than reflective displays.

LCD displays can also be classified as passive LCD displays and active LCD displays depending upon the nature of the activation circuit. Passive displays use components that do not supply their own energy to turn ON or turn OFF the desired pixels. They are made up of a set of multiplexed transparent electrodes arranged in a two-dimensional pattern of rows and columns. To address a pixel, the column containing the pixel is sent a charge and the corresponding row is connected to the ground. Passive displays can have either direct-drive or multiplex-drive circuitry. For larger displays multiplex-drive circuits are used as it is not possible and economical to have separate connections for each segment. However, as the number of multiplexed lines increase, the contrast ratio decreases due to the cross-talk phenomenon wherein a voltage applied to the desired pixel causes the liquid-crystal molecules in the adjacent pixels to partially untwist.

These inherent problems of passive displays are removed in active displays. Active displays use an active device such as a transistor or a diode in each pixel which acts like a switch that precisely controls the voltage that each pixel receives. Active displays are further classified as thin film transistor (TFT) displays and thin film diode (TFD) displays depending upon whether the active device used is a transistor or a diode. In both these devices a common electrode is placed above the liquid-crystal matrix. Below the liquid crystal is a conductive grid connected to each pixel through a TFT or a TFD. The gate of each TFT is connected to the row electrode, the drain to the column electrode and the source to the liquid crystal. The display is activated by applying the display voltage to each row electrode line by line. One of the major advantages of active displays is that nearly all effects of cross-talk are eliminated.

Advantages and Disadvantages

As LCD displays are not active sources of light, they offer considerable advantages such as very low power consumption, low operating voltages and good flexibility. However, their response time is too slow for many applications, they offer limited viewing angles and are temperature sensitive.

7.12 Cathode Ray Tube Displays

Cathode ray tube (CRT) displays are used in a wide range of systems ranging from consumer electronic systems like television and computer monitors to measuring instruments like oscilloscopes to military systems like radar and so on. CRT display is a specialized vacuum tube in which the images are produced when the electron beam strikes the fluorescent screen. CRT displays can be monochrome displays as well as colored displays.

Monochrome CRT displays comprise a single electron gun, a fluorescent screen and an internal or external mechanism to accelerate and deflect the electron beam. Figure 7.48 shows the cross-sectional view of a CRT

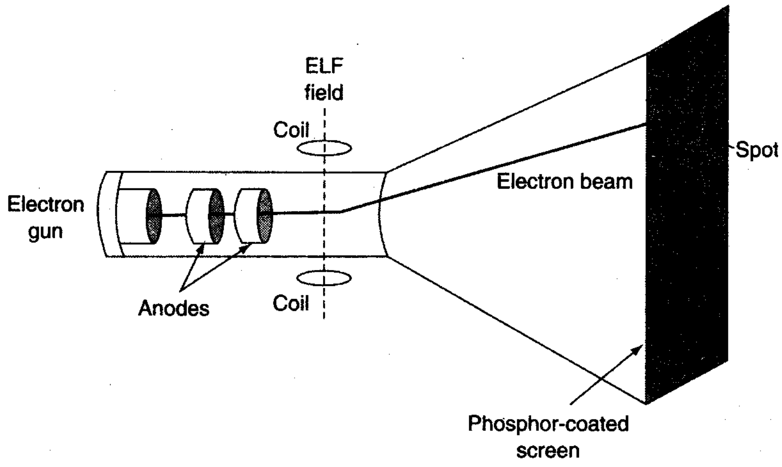


Figure 7.48 Cross-section of a monochrome CRT display.

display. The electron gun produces a narrow beam of electrons that are accelerated by the anodes. There are two sets of deflecting coils, namely, the horizontal coil and the vertical coil. These coils produce an extremely low frequency electromagnetic field in the horizontal and vertical directions to adjust the direction of the electron beam. CRT tubes also have a mechanism to vary the intensity of the electron beam. In order to produce moving pictures in natural colors on the screen, complex signals are applied to the deflecting coils and to the circuitry responsible for controlling the intensity of the electron beam. This results in movement of the spot from right to left and from top to bottom in a sequence of horizontal lines referred to as a raster. The speed of the spot movement is so fast that the person viewing the screen sees a constant image on the entire screen.

Colored CRT displays comprise three electron guns, one each for the three primary colors, namely, red, blue and green. The CRT produces three overlapping images, one in red (R), one in green (G) and one in blue (B). This is referred to as the RGB color model.

Advantages and Disadvantages

CRT displays offer very high resolution and as these displays emit their own light; therefore, they have very high values of peak luminances. Moreover, these displays offer wide viewing angles of the order of 180°. Also, CRT display technology is more mature as compared to alternate display technologies and they are cheaper as compared to other displays.

Inspite of the significant advantages offered by CRT displays as mentioned above, alternate display technologies are slowly replacing the CRT displays due to the drawbacks of these displays. CRT displays are bulky and consume significant power. Moreover they require high voltages to operate and they cause fatigue and strain to the human eye.

