19

Optoelectronic Devices

Introduction

Optoelectronic devices are light-operated (photoelectric) devices, light-emitting devices, or devices that modify light.

Photoelectric devices can be categorized as *photoemissive*, *photoconductive*, or *photovoltaic*. In photoemissive devices, radiation falling upon a cathode causes electrons to be emitted from the cathode surface. In photoconductive devices, the resistance of a material is changed when it is illuminated. Photovoltaic cells generate an output voltage that is proportional to radiation intensity.

Any light source emits energy only over a certain range of frequencies or wavelengths. A graph of energy output plotted versus either frequency or wavelength is termed the *emission spectrum* for the source. An electronic device which is affected by light is sensitive only to a certain range of radiation frequencies. A graph of device current, voltage, or resistance plotted versus radiation frequency is known as its *spectral response*. For a given photosensitive material, there is a minimum radiation frequency (or maximum wavelength) that can produce a photoelectric effect; this frequency is known as the *threshold frequency*.

19-1 Light Units

The total light energy output, or *luminous flux*, from a source can be measured in *milliwatts* (mW) or in *lumens* (lm), where

$$1 \text{ lm} = 1.496 \text{ mW}$$

Light intensity is the amount of light that falls on a unit area. Light intensity is expressed in *milliwatts per square centimeter* (mW/cm^2), in *lumens per square meter* (lm/m^2), or in the older unit *lumens per square foot* (lm/ft^2), which is also known as a *foot candle* (fc), where

$1 \text{ fc} = 10.764 \text{ lm/m}^2$

The light intensity of sunlight on the earth at noon on a clear day is approximately 10,000 fc, or 107,640 lm/m². Using 1 lm = 1.496 mW, this value converts to 161 W/m².

Consider a point source which emits light evenly in all directions. To determine the light intensity at a given distance from the source, it is necessary to consider the surface area of a sphere surrounding the source.

At a distance of 1 m from the source the luminous flux is spread over a total surface area of a sphere with a radius of 1 m. Thus,

Surface area of sphere $= 4\pi r^2$

$$\text{Light intensity} = \frac{\text{luminous flux}}{4\pi r^2} \tag{19-1}$$

Example 19-1 Calculate the light intensity at a distance 3 m from a lamp which emits 25 W of light energy. Also, determine the total luminous flux which strikes an area of 0.25 cm² at 3 m from the lamp.

Solution

From Eq. 19-1,

$$\text{Light intensity} = \frac{25 \text{ W}}{4\pi \times (3\text{m})^2}$$

$$= 221 \text{ mW/m}^2 = 22.1 \ \mu\text{W/cm}^2$$

$$\text{Total flux} = (\text{flux per unit area}) \times (\text{area})$$

$$= (\text{light intensity}) \times (\text{area})$$

$$= (22.1 \ \mu\text{W/cm}^2) \times (0.25 \text{ cm}^2)$$

$$\approx 5.5 \ \mu\text{W}$$

Light energy is electromagnetic radiation; i.e., it is in the form of electromagnetic waves. Therefore, it can be defined in terms of *frequency* or *wavelength*, as well as intensity. Wavelength, frequency, and velocity are related by the equation

$$c = f\lambda \tag{19-2}$$

where c = velocity

$= 3 \times 10^8$ m/s for electromagnetic waves

f = frequency in Hz

λ = wavelength in meters

Unit. 4

The wavelength of visible light ranges from violet at approximately 380 nm (380 nanometers, or 380×10^{-9} m) to red at 720 nm. From Eq. 19-2, the frequency extremes are

$$f_{violet} = \frac{c}{\lambda_{violet}} = \frac{3 \times 10^8}{380 \times 10^{-9}} \simeq 8 \times 10^{14} \text{ Hz}$$

and

$$f_{red} = \frac{3 \times 10^8}{720 \times 10^{-9}} \simeq 4 \times 10^{14} \text{ Hz}$$

19-2. Photomultiplier Tube

Although many solid-state photoelectric devices are available today, the photomultiplier tube is still widely applied, mainly because it is an extremely sensitive device. A *photomultiplier tube* consists of an evacuated glass envelope containing a *photocathode*, an *anode*, and several additional electrodes termed *dynodes*. Figure 19-1 illustrates the principle of the photomultiplier. Radiation striking the photocathode imparts energy to electrons within the surface material of the cathode. When the radiation frequency exceeds the threshold frequency of the cathode material, electrons are emitted from the surface. The emitted electrons (negative charge carriers) are accelerated toward dynode 1 by the positive potential on that dynode. The dynodes have surfaces which facilitate *secondary emission*. Thus, if the electrons strike the

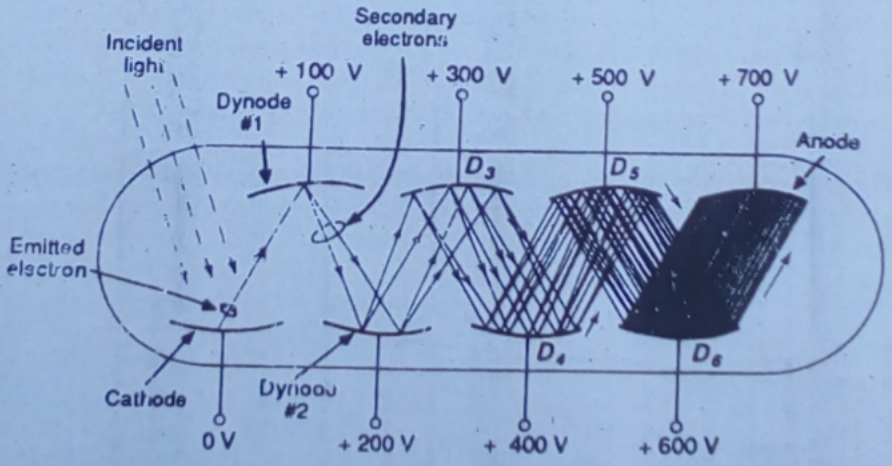


Figure 19-1 In a photomultiplier tube, incident light produces electron emission from the cathode. The electrons are accelerated successively to several dynodes, where they produce secondary emission and thus multiply the current level.

surface of dynode 1 with sufficient energy, *secondary* electrons are knocked out of the surface and are accelerated toward the more positive dynode 2. Each electron which strikes dynode 2 produces more secondary electrons, which are then accelerated to dynode 3, and so on.

The electrons emitted from the dynode surface are termed *secondary electrons* to distinguish them from the *primary* or *incident electrons*. The energy of the incident electrons depends upon the voltage applied to accelerate them, i.e., the dynode voltage. Since there are many more secondary electrons than primary electrons, the original photoemission current is amplified, or, in other words, the number of electrons is multiplied.

After moving from dynode 1 to dynode 2 and successive dynodes, the electrons are finally collected at the anode. In this way, photoemission currents of the order of microamperes are converted to more useful milliampere levels. Current amplifications of up to 10^6 are possible, depending upon the number of dynodes employed.

The characteristics of a typical photomultiplier tube are shown in Fig. 19-2. High voltages are required to operate the device. Anode voltages used with various photomultiplier tubes range from 500 V to 5000 V. The *dark current*, which flows when the cathode is not illuminated, results from *thermal emission* and the influence of the high-voltage electrodes. For incident illumination of a given wavelength, the number of electrons emitted is directly proportional to the illumination intensity. Thus, for a particular illumination intensity, the anode current of the photomultiplier tube should tend to remain constant as the anode voltage is increased. However, the dark current always

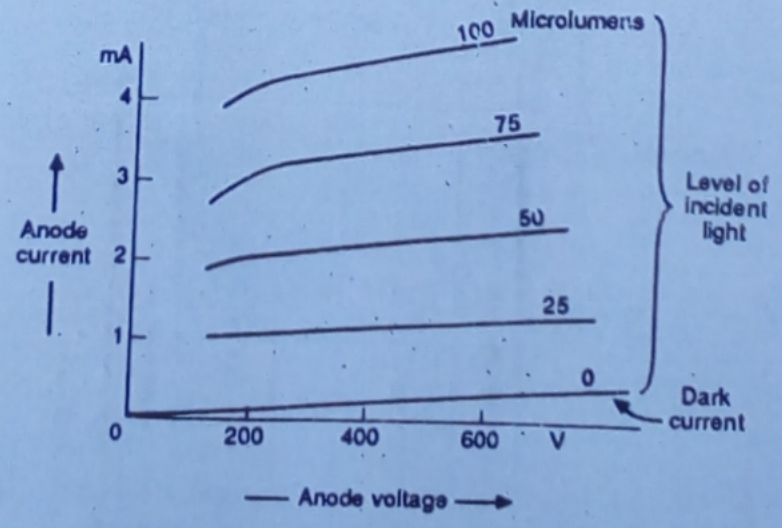
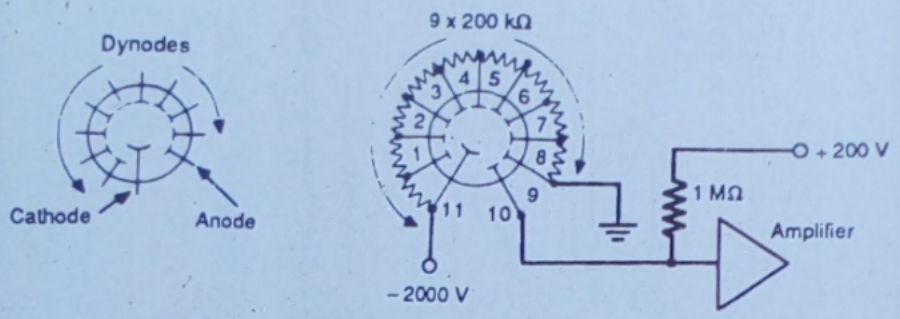


Figure 19-2 The current/voltage characteristics of a photomultiplier tube show that the anode current is approximately constant for each level of illumination.



(a) Photomultiplier circuit symbol

(b) Typical photomultiplier circuit

Figure 19-3 A photomultiplier tube connected into a circuit normally has its cathode biased to high negative voltage with respect to ground. The anode voltage is slightly above ground, and the dynodes are biased by means of a potential divider.

adds to the anode current produced by illumination, and secondary emission improves with increase in applied voltage; consequently, the anode current tends to increase slightly with increase in anode voltage.

Since the illumination levels indicated on the characteristics are measured in *microlumens*, it is seen that the photomultiplier tube is very sensitive indeed. In fact, the device is so sensitive that destructively large currents could flow if it is exposed to ordinary daylight levels when voltage is applied to its electrodes. Various spectral responses are available in photomultiplier tubes, ranging approximately from 150 nm to 600 nm, or from 400 nm to 1000 nm.

