FIG. 16.11
Tuning network employing a varactor diode.

16.4 SOLAR CELLS

In recent years, there has been increasing interest in the solar cell as an alternative source of energy. When we consider that the power density received from the sun at sea level is about 100 mW/cm^2 (1 kW/m^2), it is certainly an energy source that requires further research and development to maximize the conversion efficiency from solar to electrical energy.

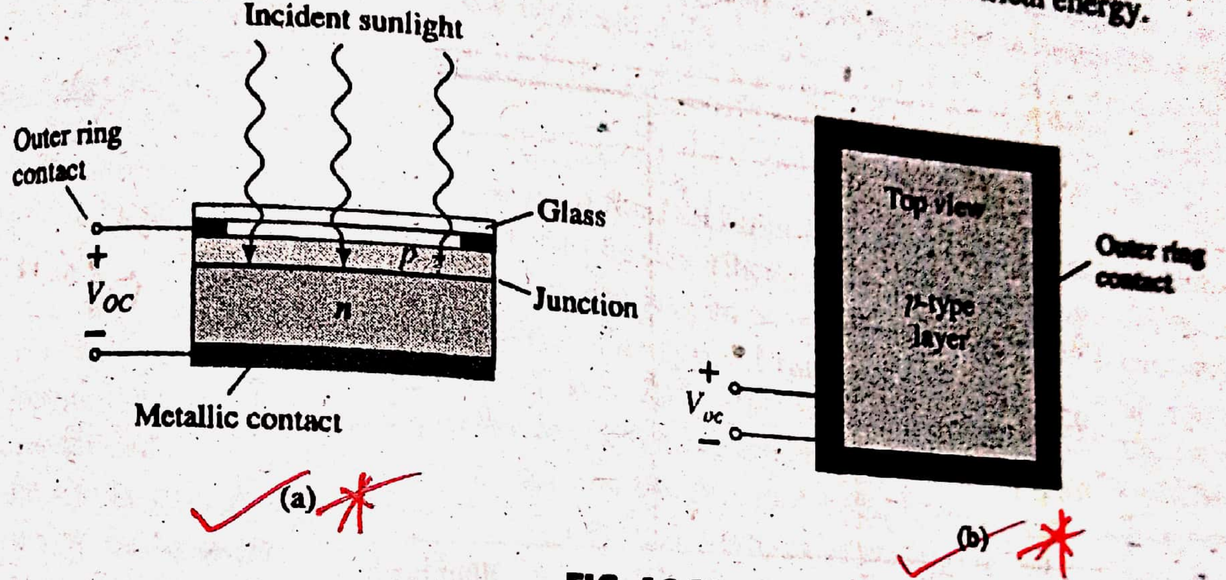

FIG. 16.12
Solar cell: (a) cross section; (b) top view.

The basic construction of a silicon p–n junction solar cell appears in Fig. 16.12. As shown in the top view, every effort is made to ensure that the surface area perpendicular to the sun is a maximum. Also note that the metallic conductor connected to the p-type material and the thickness of the p-type material are such that they ensure that a maximum number of photons of light energy will reach the junction. A photon of light energy in this region may collide with a valence electron and impart to it sufficient energy to leave the parent atom. The result is a generation of free electrons and holes. This phenomenon will occur on each side of the junction. In the p-type material, the newly generated electrons are minority carriers and will move rather freely across the junction as explained for the basic p–n junction with no applied bias. A similar discussion is true for the holes generated in the n-type material. The result is an increase in the minority-carrier flow, which is opposite in direction to the conventional forward current of a p–n junction. The current for a single-cell silicon solar cell will increase in an almost linear fashion with the intensity of the incident light as shown in Fig. 16.13. Double the incident light will double the resulting current and so on. The plot is for the maximum current generated for a particular level of incident light. Since maximum conditions result when the output is short-circuited as shown in Fig. 16.13, the label for the resulting current is I_{SC}. Under short-circuit conditions the output voltage is 0 V as shown in the same figure.

Defi + figure + Short describe

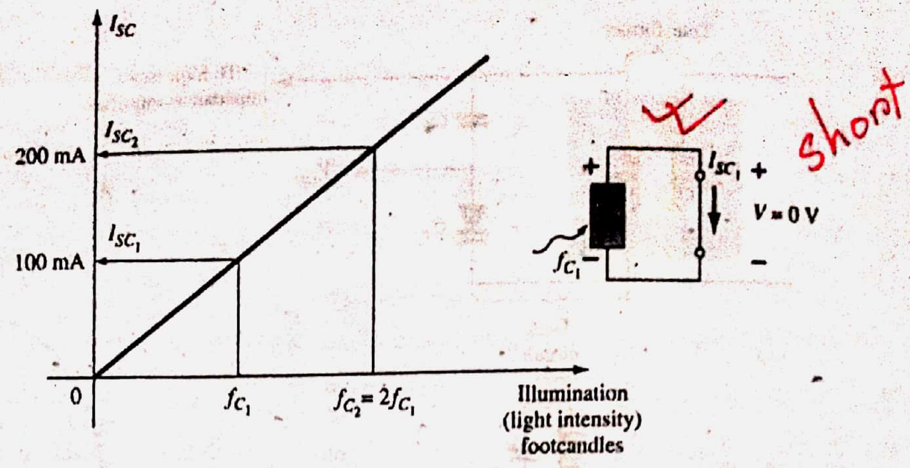

FIG. 16.13
Effect of light intensity on the short-circuit current.