7.13 Emerging Display Technologies

This section gives an introduction to the emerging display technologies including organic light-emitting diodes (OLEDs), digital light-processing technology (DLP), plasma displays, field emission displays (FEDs) and electronic ink displays. All these display technologies are explained in brief in this section. Detailed description of these technologies is beyond the scope of the book.

Organic Light-Emitting Diodes (OLEDs)

OLEDs are composed of a light-emitting organic material sandwiched between two conducting plates, one of N-type material and the other of P-type material. When an electric potential is applied between these plates, holes are ejected from the P-type plate and electrons are ejected from the N-type plate. Owing to the recombination of these holes and electrons, energy is released in the form of light photons. The wavelength of light emitted depends upon the bandgap energy of the semiconductor material used. In order to produce visible light, bandgap energy of the semiconductor material should be of the order of 1.5–3.5 eV.

Depending upon their basic structure, OLEDs can be classified into three types, namely, small molecule OLEDs (SMOLEDs), polymer LEDs (PLEDs) and dendrimer OLEDs. OLEDs can be driven using passive as well as active matrix driver circuits.

As OLEDs are emissive devices, they offer significant advantages as compared to LCD displays like faster switching speeds, higher refresh rates, lower operating voltages and larger viewing angles.

Digital Light Processing (DLP) Technology

DLP technology makes use of an optical semiconductor device referred to as digital micromirror device (DMD) which is basically a precise light switch that can digitally modulate light through a large number of microscopic mirrors arranged in a rectangular array. These mirrors are mounted on tiny hinges and can be tilted away or towards the light source with the help of the DMD chip and thus projecting a light or a dark pixel on the screen. Use of DLP technology is currently limited to large projection systems.

Plasma Display Panels (PDP)

Plasma displays are composed of millions of cells sandwiched between two panels of glass. Two electrodes, namely, the address electrodes and display electrodes, are also placed between the two glass plates covering the entire screen. The address electrodes are printed on the rear glass plate and the transparent display electrodes are located above the cells along the front glass plate. These electrodes are perpendicular to each other forming a grid network.

Each cell is filled with xenon and neon gas mixture. The electrodes intersecting at a specific cell are charged to excite the gas mixture in that cell. When the gas mixture is excited, a plasma is created releasing ultraviolet light which then excites the phosphor electrons located on the sides of the cells. These electrons in turn release visible light and return to their lower energy state. Each pixel is composed of three cells containing red, green and blue phosphors.

Plasma displays offer several advantages like each pixel generates its own light offering large viewing angles, generates superior image quality and the image quality is not affected by the area of the display. However, these displays are fragile in nature and are susceptible to burn-out from static images.

Field Emission Displays (FEDs)

FEDs function much like the CRT displays with the main difference being that these displays use millions of small electron guns to emit electrons at the screen instead of just one as in case of CRT displays. The extraction of electrons in FEDs is based on the "tunneling effect." FED displays produce the same quality of image as produced by the CRT displays without being bulky as the CRT displays. Infact these displays can be as thin as LCD displays and as large as plasma displays.

Electronic Ink Displays

Electronic ink displays, also referred to as electronic paper, are active matrix displays making use of pigments that resemble the ink used in print.

7.14 Optocouplers

An optocoupler, also referred to as an optoisolator, is a device that uses a short optical transmission path to transfer signals between the elements of a circuit. Optocouplers are sealed units that house an optical transmitting device and a photosensitive device that are coupled together optically. The optical path may be air or a dielectric waveguide. Figure 7.49 shows the basic structure of an optocoupler.

The transmitter unit contains either a lamp, an LED or in some cases a laser diode. The receiver unit may be a photodiode, a phototransistor, a photoFET, a photoSCR, a photoDIAC, a photoTRIAC, a photoconductor or any other photosensitive material. As the coupling between the source and the photosensor is optical, high isolation exists between the input and the output circuitry. Hence, low power level, sensitive circuits can be used to actuate high power devices using optocouplers. In other words, optocouplers are used in applications that require isolation between input and output signals. Optocouplers have also replaced low power relays and pulse transformers in many applications. They can also be used for applications like detection of objects, liquid-level detection, smoke and fog detection, end-of-tape detection and so on.

Optocouplers with photodiodes [Figure 7.50(a)], phototransistors [Figure 7.50(b)], photo-Darlington transistors [Figure 7.50(c)], photoconductor [Figure 7.50(d)] and photoFET [Figure 7.50(e)] detectors at the receiving end are referred to as non-latching optocouplers. Optocouplers with photoSCR [Figure 7.51(a)], photoDIAC [Figure 7.51(b)] and photoTRIAC [Figure 7.51(c)] at the receiving side are referred to as latching optocouplers.

Optocoupler Parameters

The important parameters that define the performance of an optocoupler include forward optocoupling efficiency, input-to-output isolation voltage, input current, bandwidth and temperature response.