The symbol for a photomultiplier tube and a typical circuit arrangement are shown in Fig. 19-3. The cathode is provided with a high negative voltage, and the dynodes are biased via a potential divider arrangement between ground and the negative supply. The anode is connected via a high value of load resistance to a level that is more positive than ground. Although the device requires high operating voltages, the circuit arrangement enables the output voltage to be relatively close to ground.

19-3 Photoconductive Cell

Light striking the surface of a material can provide sufficient energy to cause electrons within the material to break away from their atoms. Thus, free electrons and holes (i.e , charge carriers) are created within the material, and consequently its resistance is reduced. The circuit symbol and construction of a typical photoconductive cell are shown in Fig. 19-4. Light-sensitive material is arranged in the form of a long strip, zigzagged across a disc-shaped base with

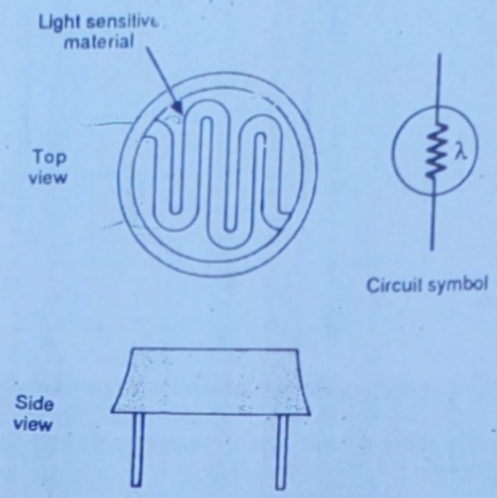


Figure 19-4 A photoconductive cell consists of a strip of light-sensitive material with two terminals.

protective sides. For added protection, a glass or plastic cover may be included. The two ends of the strip are brought out to connecting pins below the base.

From the illumination characteristic shown in Fig. 19-5, it is seen that, when the cell is not illuminated its resistance may be greater than 100 kΩ. This is known as the *dark resistance* of the cell. When the cell is illuminated, its resistance may fall to a few hundred ohms. Note that the scales on the illumination characteristic are logarithmic. Cell *sensitivity* may be expressed in terms of the cell current for a given voltage and given level of illumination.

The two materials normally employed in photoconductive cells are *cadmium sulfide* (CdS) and *cadmium selenide* (CdSe). Both materials respond rather slowly to changes in light intensity. For cadmium selenide, the response time is around 10 ms, while for cadmium sulfide it may be as long as 100 ms. Another important difference between the two materials is their temperature sensitivity. There is a large change in the resistance of a cadmium selenide cell with changes in ambient temperature, but the resistance of cadmium sulfide remains relatively stable. As with all other devices, care must be taken to ensure that the power dissipation is not excessive. The *spectral response* of a cadmium sulfide cell is similar to that of the human eye; i.e., it responds to visible light. For a cadmium selenide cell, the spectral response is at the longer wavelength end of the visible spectrum and extends into the infrared region.

Figure 19-6 shows a photoconductive cell used for relay control. When the cell is illuminated, its resistance is low and the relay current is at its maximum. Thus, the relay will be energized. When the cell is dark, its high

Cds Cdse
100ms 10ms
Res Stable Large Temp
Spectr Human eye Longer wavelen
end of visible — infrared

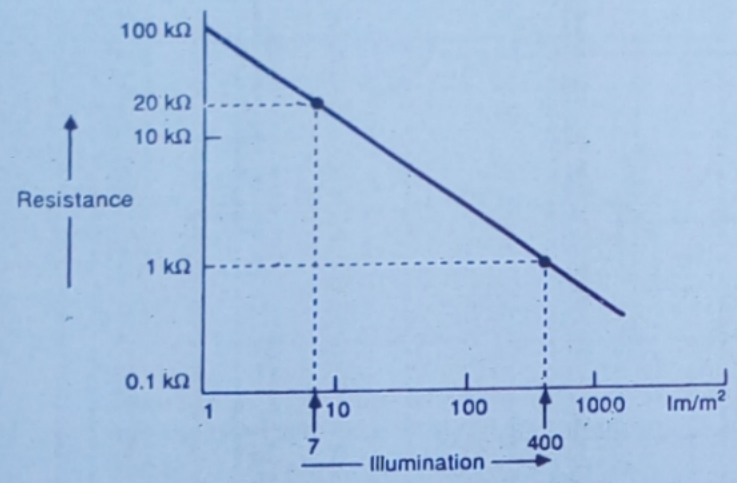


Figure 19-5 The illumination characteristic of a photoconductive cell shows that the resistance of the device can be very high when the cell is dark and relatively low when it is illuminated.

resistance cuts the current down to a level too low to energize the relay. Resistance R_1 is included to limit the relay current to the desired level when the cell resistance is low.

In Fig. 19-7 photoconductive cells are employed to switch transistors on and off. When the cell in Fig. 19-7(a) is dark, the transistor base is biased

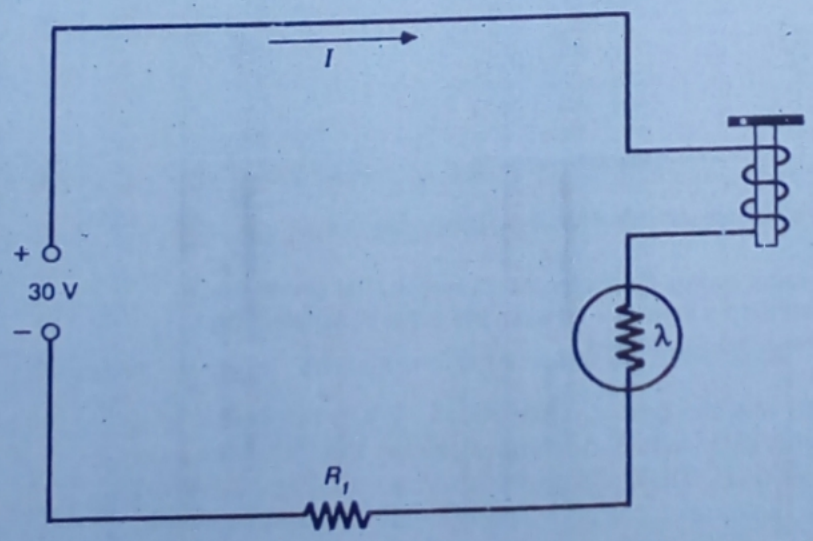
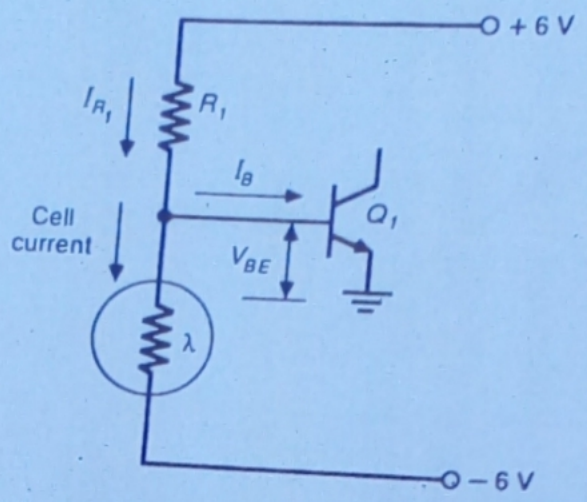
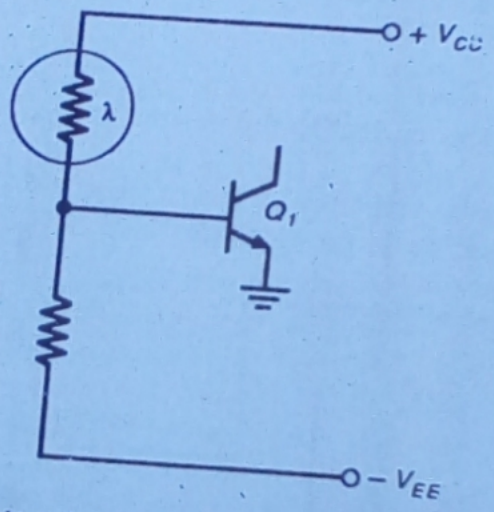


Figure 19-6 Relay controlled by a photoconductive cell. When the cell is dark, its high resistance keeps the current too low to energize the relay. When the cell is illuminated, substantial coil current flows.



(a) Circuit to switch transistor off when photoconductive cell is illuminated



(b) Circuit to switch transistor on when cell is illuminated

Figure 19-7 Transistor control by photoconductive cell. The circuit can be arranged to (a) switch the transistor off when the cell is illuminated, (b) turn the transistor on when illuminated.

above its emitter level, and the device is turned on. When the cell is illuminated, the lower cell resistance in series with R_1 biases the transistor base voltage below its emitter level. Thus, the device is turned off. Figure 19-7(b) shows a circuit in which the transistor is biased on when the cell is illuminated, and off when dark.

A photoconductive cell can be employed in a light meter. Figure 19-8 is really a simple ohmmeter circuit which gives maximum deflection when the cell resistance is low, i.e., when the cell is illuminated. As the cell resistance

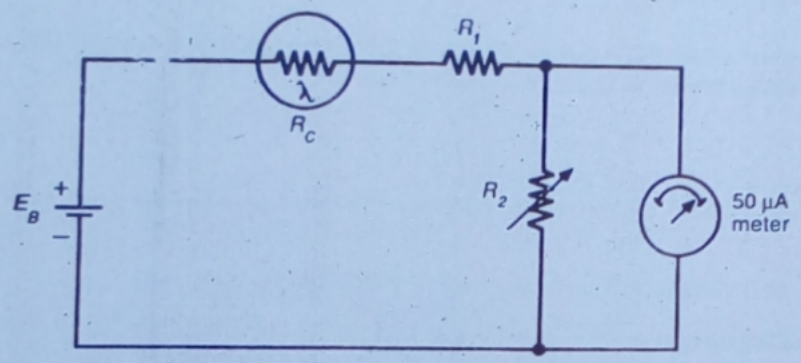


Figure 19-8 Light meter employing a photoconductive cell. Meter current increases with increase in cell illumination level.

increases with lower levels of illumination, the meter current drops. Thus, the meter scale can be calibrated to measure illumination intensity.

Example 19-2

A relay is to be controlled by a photoconductive cell as in Fig. 19-6. The cell has the characteristics shown in Fig. 19-5. The relay is to be supplied with 10 mA from a 30 V supply when the cell is illuminated with about 400 lm/m^2. Calculate the required series resistance and the level of the dark current.