A plot of the open-circuit voltage for the same levels of incident light is provided in Fig. 16.14. Note that it increases very rapidly to a level that stays within the boundaries of 0.5 V to 0.6 V. That is, for the broad range of incident light in Fig. 16.14, the terminal voltage is fairly constant. Since the output voltage is the open-circuit voltage as shown in the same figure, the label for the resulting voltage at each level of incident light is V_{OC}.

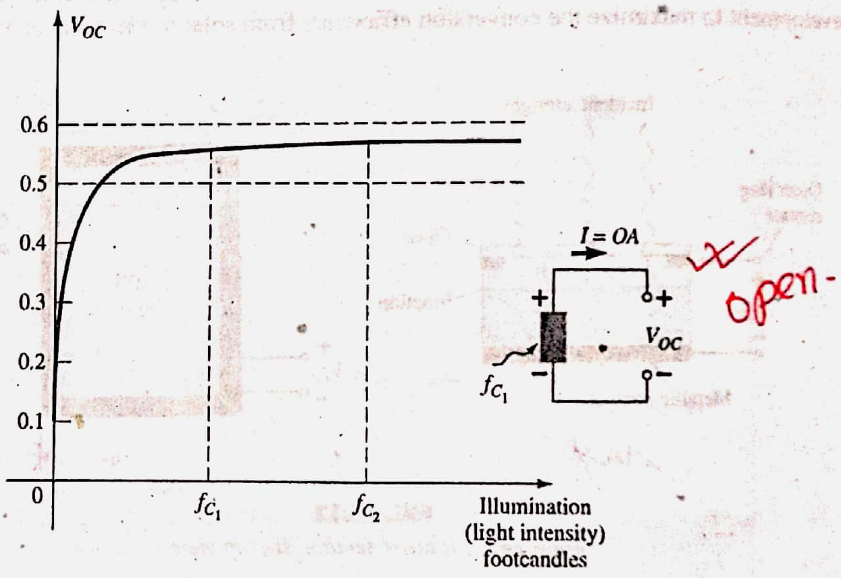

FIG. 16.14
Effect of light intensity on the open-circuit voltage.

main Summary

In general, therefore,

The open-circuit potential generated by a solar cell is fairly constant, while the short-circuit maximum current will increase in a linear fashion.

Since the voltage is fairly constant, higher output voltages can be established by connecting the solar cells in a series. The current generated in a series configuration will be the same as generated by a single cell. For increased current levels at a single cell open-circuit voltage, solar cells can be connected in parallel.

If a plot of current versus voltage is generated as shown in Fig. 16.15 for a particular incident light, a curve for the power associated with the solar cell can be generated by simply using the equation $P = VI$.

Note in Fig. 16.15 that the short-circuit current is the maximum current with the level of current decreasing with increasing terminal voltage. Also take note that the level of voltage is fairly constant for the range of current from 0 A to just short of the maximum power point. Since the current curve is fairly level for the lower voltage levels, the increase in power is

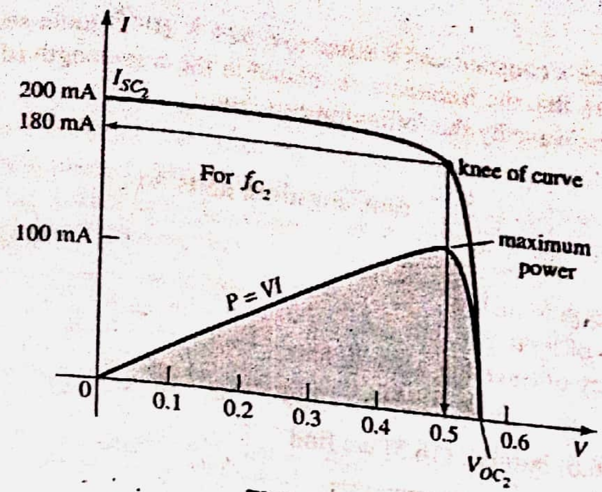

FIG. 16.15
Sketching the power curve for the light intensity fc_2.

due primarily to the increasing levels of voltage using the power equation $P = VI$. Eventually, however, even though the voltage continues to increase, the current drops dramatically near V_{OC} and the power curve drops accordingly. The maximum power occurs in the knee region of the I–V curve as shown in Fig. 16.15. For this cell at fc_2 it is approximately

$$P = VI = (0.5\text{ V})(180\text{ mA}) = \mathbf{90\text{ mW}}$$

The level of current that results in a solar cell is directly related to the absorption characteristics of the material (referred to as the absorption coefficient), the wavelength of the incident light, and the intensity of the incident light.