1. **Forward Optocoupling Efficiency:** The forward optocoupling efficiency is specified in terms of the current transfer ratio (CTR). CTR is the ratio of the output current to the input current. For logic output optocouplers, the coupling efficiency is defined as the input current to the LED that would cause a change in the logic state of the optocoupler's output. To ensure high coupling efficiency, the wavelength response of the receiver is matched to the emission spectrum of the phototransmitter. Typical values of CTR range from 10% to 50% for optocouplers having phototransistors as the photosensor and can be even as high as 200% for optocouplers having photo-Darlington transistors at the output.
2. **Isolation Voltage:** It is the maximum permissible DC potential that can be allowed to exist between the input and the output circuits. Typical values of isolation voltages offered by optocouplers are in the range of 500–4000 V.

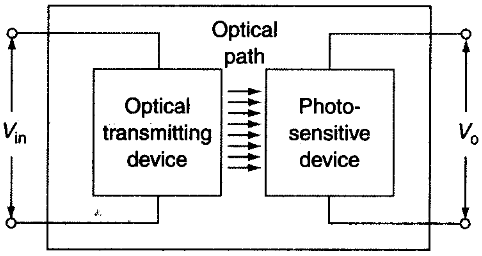
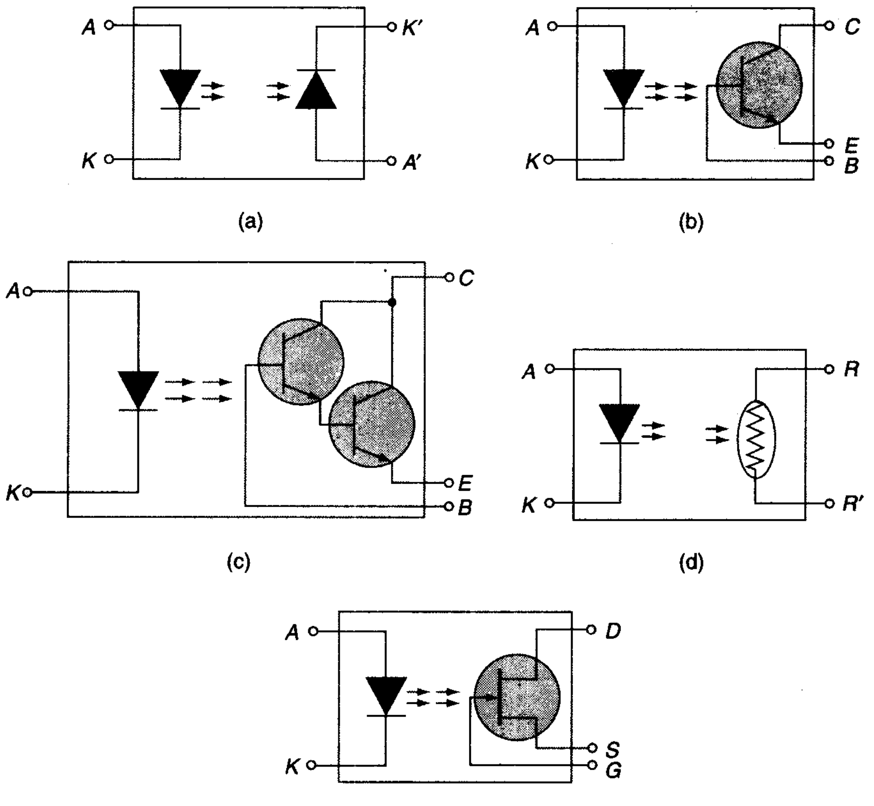


Figure 7.49 | Basic structure of an optocoupler.

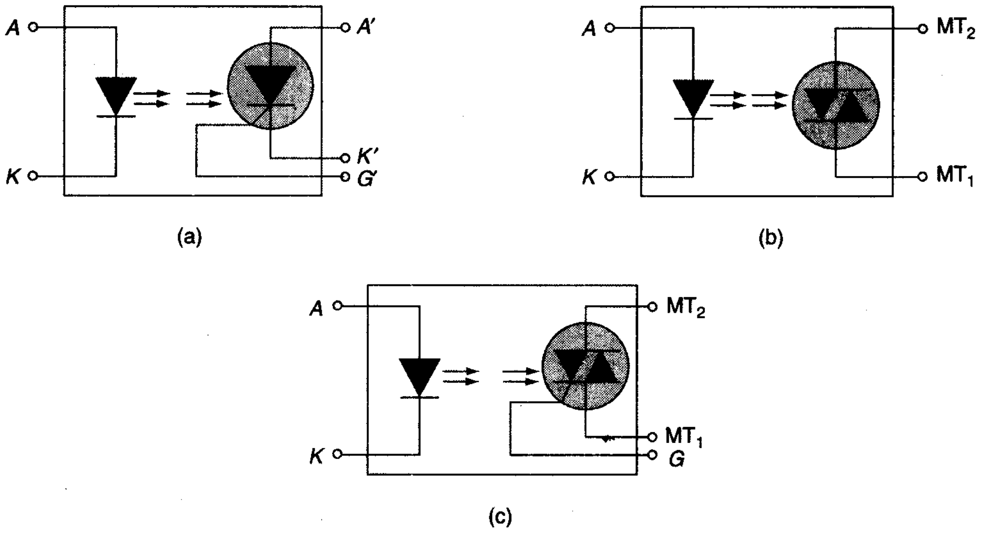


(a) (b)

(c) (d)

(e)

Figure 7.50 | Non-latching optocoupler configurations.