Solution

The current is

$$I = \frac{30\text{ V}}{R_1 + (\text{cell resistance})}$$

or

$$R_1 = \frac{30}{I} - (\text{cell resistance})$$

From Fig. 19-5, the cell resistance at 400 lm/m^2 ≈ 1 kΩ. Thus,

$$R_1 = \frac{30\text{ V}}{10\text{ mA}} - 1\text{ k}\Omega = 2\text{ k}\Omega$$

From Fig. 19-5, the cell dark resistance ≈ 100 kΩ. Therefore,

$$\text{Dark current} \approx \frac{30\text{ V}}{2\text{ k}\Omega + 100\text{ k}\Omega} \approx 0.3\text{ mA}$$

Example 19-3

An *npn* transistor is to be biased on when a photoconductive cell is dark, and off when it is illuminated. The supply voltage is ±6 V, and the transistor

base current is to be 200 μA when on. If the photoconductive cell has the characteristics shown in Fig. 19-5, design a suitable circuit.

Solution

The circuit is as shown in Fig. 19-7(a).

From Fig. 19-5, the cell dark resistance ≈ 100 kΩ. So *when the transistor is on*,

$$\text{Cell voltage} = 6\text{ V} + V_{BE} = 6.7\text{ V (for a silicon transistor)}$$

$$\text{Cell current} = \frac{6.7\text{ V}}{100\text{ k}\Omega} = 67\ \mu\text{A}$$

The current through R_1 is

$$\text{Cell current} + I_B = 67\ \mu\text{A} + 200\ \mu\text{A} = 267\ \mu\text{A}$$

The voltage across $R_1 = 6\text{ V} - V_{BE} = 5.3\text{ V}$. So

$$R_1 = \frac{5.3\text{ V}}{267\ \mu\text{A}} \approx 20\text{ k}\Omega$$

When the transistor is off, the transistor base is at or below zero volts. Thus,

$$V_{R_1} \approx 6\text{ V}$$

and

$$I_{R_1} = \frac{6\text{ V}}{20\text{ k}\Omega} = 300\ \mu\text{A}$$

Since $I_B = 0$, cell current $= I_{R_1}$, and cell voltage ≈ 6 V. Therefore,

$$\text{Cell resistance} = \frac{6\text{ V}}{300\ \mu\text{A}} = 20\text{ k}\Omega$$

Consequently, Q_1 will be off when the cell resistance is 20 kΩ or less, i.e., when the illumination level is above approximately 7 lm/m² (see characteristics).

19-4 Photodiode

When the *pn*-junction is reverse biased, a reverse saturation current flows due to thermally generated holes and electrons being swept across the junction as minority carriers. Increasing the junction temperature will generate more hole–electron pairs, and so the minority carrier (reverse) current will be increased. The same effect occurs if the junction is illuminated. Hole–electron pairs are generated by the incident light energy, and minority charge carriers are swept across the junction. Increasing the level of illumination increases the number of charge carriers generated, and thus increases the level of reverse current flowing. Increasing the reverse voltage does not increase the reverse

current significantly, because all available charge carriers are already being swept across the junction. Even when the applied external bias is reduced to zero, the available minority carriers are swept across the junction by the junction barrier potential. To reduce the current to zero, it is necessary to forward bias the junction by an amount equal to the barrier potential.

Consider the typical illumination characteristics of a photodiode as shown in Fig. 19-9. When the cell is dark, $I_R \approx 20\ \mu A$ at $E_R = -2$ V. So

$$\text{Dark resistance} = \frac{E_R}{I_R} \approx \frac{2\text{ V}}{20\ \mu\text{A}} = 100\ \text{k}\Omega$$

When the cell is illuminated with 25,000 lm / m^2,

$$I_R \approx 375\ \mu A$$

and

$$\text{Illuminated resistance} \approx \frac{2\text{ V}}{375\ \mu\text{A}} = 5.3\ \text{k}\Omega$$

The resistance has changed by a factor of approximately 20, and it is seen that the photodiode can be employed as a *photoconductive device.*

When the reverse-bias voltage across a photodiode is removed, minority charge carriers will continue to be swept across the junction while the diode is illuminated. This has the effect of increasing the number of holes in the *p*-side and the number of electrons in the *n*-side. But the barrier potential is negative on the *p*-side and positive on the *n*-side, and was produced by holes

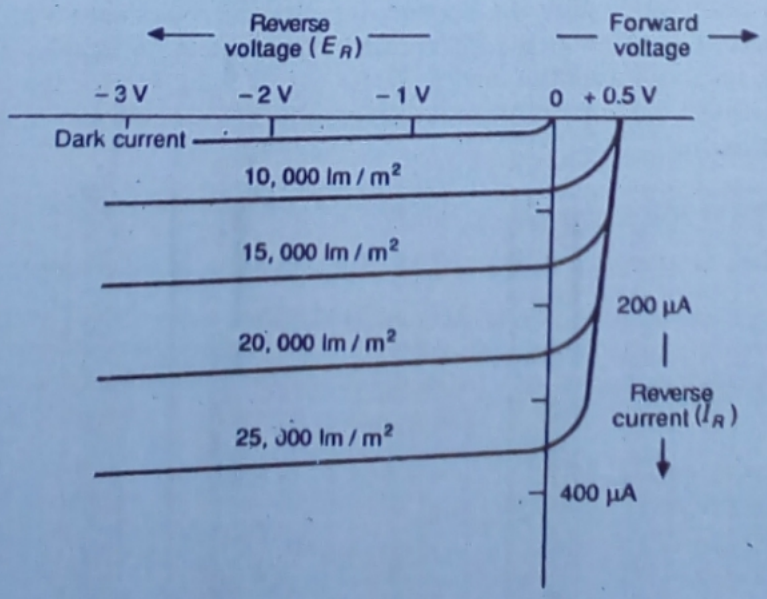


Figure 19-9 In a photodiode the reverse current has a constant level depending upon the level of illumination. The diode must be forward biased to reduce the reverse current to zero.

flowing from p to n and electrons from n to p during fabrication of the junction. Therefore, the miniority carrier flow tends to reduce the barrier potential. When an external circuit is connected across the diode terminals, the minority carriers will return to the original side via the external circuit. The electrons which crossed the junction from p to n will now flow out through the n-terminal and into the p-terminal. This means that the device is behaving as a voltage cell with the n-side being the negative terminal and the p-side the positive terminal. In fact, a voltage can be measured at the photodiode terminal, positive on the p-side and negative on the n-side. Thus, the photodiode is a *photovoltaic* device as well as a *photoconductive* device.

Typical silicon photodiode illumination characteristics (plotted in the first and second quadrants for convenience) are shown in Fig. 19-10. When the device operates with a reverse voltage applied, it functions as a photoconductive device. When operating without the reverse voltage, it operates as a photovoltaic device. It is also possible to arrange for a photodiode to change from the photoconductive mode to the photovoltaic mode. The circuit symbol for the device is also shown in Fig. 19-10. When a photodiode is operated in series with a load resistor R_1, as illustrated in Fig. 19-11, the dc load line can be drawn on the device characteristics in the usual way.

Example 19-4 A photodiode with the illumination characteristics shown in Fig. 19-10 is connected in series with a 200 Ω resistance and a 0.5 V supply. The supply polarity reverse biases the device. Draw the dc load line for the circuit and determine the diode currents and voltages at 1500, 10 000, and 20 000 lm/m² of illumination.

Solution

The circuit is as shown in Fig. 19-11. The equation for the supply voltage is

$$E_S = I_D R_1 + V_D$$

When $I_D = 0$,

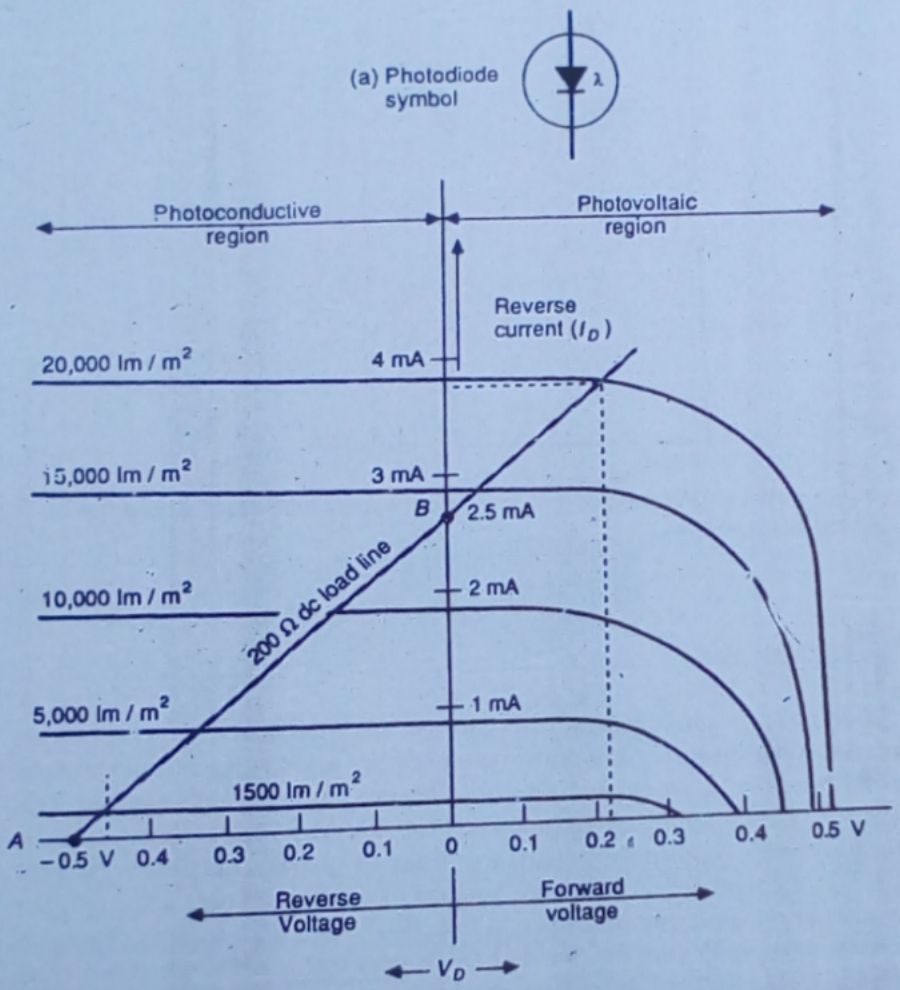
$$V_D = E_S = -0.5 \text{ V}$$

Plot point A on Fig. 19-10 at $I_D = 0$ and $V_D = -0.5$ V.

When $V_D = 0$, $V_{R_1} = E_S$. So

$$I_D = \frac{V_{R_1}}{R_1} = \frac{-0.5 \text{ V}}{200 \Omega} = 2.5 \text{ mA}$$

Plot point B at $I_D = -2.5$ mA and $V_D = 0$ V. Then draw the dc load line through points A and B.