(a) (b)

(c)

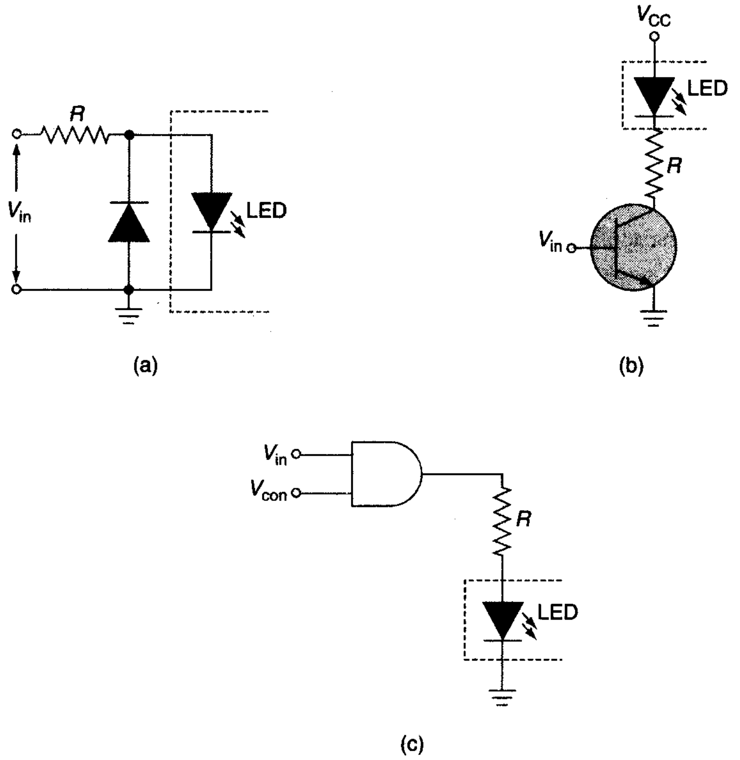
Figure 7.51 | Latching optocoupler configurations.

3. **Input Current:** It is the maximum permissible forward current that is allowed to flow into the transmitting LED. Typical value of forward current varies in the range of 10–100 mA.
4. $V_{CE(max)}$: It is applicable for optocouplers having phototransistors at the output. It is defined as the transistor's maximum collector–emitter voltage rating. It limits the supply voltage that can be applied to the output circuit.
5. **Bandwidth:** It determines the maximum signal frequency that can be successfully passed through the optocoupler. The bandwidth of an optocoupler depends upon its switching speed. Optocouplers offer bandwidths in the range of 10 kHz to 1 MHz, depending upon the device construction. To achieve faster operating speeds, integrated photodiode-transistor detectors or Schottky transistors are used.

Optocoupler Application Circuits

The simplest way to visualize an optocoupler is in terms of its two important components, namely, the input optical transmitting element and the output photosensor. As in an optocoupler, the transmitting and the receiving elements are electrically isolated; hence there exists a lot of flexibility in connecting them.

The transmitting element most commonly used in an optocoupler is an LED. The LED in an optocoupler can be driven in a manner similar to that for a discrete LED. Figure 7.52 shows the various configurations in which the LEDs in an optocoupler can be connected. These circuits are similar to those discussed in Section 7.10 on LEDs. Figure 7.52(a) shows a conventional circuit for driving the LED. The diode across



(a) (b)

(c)

Figure 7.52 Driving LEDs of an optocoupler.

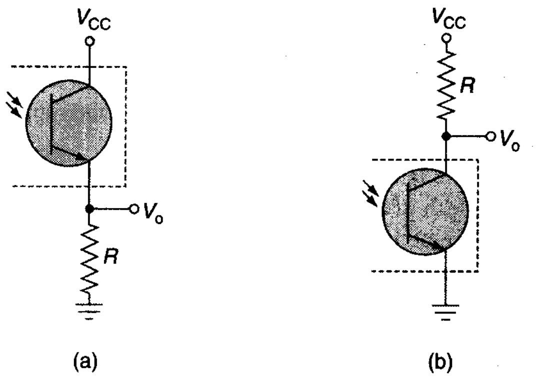


Figure 7.53 Driving the phototransistors of an optocoupler.

the LED is used for protecting the LED against reverse polarity voltages. Figures 7.52(b) and (c) show how to drive an LED using a transistor and a logic buffer, respectively. For both the circuits, the LED is ON for logic HIGH input and is OFF for logic LOW input.

At the receiving side of the optocoupler, the photosensor used may be a photodiode, a phototransistor, a photo-Darlington transistor, a photoFET, a photoDIAC or a photoTRIAC. Circuits for driving these photosensors are similar to that used for driving discrete sensors. It may be mentioned here that the output circuit is configured depending upon the intended application.

In many cases, the phototransistors are simply connected as light-operated switches as shown in Figures 7.53(a) and (b). The phototransistor is used in the pull-up mode in Figure 7.53(a) and is used in the pull-down mode in Figure 7.53(b). The output of the phototransistor can be connected to a logic gate, a transistor or an operational amplifier. The optocoupler having a photo-Darlington transistor can also be driven in a similar manner.

Figure 7.54 shows the application circuit of an optocoupler having a photoDIAC as a photosensing element. In the circuit, the photoDIAC is used to trigger a TRIAC. The circuit employs a filter/delay circuit comprising resistors R_1 and R_2 and capacitor C_1 and also a snubber circuit across the TRIAC comprising resistor R_S and capacitor C_S to ensure correct triggering with inductive loads.

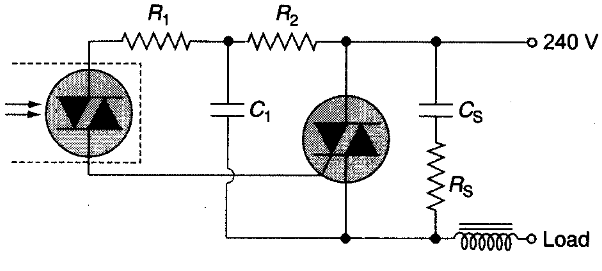
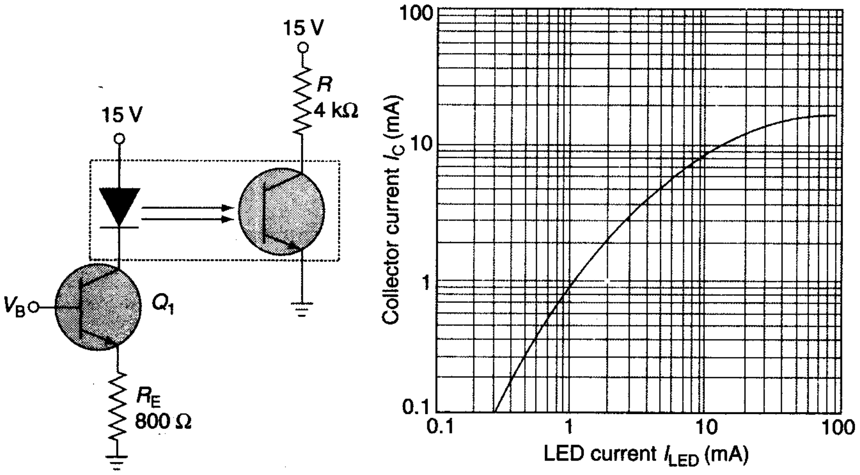


Figure 7.54 Application circuit of an optocoupler having a photoDIAC.

EXAMPLE 7.9

For the optocoupler circuit of Figure 7.55(a), the voltage across the resistor R is 4 V. Determine the value of the voltage V_B applied to the base of the transistor Q_1. The relationship between the input current flowing through the LED and the output phototransistor collector current is shown in Figure 7.55(b). The base–emitter voltage of transistor Q_1 is equal to 0.7 V.



(a) (b)

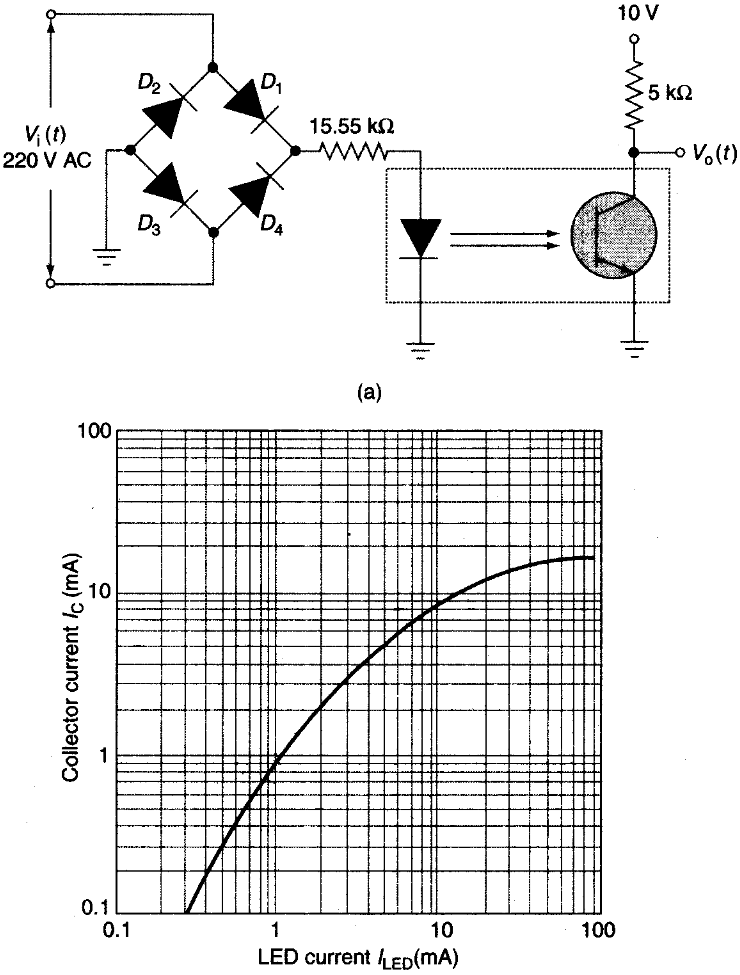
Figure 7.55 | Example 7.9.