(b) Illumination characteristics

Figure 19-10 Photodiode characteristics have a photoconductive region and a photovoltaic region. The device operating conditions may move from one region of the characteristics to the other when the illumination level changes.

From the load line,

At 1500 lm/m², $I_D \approx -0.2$ mA, $V_D \approx -0.45$ V
At 10 000 lm/m², $I_D \approx -1.9$ mA, $V_D \approx -0.12$ V
At 20 000 lm/m², $I_D \approx -3.7$ mA, $V_D \approx +0.22$ V

Note that the polarity of V_D changes from negative to positive at the highest level of illumination.

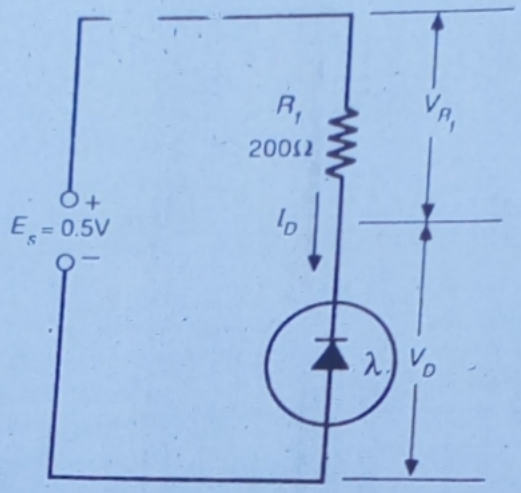


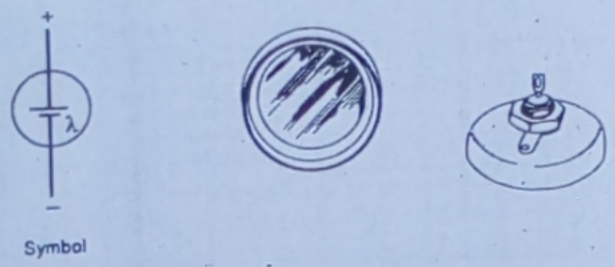
Figure 19-11 Photodiode with series-connected load resistor, and (reverse bias) supply.

19-5 Solar Cell

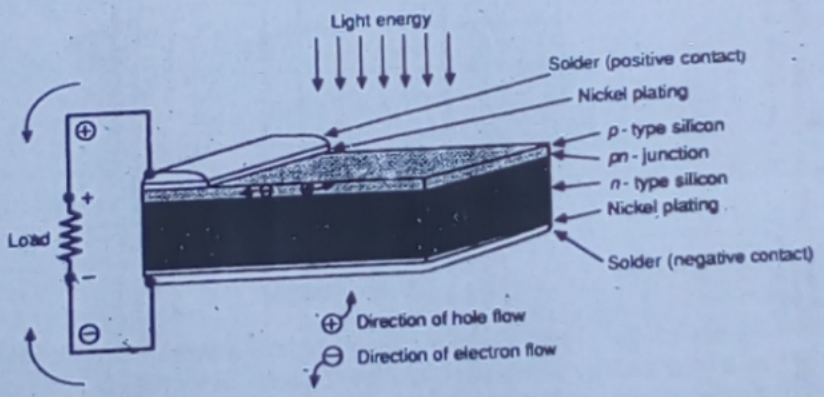
The *solar cell*, or *solar energy converter*, is essentially a large photodiode designed to operate solely as a photovoltaic device and to give as much output power as possible. Low-current photodiodes are generally packaged in TO-type cans with an opening or a window on top. Devices for operation as *solar energy converters* require larger surface areas to provide maximum current capacity. The construction and cross section of a typical power solar cell for use as an energy converter are shown in Fig. 19-12. The surface layer of *p*-type material is extremely thin so that light can penetrate to the junction. The nickel-plated ring around the *p*-type material is the positive output terminal, and the plating at the bottom of the *n*-type material is the negative output terminal. Power solar cells are also available in flat strip form for efficient coverage of available surface areas. The circuit symbol normally used for a photovoltaic device is also shown in Fig. 19-12.

Typical output characteristics of a power photocell are shown in Fig. 19-13. Consider the device characteristic when the incident illumination is 100 mW/cm². If the cell is short-circuited, the output current is 50 mA. Since the cell voltage is zero, the output power is zero. If the cell is open-circuited, the output voltage is approximately 0.55 V but the output current is zero. Therefore, the output power is again zero. For maximum output power, the device must be operated on the knee of the characteristic. As in the case of all other devices, the output power must also be derated at high temperatures.

Figure 19-14 shows a group of series–parallel connected solar cells operating as a battery charger. Several cells must be series connected to produce



(a) Symbol and Construction



(b) Cross section

Figure 19-12 Construction and cross section of a solar cell. (Courtesy of Solar Systems, Inc.) A solar cell is essentially a large photodiode designed to operate as a photovoltaic device.

the required output voltage, and several of these series-connected groups must be connected in parallel to provide the necessary output current.

Example 19-5

An earth satellite has 12 V batteries which supply a continuous current of 0.5 A. Solar cells with the characteristics shown in Fig. 19-13 are employed to keep the batteries charged. If the illumination from the sun for 12 hours in every 24 is 125 mW/cm^2, determine approximately the total number of cells required.

Solution

The circuit for the solar cell battery charger is as shown in Fig. 19-14.

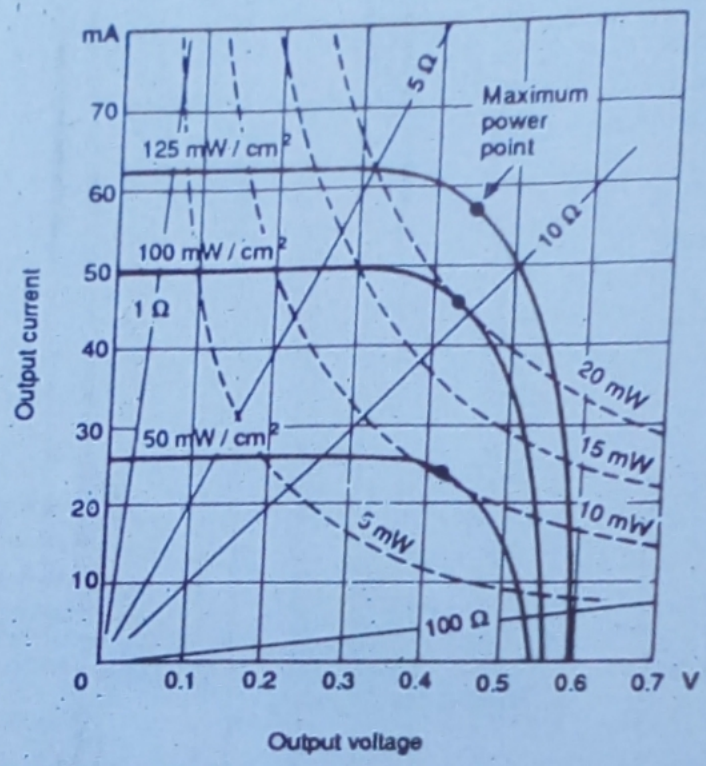


Figure 19-13 Typical output characteristics of power photocell for use as a solar energy converter. (Courtesy of Solar Systems, Inc.) The device is normally operated at the maximum power point.

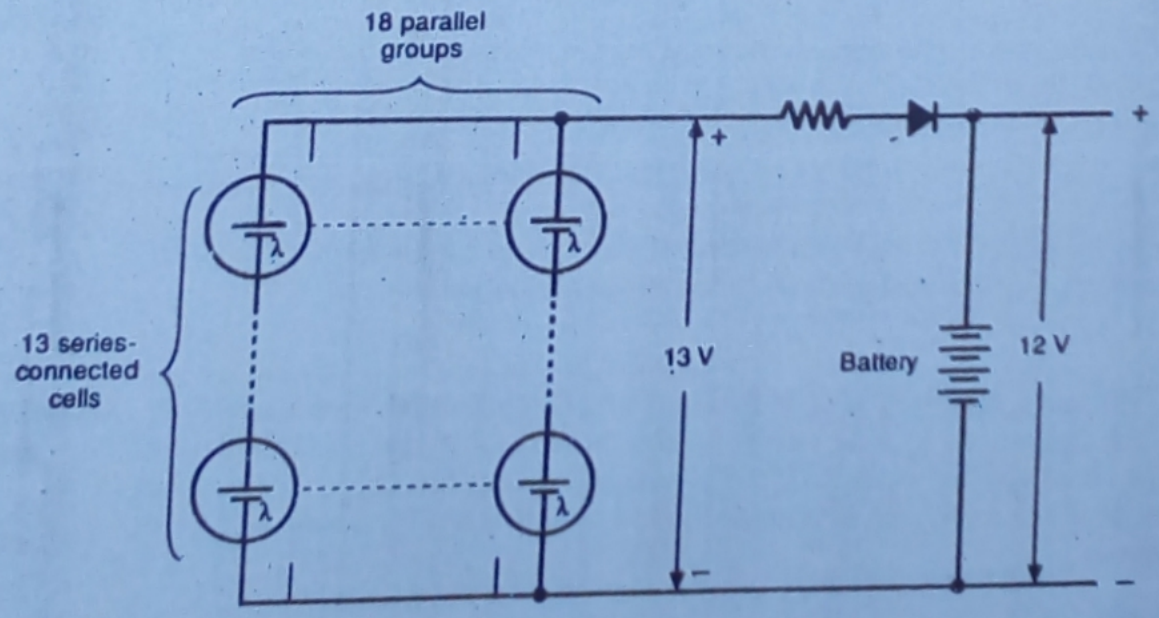


Figure 19-14 Array of solar cells connected as a battery charger. Solar cells can be series connected to provide a desired output voltage, and several series-connected groups can be paralleled to provide a desired output current level.

For maximum output power, each device should be operated at approximately 0.45 V and 57 mA (Fig. 19-13). Allowing for the voltage drop across the rectifier, a maximum output of approximately 13 V is required. Thus,

$$\text{Number of series-connected cells} = \frac{\text{output voltage}}{\text{cell voltage}} = \frac{13\text{ V}}{0.45\text{ V}} \approx 29$$

The charge taken from the batteries over a 24-hour period is 24 hours × 0.5 A, or 12 ampere-hours. Therefore, the charge delivered by the solar cells must be 12 ampere-hours.