Solution

1. The current flowing across the resistor $R = 4/(4 \times 10^3) = 1 \times 10^{-3}$ A = 1 mA.
2. The collector current of the phototransistor (I_C) is equal to the current across resistor R. Therefore, $I_C = 1$ mA.
3. From the curve of Figure 7.55(b), the input current flowing through the LED is approximately equal to 1.1 mA.
4. The current flowing through the LED is equal to the collector current of transistor Q_1.
5. As the collector current of the transistor is approximately the same as its emitter current, therefore the emitter current is equal to 1.1 mA.
6. The voltage drop across resistor $R_E = 800 \times 1.1 \times 10^{-3} = 0.88$ V.
7. The voltage $V_B = V_E + V_{BE} = 0.88 + 0.7 = 1.58$ V.

EXAMPLE 7.10

The optocoupler-based circuit of Figure 7.56(a) is used to provide isolation from the power line and detect zero crossings of the line voltage. The relationship between the input LED current and the output current of the phototransistor for the optocoupler is shown in Figure 7.56(b). Draw the output waveform $V_o(t)$. Assume the diodes to be ideal.



(a)

(b)

Figure 7.56 | Example 7.10.

Solution

1. The bridge rectifier produces a full-wave rectified output. Therefore, the current through the LED is also a full-wave rectified waveform. The peak current through the LED is $I_{\text{LEDpeak}} = (1.414 \times 220)/(15.55 \times 10^3) = 20 \times 10^{-3}$ A = 20 mA.
2. The value of collector current when the phototransistor is in saturation $I_{\text{Csat}} = 10/(5 \times 10^3) = 2 \times 10^{-3} = 2$ mA.
3. From Figure 7.53(b), the collector current corresponding to the LED current of 20 mA is 14 mA. The collector current of the phototransistor never reaches 14 mA as it saturates at 2 mA.

4. The phototransistor is saturated during most of the cycle as the phototransistor saturates for all values of LED currents that produce more than 2 mA of phototransistor collector current. Therefore, the output voltage is zero for most of the cycle.
5. When the line voltage changes polarity, that is, when zero crossings occur, the LED current drops to zero. The phototransistor stops conducting and the output voltage is equal to the supply voltage 10 V, that is, $V_o(t) = 10$ V.
6. Figure 7.57 shows the output waveform.

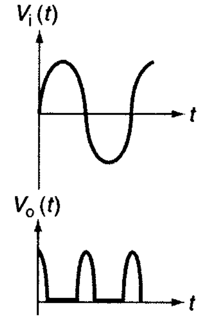


Figure 7.57 | Solution to Example 7.10.

KEY TERMS

- Avalanche photodiode
- Cathode ray tube (CRT) display
- Current transfer ratio (CTR)
- Dee-star
- Detectivity
- Digital light processing (DLP)
- Field emission display (FED)
- Flicker noise
- Flux
- Illuminance
- Image intensifier
- Intensity
- Johnson noise
- Light dependent resistor (LDR)
- Light-emitting diode (LED)
- Liquid-crystal display (LCD)
- Luminous intensity
- Noise equivalent power (NEP)
- Optocoupler
- Optoelectronic device
- Optoisolator
- Organic light-emitting diode (OLED)
- Photoconductive mode
- Photoconductor
- Photodiode
- Photoelectric sensor
- Photoemitter
- PhotoFET
- Photometry
- Photomultiplier tube
- Photoresistor
- Photosensor
- Phototransistor
- Photovoltaic mode
- PIN photodiode
- Plasma display
- PN photodiode
- Quantum efficiency
- Radiant incidence
- Radiometeric intensity
- Radiometry
- Response time
- Responsivity
- Rise time
- Schottky photodiode
- Shot noise
- Spectral response
- Thermal sensor
- Time constant
- Vacuum photodiode

OBJECTIVE-TYPE EXERCISES

Multiple-Choice Questions

1. What factors determine the type of photodetector you select?
   - **a.** Speed of response
   - **b.** Minimum and maximum light levels
   - **c.** Spectral response
   - **d.** (a) and (b)
   - **e.** All the above
2. A photocell's resistance versus light can vary as much as
   - **a.** 10:1.
   - **b.** 20:1.
   - **c.** 50:1.
   - **d.** several orders of magnitude.
3. LED's efficiency is a measure of the electrical energy required to produce a certain
   - **a.** current.
   - **b.** resistance.
   - **c.** photometric efficiency.
   - **d.** light output.
4. The resistance of a photoconductor
   - **a.** decreases with increase in light intensity.
   - **b.** increases with increase in light intensity.
   - **c.** does not change with light intensity.
   - **d.** can increase or decrease with increase in light intensity.
5. Increase in reverse-bias voltage across the photodiode
   - **a.** increases the rise time and decreases the width of the depletion region of the photodiode.
   - **b.** decreases the rise time and decreases the width of the depletion region of the photodiode.
   - **c.** decreases the rise time and increases the width of the depletion region of the photodiode.
   - **d.** increases the rise time and increases the width of the depletion region of the photodiode.
6. The noise current and responsivity of a sensor are 10 nA and 1 A/W, respectively. Its NEP is
   - **a.** 10 nW.
   - **b.** 1 nW.
   - **c.** 100 nW.
   - **d.** 0.1 nW.
7. The output wavelength of an LED is
   - **a.** directly proportional to the bandgap energy of the semiconductor material.
   - **b.** inversely proportional to the bandgap energy of the semiconductor material.
   - **c.** proportional to the square of the bandgap energy of the semiconductor material.
   - **d.** inversely proportional to the square of the bandgap energy of the semiconductor material.
8. The best parameter to compare the noise performance of any two sensors is
   - **a.** NEP.
   - **b.** dee-star.
   - **c.** detectivity.
   - **d.** none of these.
9. Which of the following statements is true?
   - **a.** Drive waveform for a LCD display is a DC voltage.
   - **b.** Drive waveform for a LCD display is an AC waveform with zero RMS value.
   - **c.** Drive waveform for a LCD display is an AC waveform with zero DC value.
   - **d.** Drive waveform for a LCD display can be a DC or an AC waveform.
10. Typical range of CTR value for an optocoupler having a phototransistor at the output is
    - **a.** 10% to 50%.
    - **b.** 1% to 10%.
    - **c.** 60% to 90%.
    - **d.** 10% to 70%.

Fill in the Blanks

1. Dark current in a photodiode is a measure of its __________ current.
2. __________ photosensor can be used to count even a single photon.

3. The width of the depletion region of a photodiode is __________ proportional to the applied reverse-bias voltage.
4. __________ is the most important photosensor parameter to be considered for low noise applications.
5. When you are looking for an ultra low noise performance and the frequency of operation is less than 1 kHz, you operate the photodiode in __________ mode.
6. LCD displays offer __________ viewing angle as compared to the LED displays.
7. Main component of a CRT display is an __________.
8. LEDs are __________ biased for their normal operation.
9. Optocouplers are mostly used in applications to provide __________ between the input and output circuits.
10. Phototransistors offer __________ response time as compared to photodiodes.

REVIEW QUESTIONS

1. Name the two operating modes of a photodiode? Describe the difference between these two modes using schematic diagrams to highlight the operation of the photodiode in both the modes.
2. What is a phototransistor? Draw the schematic symbol of a phototransistor. State any two application areas of phototransistors.
3. Explain in detail the principle of operation of an LED. Also explain the factors that determine the output wavelength of LEDs.
4. Name the most sensitive photosensor. Also explain in brief its principle of operation.
5. What are optocouplers? Also explain the important characteristic parameters of optocouplers.
6. Explain the following terms:
   - a. NEP
   - b. Illuminance
   - c. Thermal noise
   - d. Current transfer ratio
7. Compare and contrast the following:
   - a. Radiometry and photometry
   - b. Detectivity and Dee-star
   - c. Thermal detectors and photoelectric detectors
   - d. Radiant intensity and illuminance
8. How does the response time of an LCD display vary with temperature?
9. Explain the different modes of operation of an LCD display. Also mention the advantages and disadvantages of each of these operating modes.
10. Mention any two important applications of optocouplers. Draw the basic circuits that can be used for these applications.
11. Explain in detail the difference between bolometers and photoconductors.
12. Which photosensor is used in night vision devices? Explain in brief its principle of operation.
13. Which parameters of a photosensor are of utmost importance while designing a receiver for detecting weak optical signals?
14. How does the wavelength of an LED vary with change in the bandgap energy of the semiconductor material?
15. What are the design considerations to be kept in mind while connecting LEDs in series and in parallel?

PROBLEMS

1. For the circuit shown in Figure 7.58, determine the current flowing through the LED? The base–emitter voltage of the PNP transistor is –0.6 V and the forward voltage drop of the LED is 1.4 V.

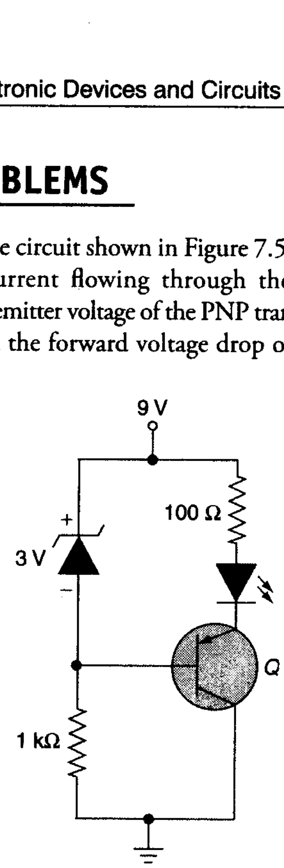


Figure 7.58 | Problem 1.