The solar cells deliver current only while they are illuminated, i.e., for 12 hours in every 24. Thus, the necessary charging current from the solar cells is 12 ampere-hours/12 hours, or 1 A. Hence,

$$\text{Total number of groups of cells in parallel} = \frac{\text{output current}}{\text{cell current}}$$

$$= \frac{1\text{ A}}{57\text{ mA}} \approx 18$$

The total number of cells required is (number in parallel) × (number in series) = 18 × 29 = 522

19-6 Phototransistor and Photodarlington

A phototransistor is similar to an ordinary bipolar transistor, except that no base terminal is provided. Instead of a base current, the input to the transistor is in the form of light. Consider an ordinary transistor with its base terminal open-circuited (Fig. 19-15(a)). The collector–base leakage current I_{CBO} will act as a base current.

From Eq. 3-6, $I_C = h_{FE} I_B + (h_{FE} + 1) I_{CBO}$

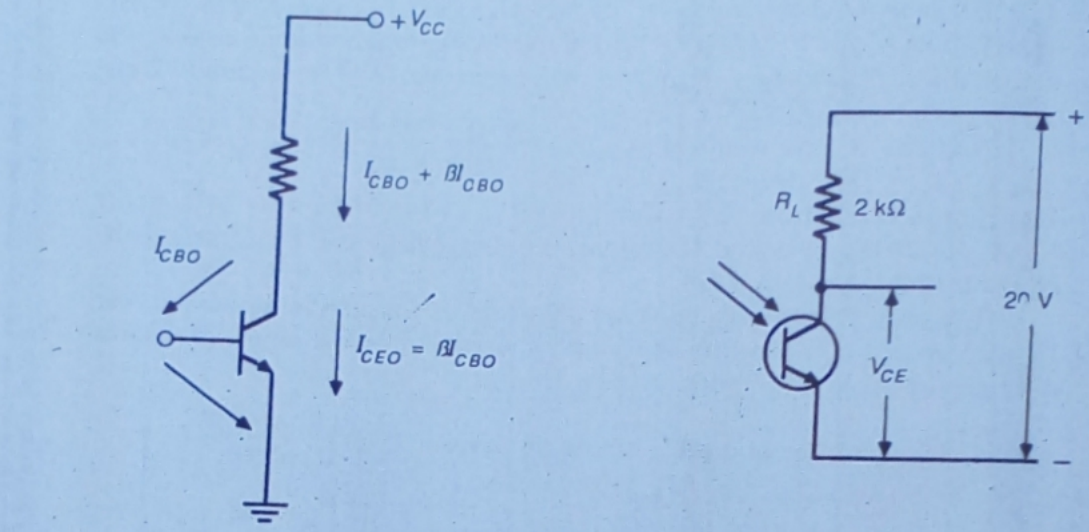
and $I_B = 0$

it follows that

$$I_C = (h_{FE} + 1) I_{CBO}$$

In this case, $I_C = I_{CEO}$, the collector–emitter leakage current with the base open-circuited.

In the case of the photodiode, it was shown that the reverse saturation current is increased by the light energy incident on the junction. Similarly, in the phototransistor I_{CBO} increases when the collector–base junction is illuminated. When I_{CBO} is increased, the collector current $(h_{FE} + 1) I_{CBO}$ is also increased. Therefore, for a given amount of illumination on a very small area, the phototransistor provides a much larger output current than that available from a photodiode, i.e., the phototransistor is the more sensitive of the two devices.



(a) Currents in a transistor with its base open circuited.

(b) Phototransistor circuit.

Figure 19-15 In a phototransistor, the collector current is dependent upon the level of illumination at the collector–base junction.

The circuit symbol for the phototransistor is shown in Fig. 19-15(b), and typical output characteristics are shown in Fig. 19-16. Some phototransistors have no base terminal and rely upon the incident illumination to generate a base current. Others have a base connection provided so that an external bias circuit may be connected. The device is usually packaged in a metal can with a lens on top. Clear plastic encapsulated phototransistors are also available.

Arrays of phototransistors and photodiodes are widely applied as *photodetectors* for such applications as punched card and tape *readout*. Phototransistors have the advantage of greater sensitivity than photodiodes. For a given level of illumination, a greater output current is produced by a phototransistor than by a photodiode. However, photodiodes are the faster of the two, switching in less than nanoseconds compared to typical phototransistor switching times of microseconds.

Example 19-6 A phototransistor having the characteristics shown in Fig. 19-16 has a supply of 20 V and a collector load resistance of 2 kΩ, as in Fig. 19-15. Determine the output voltage when the illumination level is (a) zero, (b) 20 mW/cm^2, (c) 40 mW/cm^2.

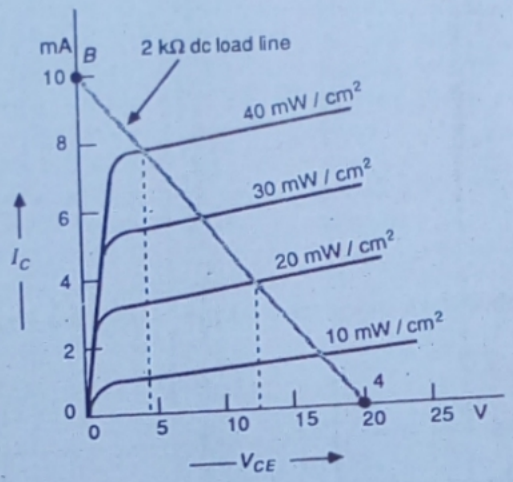


Figure 19-16 The I_C / V_{CE} characteristics of a phototransistor are similar to those of an ordinary transistor, except that illumination level is substituted for base current.

Solution

The load line is drawn in the usual way. When $I_C = 0$, $V_{CE} = V_{CC}$. So plot point A at $I_C = 0$, $V_{CE} = 20$ V.

When $V_{CE} = 0$, $I_C = V_{CC} / R_L = 20 \text{ V} / 2 \text{ k}\Omega = 10$ mA. So plot point B at $V_{CE} = 0$, $I_C = 10$ mA. Then draw the dc load line through points A and B.

From the intersections of the load line and the characteristics,

At illumination level = 0, output voltage $\approx V_{CE} = 20$ V
At illumination level = 20 mW / cm², output ≈ 12.5 V
At illumination level = 40 mW / cm², output ≈ 4 V

The *photodarlington* (Fig. 19-17) consists of a phototransistor connected in Darlington arrangement with another transistor. The device is capable of much higher output currents than a phototransistor, and so it has a greater sensitivity to illumination levels than either a phototransistor or a photodiode. With the additional transistor involved, the photodarlington has a considerably longer switching time than a phototransistor.

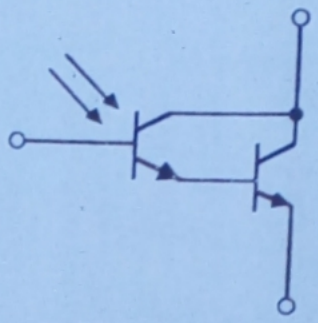
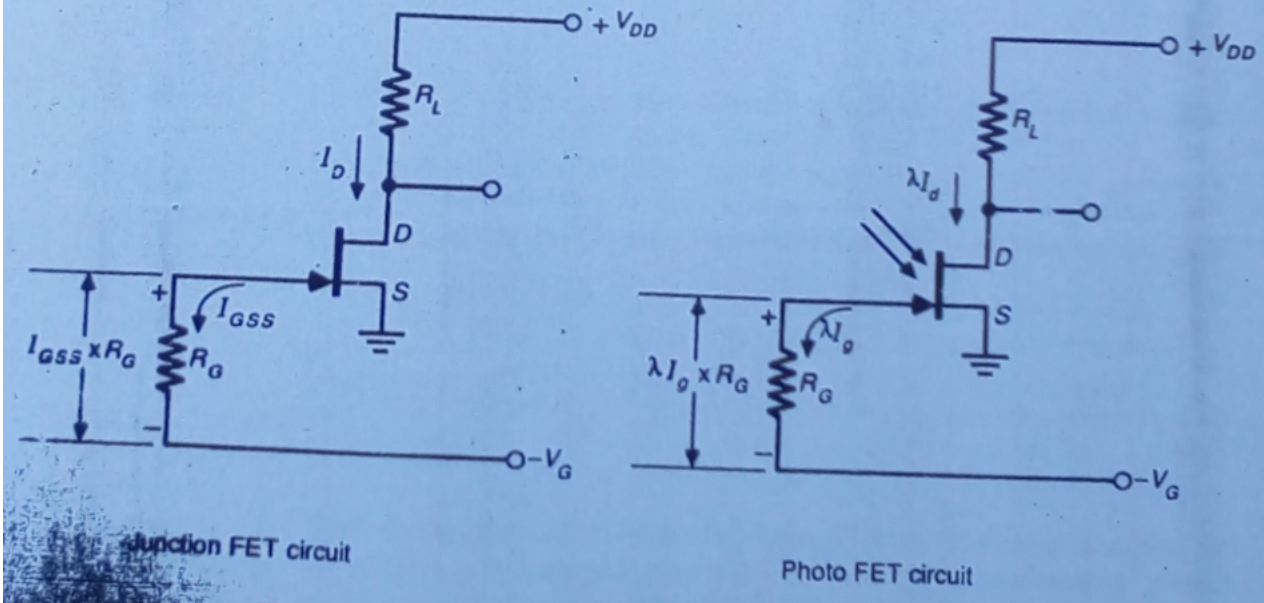


Figure 19-17 The photodarlington gives a larger output current than a phototransistor.

19-7 PhotoFET

If an appropriately designed junction field effect transistor has light focused on its gate–channel junction, the light will act as a signal and produce a change in the drain current. Consider the *n*-channel junction FET and the photoFET in Fig. 19-18. The gate–source leakage current I_{GSS} is the *reverse saturation current* at a reverse-biased *pn*-junction, and it is temperature dependent. As in the case of the phototransistor, the junction reverse saturation current is



Junction FET circuit

Photo FET circuit

Figure 19-18 In a photoFET, the leakage current at the gate–channel junction is dependent upon illumination level. This current flows in the bias resistor and controls the level of gate voltage.

also susceptible to light. Illumination on the junction causes more charge carriers to be generated and hence causes I_{GSS} to increase. I_{GSS} flows through bias resistance R_G and causes a voltage drop across R_G with the polarity shown. Thus, if $-V_G$ were just sufficient to bias the device off when dark, then when the junction is sufficiently illuminated, the increase in I_{GSS} causes the gate voltage to increase and bias the FET on. A gate-bias voltage that biases the device on might also be employed, so that increasing and decreasing the light level would cause I_D to increase and decrease. In a photoFET, the light-controlled I_{GSS} is referred to as the *gate current* λI_g. I_{GSS} then becomes the *dark gate-leakage current*. The light-controlled drain current is designated λI_d.