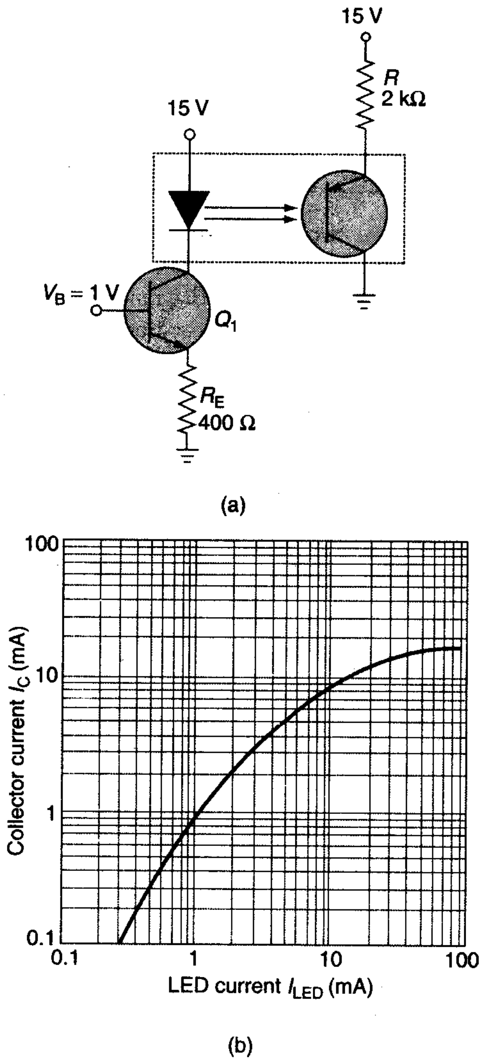
2. Design a panel of solar cells capable of delivering an output voltage of 5 V with a load-delivering capability of 1 A. Each of the solar cell is capable of generating an output voltage of 0.48 V with an output current of 150 mA.

3. A laser pulse with a rise time of 10 ns is incident on a PIN photodiode. The electrical pulse is seen on an oscilloscope having a bandwidth of 35 MHz and the rise time is measured to be 20 ns. Determine the rise time of the photodiode.

4. a. A photosensor has total noise current of 100 pA, responsivity of 1 A/W, active area of 2 mm^2 and rise time of 3.5 ns. Determine its (i) NEP; (ii) detectivity and (iii) Dee-star.

   b. Compare the NEP, detectivity and Dee-star parameters of the sensor in Problem 4(a) with another photosensor having same parameters as that of the sensor in Problem 4(a) except that the active area of the photosensor is 8 mm^2 and the noise current is 10 nA.

5. For the optocoupler circuit of Figure 7.59(a), determine the voltage across the resistor R, given that the value of the voltage V_B applied to the base of the transistor Q_1 is 1 V. The relationship between the input current flowing through the LED and the output phototransistor collector current is shown in Figure 7.59(b). The base–emitter voltage of transistor Q_1 is equal to 0.7 V.



(a)

(b)

Figure 7.59 | Problem 5.

ANSWERS

Multiple-Choice Questions

1. (e)
2. (d)
3. (d)
4. (a)
5. (c)
6. (a)
7. (b)
8. (b)
9. (c)
10. (a)

Fill in the Blanks

1. Reverse saturation
2. Photomultiplier tube
3. Directly
4. NEP
5. Photovoltaic
6. Smaller
7. Electron gun
8. Forward
9. Isolation
10. Larger

Problems

1. 10 mA
2. Figure 7.60
3. 14.14 ns
4. **a.** 0.1 nW, 10^{10} W^{-1} and 1.414×10^{13} $W^{-1}cmHz^{1/2}$
  b. 10 nW, 10^{8} W^{-1} and 2.828×10^{11} $W^{-1}cmHz^{1/2}$
5. 1.24 V

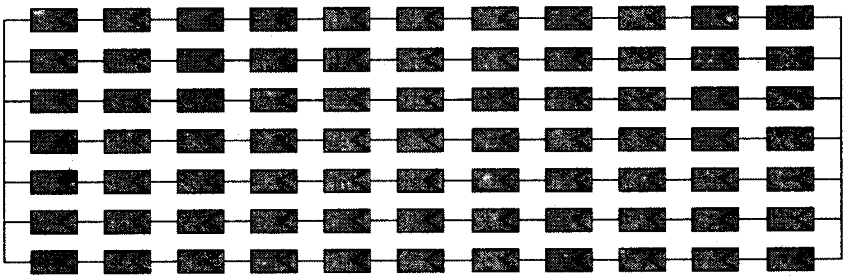


Figure 7.60 Solution to Problem 2.