The gate–source voltage changes are proportional to the gate current and the gate bias resistance. That is,

$$\Delta V_{GS} = \lambda I_g \times R_G$$

and

$$\lambda I_d = g_m \times \Delta V_{GS}$$
$$= g_m \lambda I_g R_G$$

The selected value of R_G determines the sensitivity of the photoFET. For $\lambda I_g = 10$ nA, $g_m = 8$ mA/V, and $R_G = 1$ MΩ,

$$\lambda I_d = 8 \text{ mA/V} \times 10 \text{ nA} \times 1 \text{ MΩ}$$
$$= 80 \text{ μA}$$

If R_G is increased to 10 MΩ, λI_d becomes 800 μA.

Typical photoFET currents are

$$I_{GSS} = 0.5 \text{ nA}$$
$$\lambda I_g = 50 \text{ nA}/\mu\text{W}/\text{cm}^2$$
$$\lambda I_d = 500 \text{ μA}/\mu\text{W}/\text{cm}^2$$

19-8 Light Emitting Diode (LED)

Charge carrier recombination takes place at a *pn*-junction as electrons cross from the *n*-side and recombine with holes on the *p*-side. Free electrons are in the conduction band of energy levels, while holes are in the valence band. Therefore, electrons are at a higher energy level than holes, and some of this energy is given up in the forms of heat and light when recombination takes place. If the semiconductor material is translucent, the light will be emitted and the junction becomes a light source, i.e., a *light-emitting* diode (LED).

A cross-sectional view of a typical diffused LED is shown in Fig. 19-19. The semiconductor material employed is *gallium arsenide* (GaAs), *gallium arsenide phosphide* (GaAsP), or *gallium phosphide* (GaP).

An *n*-type epitaxial layer is grown upon a substrate, and the *p*-region is created by diffusion. Charge carrier recombinations occur in the *p*-region, so

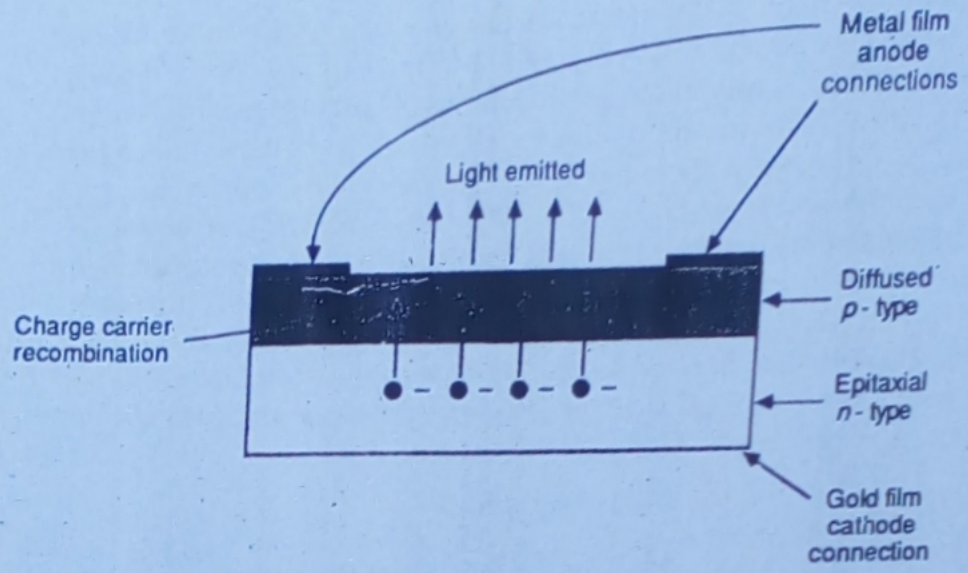


Figure 19-19 In a light emitting diode (LED), electron–hole recombination at the *pn*-junction gives up energy in the form of light.

this region must be kept uppermost. The *p*-region, therefore, becomes the surface of the device, and the metal film anode connection must be patterned to allow most of the light to be emitted. This is done by making connection to the outside edges of the *p*-type layer, or by depositing a comb-shaped pattern at the center of the *p*-type surface. A gold film is applied to the bottom of the substrate to reflect as much as possible of the light toward the surface of the device and to provide a cathode connection. LEDs made from GaAs emit infrared (i.e., invisible) radiation. GaAsP material provides either red light or yellow light, while red or green emission can be produced by using GaP.

Figure 19-20(a) shows the circuit symbol for the LED (the directions of the arrows indicate emitted light), and the typical arrangement of a seven-segment LED numerical display is shown in Fig. 19-20(b). Any desired numeral from 0 to 9 can be displayed by passing current through the appropriate segments. The actual LED device is very small, so, to enlarge the lighted surface, solid plastic *light pipes* are often employed [Fig. 19-20(c)]. The LEDs in a seven-segment display may be connected in common-anode or in common-cathode configuration [see Fig. 19-20(d)]. When selecting a LED seven-segment display, it is important to determine which of the two connecting arrangements is required.

The forward voltage for a LED is typically 1.2 V, and for forward current 20 mA is typical. The relatively large amounts of current consumed by LEDs are their major disadvantage. Excluding displays, all the circuitry of an electronic counter might require a total operating current of less than 100 mA. Four seven-segment LED displays might add 500 mA to this requirement, necessitating the inclusion of a much bulkier power supply. Apart from this disadvantage, LEDs do have the advantage of long life and ruggedness.

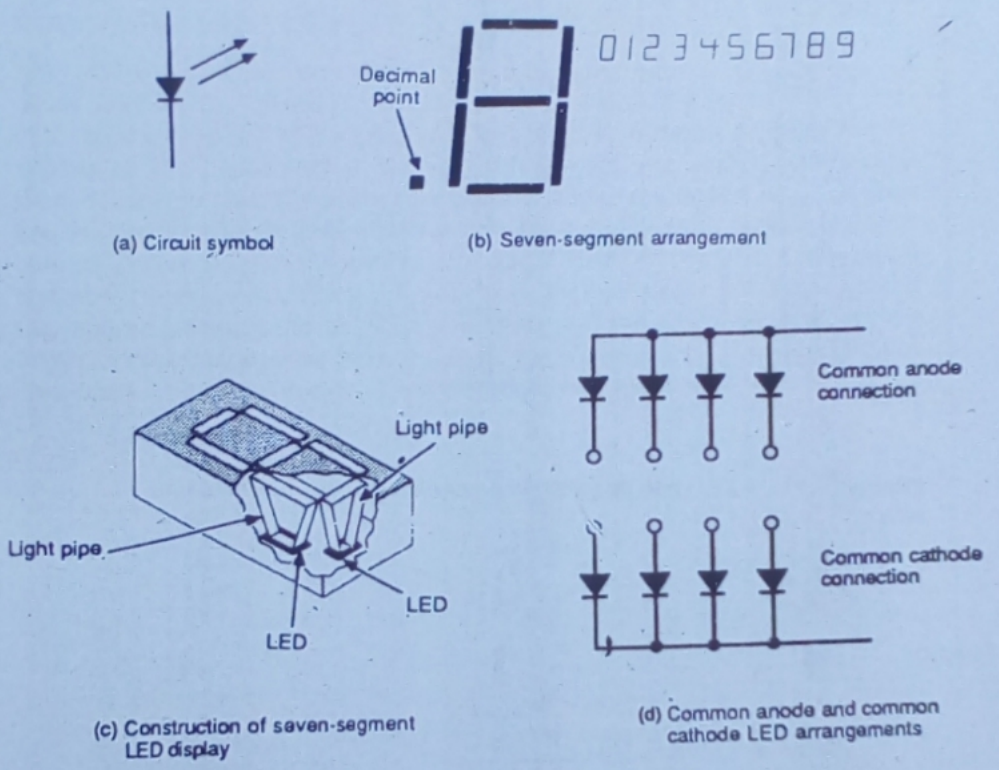


Figure 19-20 Light emitting diodes are arranged in seven-segment format for numerical displays.

Light-emitting diodes are usually switched on and off by means of a transistor circuit like the one illustrated in Fig. 19-21. The voltage drop across the LED is typically 1.2 V, and the transistor saturation voltage is approximately 0.2 V (i.e., for low I_C levels). Resistor R_2 is necessary to limit the current through the LED to the desired level. Example 19-7 shows how to design such a circuit.

Example 19-7

The LED shown in Fig. 19-21 is to have a current of approximately 10 mA passed through it when the transistor is on. The transistor employed is a 2N3904 (data sheet in Appendix 1-4). The supply voltage is $V_{CC} = 9$ V, and the input voltage is $V_i = 7$ V. Calculate the required values of R_1 and R_2.

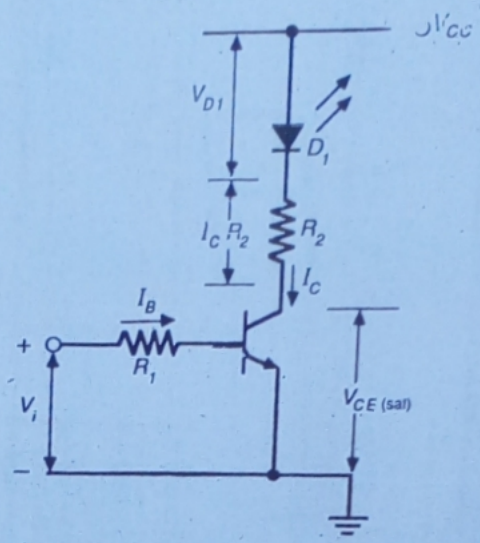


Figure 19-21 A LED can be switched *on* or *off* by means of a transistor switch.

Solution

$$V_{CC} = V_{D1} + I_C R_2 + V_{CE(sat)}$$

$$R_2 = \frac{V_{CC} - V_{D1} - V_{CE(sat)}}{I_C}$$

$$= \frac{9\text{ V} - 1.2\text{ V} - 0.2\text{ V}}{10\text{ mA}}$$

$$= 760\ \Omega \quad \text{(use 680 } \Omega \text{ standard value)}$$

I_C becomes

$$\frac{9\text{ V} - 1.2\text{ V} - 0.2\text{ V}}{680\ \Omega} = 11.2\text{ mA}$$

From Appendix 1-4, $h_{FE(min)} = 100$ when $I_C \approx 10$ mA. So

$$I_B = I_C / h_{FE(min)}$$

$$= \frac{11.2\text{ mA}}{100} = 112\ \mu\text{A}$$

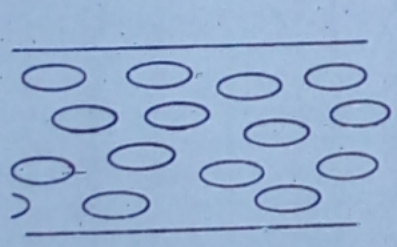
$$R_1 = \frac{V_i - V_{BE}}{I_B} = \frac{7\text{ V} - 0.7\text{ V}}{112\ \mu\text{A}}$$

$$\approx 56\ \text{k}\Omega \quad \text{(standard value)}$$

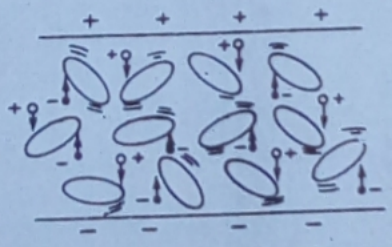
19-9 Liquid Crystal Display (LCD)

Dynamic Scattering LCD

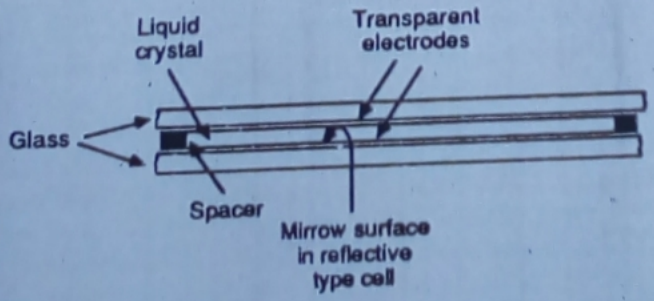
The molecules in ordinary liquids normally have random orientations. In liquid crystals the molecules are oriented in a definite crystal pattern, as illustrated in Fig. 19-22(a); (also see Section 20-1). When an electric field is applied to the liquid crystal, the molecules, which are approximately cigar shaped, tend to align themselves perpendicularly to the field. Charge carriers flowing through the liquid disrupt the molecular alignment and cause a turbulence within the liquid [see Fig. 19-22(b)]. When not activated, the liquid crystal is transparent. When it is activated, the molecular turbulence causes the light to be scattered in all directions so that the activated areas appear bright. This phenomenon is known as *dynamic scattering*. The actual liquid-crystal material may be one of several organic compounds which exhibit the



(a) Molecules in liquid crystal when no current flowing



(b) Charge carrier flow through liquid crystal disturbs molecular alignment and causes turbulence



(c) Construction of liquid-crystal cell

Figure 19-22 A liquid-crystal cell consists of a layer of liquid-crystal material sandwiched between glass sheets with transparent metal film electrodes.

optical properties of a solid while retaining the fluidity of a liquid. Examples of such compounds are *cholesteryl nonanoate* and *p-azoxyanisole*.

A liquid-crystal cell consists of a layer of liquid-crystal material sandwiched between glass sheets with transparent metal film electrodes deposited on the inside faces [Fig. 19-22(c)]. With both glass sheets transparent, the cell is known as a *transmittive-type cell*. When only one glass sheet is transparent and the other has a reflective coating, the cell is termed *reflective type*. The application of both types is illustrated in Fig. 19-23.

When not activated, the transmittive-type cell will simply transmit rear or edge lighting through the cell in straight lines. In this condition the cell will not appear bright. When the cell is activated, the incident light is diffusely scattered forward, as shown in Fig. 19-23(a), and the cell appears quite bright even under high-intensity ambient light conditions. The reflective-type cell

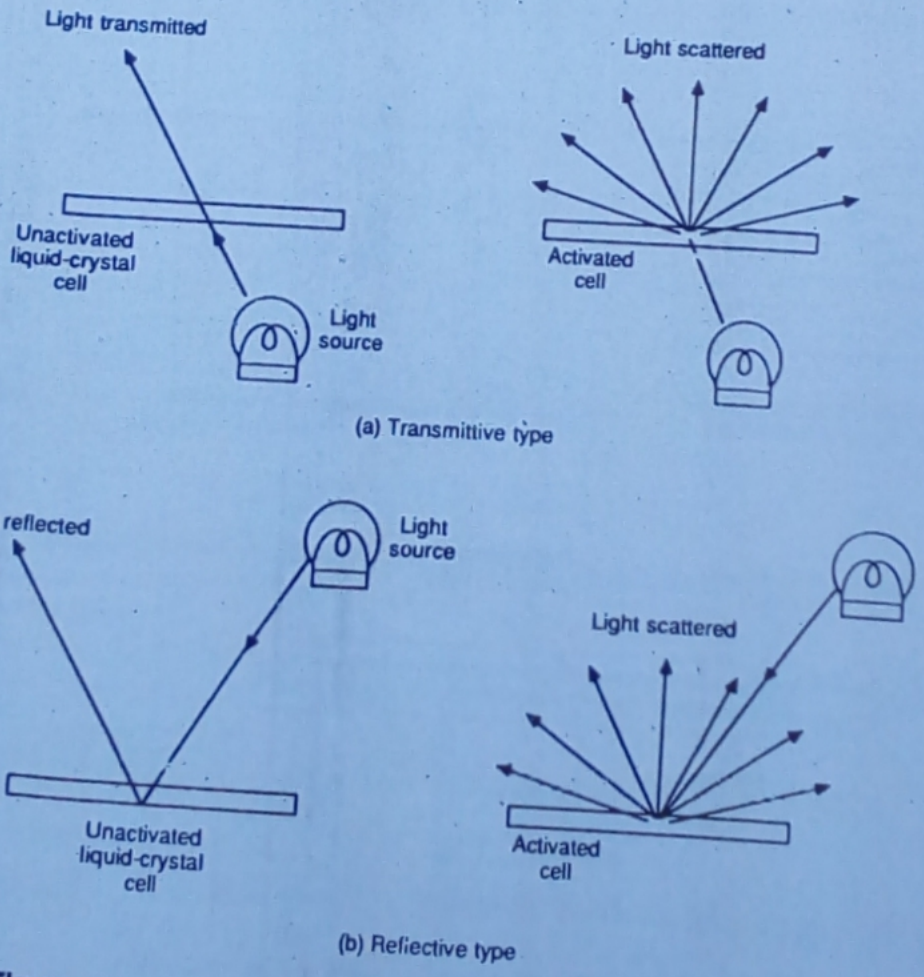


Figure 19-23 The dynamic scattering liquid-crystal display becomes very bright when activated.

operates from light incident on its front surface. When it is not activated, light is reflected in the usual way from the mirror surface, and the cell does not appear bright. When it is activated, the dynamic scattering phenomenon occurs, and the cell appears quite bright [Fig. 19-23(b)].

Field Effect LCD

The field effect LCD is constructed similarly to the dynamic scattering type [Fig. 19-22(c)], except that two thin polarizing optical filters are placed at the surface of each glass sheet. The liquid-crystal material employed is known as *twisted nematic* type, and it actually twists the light passing through when the cell is not energized. This twisting allows the light to pass through the polarizing filters. Thus, in the case of a transmittive-type cell [Fig. 19-23(a)], the unenergized cell can appear dark against a bright background. When energized, the cell becomes transparent and *disappears* into the background.

LCD Electrical Characteristics

Since liquid-crystal cells are light reflectors or transmitters rather than light generators, they consume very small quantities of energy. The only energy required by the cell is that needed to activate the liquid crystal. The total current flow through four small seven-segment displays is typically about 25 μA for dynamic scattering cells and 300 μA for field effect cells. However, the LCD requires an ac voltage supply, either in the form of a sine wave or a square wave. This is because a continuous direct current flow produces a plating of the cell electrodes, which could damage the device. Repeatedly reversing the current avoids this problem.

A typical supply for a dynamic scattering LCD is a 30 V peak-to-peak square wave with a frequency of 60 Hz. A field effect cell typically uses 8 V peak to peak. Figure 19-24 illustrates the square wave drive method for liquid-crystal cells. The *back plane*, which is one terminal common to all cells, is supplied with a square wave. A similar square wave is applied to each of the other terminals. These square waves are either in phase or in antiphase with the back plane square wave. Those cells with waveforms in phase with the back plane waveform (cells *e* and *f* in Figure 19-24) have no voltage developed across them (both terminals of the segment are at the same potential); therefore, they are *off*. The cells with square waves in antiphase with the back plane input have an ac voltage developed across them. (Positive square waves with a 15 V peak effectively produce 30 V peak to peak when in antiphase). Therefore, the cells which have square wave inputs in antiphase with the back plane input are energized and appear bright.

Unlike LED displays, which are usually quite small, liquid-crystal displays can be fabricated in almost any convenient size. The maximum power consumed for a typical LCD used in electronics equipment is around 20 μW per segment, or 140 μW per numeral when all seven segments are energized.

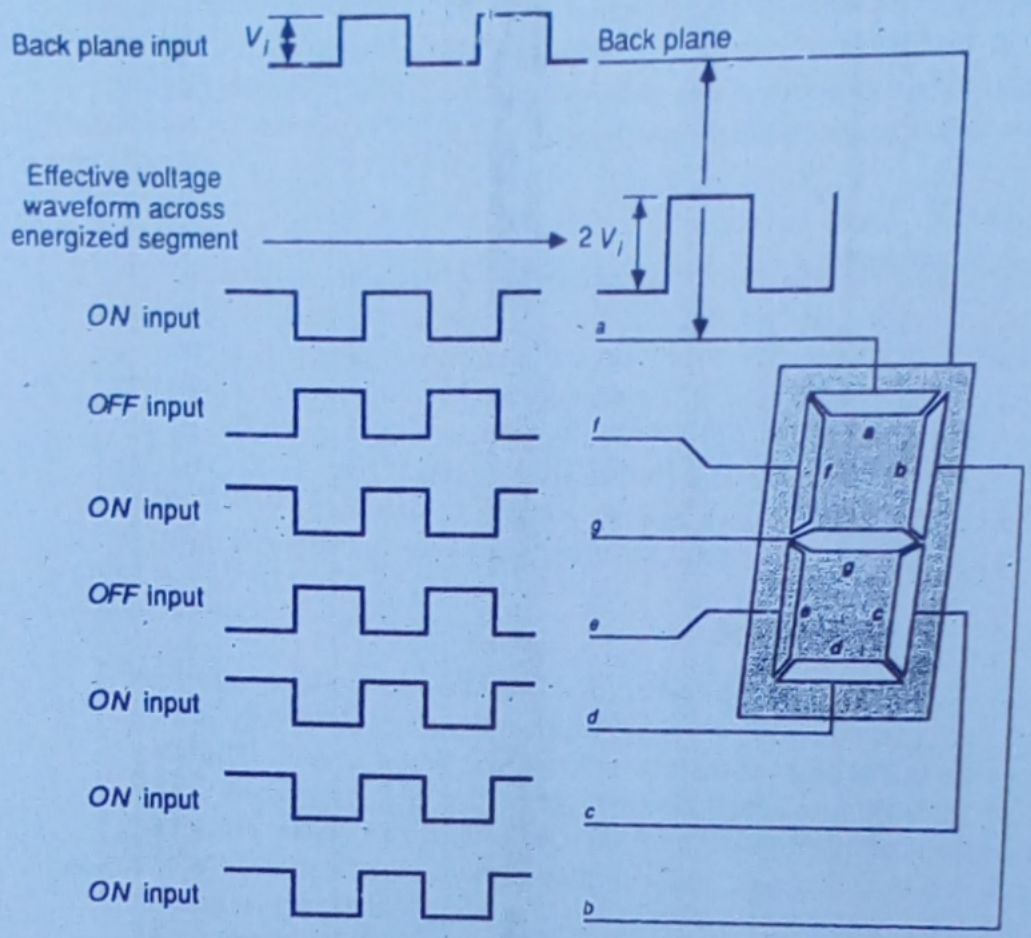


Figure 19-24 Liquid-crystal display using a square-wave supply. When the input to any segment is in antiphase to the back plane input, the segment is activated.

Comparing this value to about 400 mW per numeral for a LED display (including series resistors), the major advantage of liquid-crystal devices is obvious. Perhaps the major disadvantage of the LCD is its decay time of 150 ms (or more). This is very slow compared to the rise and fall times of LEDs. In fact, the human eye can sometimes observe the fading out of LCD segments switching off. At low temperatures the response time is considerably increased.

19-10 Gas Discharge Displays

The type of seven-segment gas-discharge display illustrated in Fig. 19-25 is applied today in some portable electronic calculators. The display is actually a gas-filled tube. Separate cathodes in seven-segment format are provided on the base of the device, and the anode (for each seven-segment group) is a transparent metal film deposited on the covering transparent faceplate. Gas is contained in the narrow space between the faceplate and the base.

When a high voltage is provided between the anode (positive polarity) and one or more of the cathodes, the gas is ionized, causing a glow around

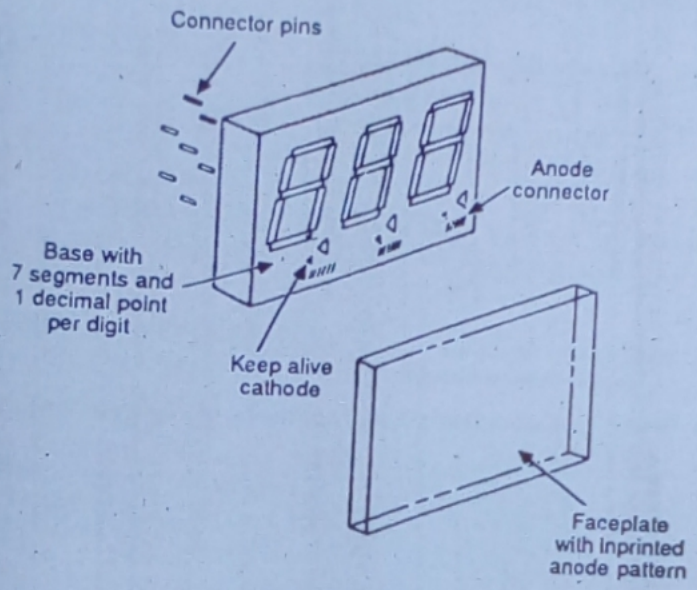


Figure 19-25 In a seven-segment gas discharge display, the cathodes (segments) glow when energized.

each cathode. Thus, any desired numeral can be displayed depending upon the selected cathodes. Neon gas is usually employed, and this gives a red-orange glow; however, other colors are available with different gases.

The supply voltage required for gas-discharge displays is on the order of 140 to 200 V. This is the most serious disadvantage of the device when used with transistor circuits. Offsetting it, however, is the fact that relatively bright displays are possible with current levels of only 200 μA. A 50 μA current (not enough to produce a glow) is usually maintained through the *keep alive cathode* (see Fig. 19-25) to ensure that the device switches on rapidly.

19-11 Optoelectronic Couplers

An *optoelectronic coupler* (or *optically coupled isolator*) is basically a phototransistor and a light emitting diode combined in one package. Figure 19-26 shows the typical circuit and terminal arrangement for one such device contained in a dual-in-line plastic package.

When current flows in the diode, the light emitted is directed to the phototransistor, causing current to flow in the transistor. The coupler may be operated as a *switch*, in which case both the LED and the phototransistor are normally off. A pulse of current through the LED causes the transistor to be switched on for the duration of the pulse. Since the coupling is optical, there is a high degree of electrical isolation between input and output terminals.

Three additional types of optical couplers are illustrated in Fig. 19-27. They are (a) the Darlington output type, (b) SCR output, and (c) TRIAC

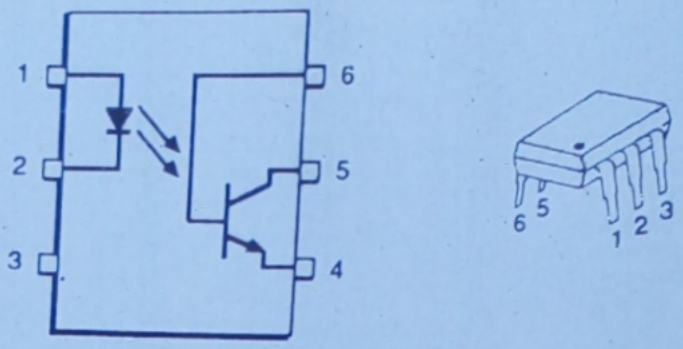


Figure 19-26 Optoelectronic coupler consisting of a light emitting diode and a phototransistor.

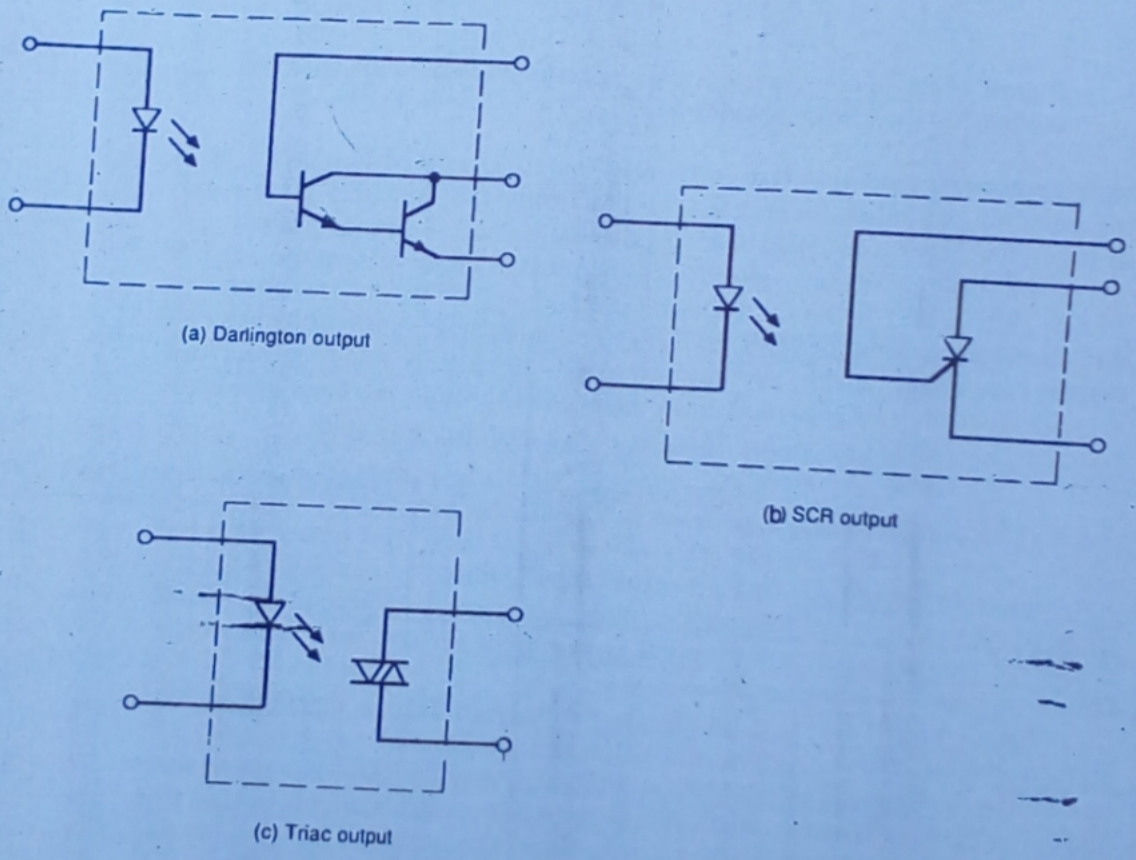


Figure 19-27 Optoelectronic couplers are available with output stages in the form of (a) Darlingtons, (b) light activated SCRs, (c) light activated TRIACs.

output. In (a), the photodarlington output stage provides much higher output current (i.e., for a given LED current) than is possible with a phototransistor output stage. The output stages in (b) and (c) are a light-activated SCR and a light-activated TRIAC, respectively. They are applied in the kind of control circuits discussed in Chapter 18, where an additional requirement is high electrical isolation between the triggering current and the control device.

The following is a list of the most important parameters for an optoelectronic coupler:

Input to Output Isolation Voltage (V_{iso}). The maximum voltage difference that can exist between input and output terminals. Typical values range up to 7500 V.

Current Transfer Ratio (CTR). The ratio of output (phototransistor) current to input (LED) current, expressed as a percentage. For a phototransistor output stage, CTR values can be anything from 10% to 150%. For a photodarlington, the CTR might easily be 500%. CTR does not apply to SCR and TRIAC output stages; instead, the required triggering current (through the LED) is of interest.

Response Time. Divided into *rise time* t_r and *fall time* t_f. For phototransistor output stages, t_r and t_f are usually around 2 to 5 μs. With a Darlington output, t_r may be 1 μs or less, while t_f could be 17 μs.

19-12 Laser Diode

Laser is the shortened form of *light amplification by stimulated emission of radiation*. A laser emits radiation of essentially one wavelength, or a very narrow band of wavelengths. This means that the light has a single color, i.e., is monochromatic. (It is not a combination of several colors.) Laser light is referred to as *coherent light* as opposed to light made up of a wide band of wavelengths, which is termed *incoherent*.

The unique property of light generated by a laser is that the emission is in the form of a very narrow beam without significant divergence. The beam of light contains sufficient energy to weld metals or to destroy cancerous growths. It can also be applied to precise measurements, to guidance of industrial machinery, and to optical fiber communication techniques.

In the light emitting diode, the source of light is the energy emitted by electrons which recombine with holes (at a lower energy level). In the case of an LED, the light is incoherent; i.e., it is made up of a wide spectrum of wavelengths.

In a laser the atoms are struck by *photons* (or packets of energy) which are exactly similar to the photons of energy emitted when recombination occurs. This triggers energy emission and results in two identical photons for