Materials

The most common material in use today in the full range of bulk and thin-film solar cells is silicon in its various forms. Each form to be described is manufactured using a different process. The **single-crystal** silicon structure has an atomic lattice that is uniform, perfectly ordered, and of the highest purity. The typical range of efficiency extends from 14% to 17% with experimental levels of over 20%. **Polycrystalline** silicon solar cells are manufactured in a different, cheaper process but have lower levels of efficiency (9%–14%). However the reduced manufacturing cost and the fact that it can be cut into thinner layers than the single-crystal lattice make such cells a viable alternative. In recent years the introduction of **thin-film** technology has had a broad impact on the cost and range of application of solar cells. The very thin (less than 1 μm in many cases) semiconductor layers are deposited (using various spraying techniques) on a supporting structure such as glass, plastic, or metal. A compound, **amorphous silicon (a-Si)**, is currently the most extensively used thin-film material. The reduced production costs, along with the high light absorption characteristics, balance out the efficiency levels that are reduced to single digits (6%–9%).

Another single-crystal compound, **gallium arsenide** (GaAs), is commonly used in bulk solar cells because of its high rate of absorption and higher energy conversion rate in the range 20%–30%. Additional thin-film materials include **cadmium telluride** (CdTe) and **copper indium diselenide** ($CuInSe_2$ or CIS). CdTe has a very high light absorption level and is less expensive to manufacture with the same conversion efficiency as silicon. CIS is used in leading-edge research with conversion levels approaching 18% with high absorption and conversion rates.

Wavelength

The energy associated with each photon is directly related to the frequency of the traveling wave and determined by the following equation:

$$\boxed{W = Kf} \quad \text{(joules)} \tag{16.5}$$

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where $\hbar$ is called Planck's constant and is equal to 6.624×10^{-34} joule-seconds. You may recall from Section 1.16 that the frequency is related to the wavelength (distance between successive peaks) of the wave by the following equation:

$$\boxed{\lambda = \frac{v}{f}} \quad \text{(nm, angstrom units Å)} \tag{16.6}$$

where λ = wavelength in meters
v = velocity of light, 3×10^8 m/s
f = frequency of traveling wave in hertz

and
$$\text{Å} = 10^{-10}\ \text{m},\ 1\ \text{nm} = 10^{-9}\ \text{m}$$

Substituting Eq. (16.6) into Eq. (16.5) we find

$$\boxed{W = \frac{\hbar v}{\lambda}} \quad \text{(joules)} \tag{16.7}$$

and find that the energy associated with a discrete package of photons is inversely proportional to the wavelength.

Clearly, therefore

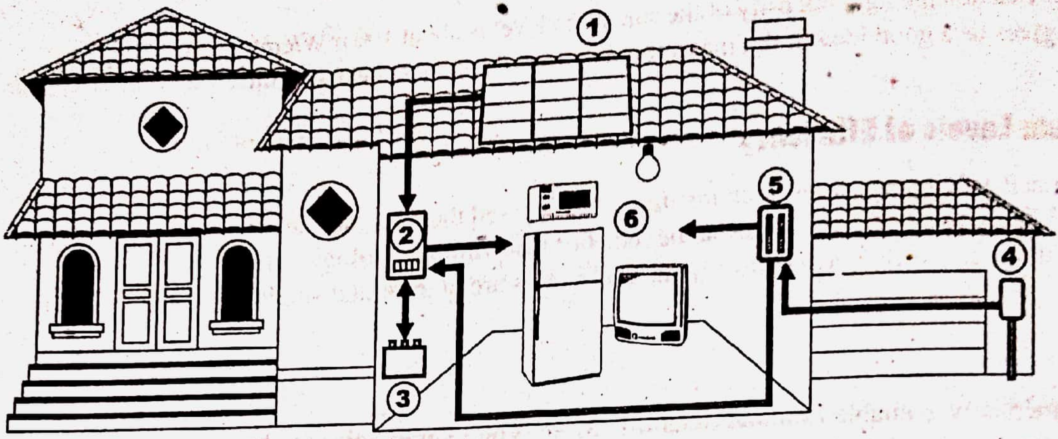
The energy associated with the photons being absorbed by the semiconductor layer of a solar cell is a function of the wavelength of the incident light, and the longer the wavelength, the less the associated energy levels.

In addition it is important to realize that

Each photon can only cause the generation of one electron-hole pair. Any photon with energy levels higher than that required to release an electron will simply contribute to the heating of the solar cell.

For silicon, the absorption curve is provided as Fig. 16.16, showing that it peaks around 850 nm. As noted above, since the wavelength is shorter, the energy level associated with the color blue of the visible spectrum is significantly higher than that of green, red, or yellow. Take particular note of the wavelength 1200 nm corresponding with the point where the curve drops to the horizontal axis. This is the highest wavelength that will provide photons with sufficient energy to liberate electrons in the silicon material. In other words, at this wavelength the energy associated with the incident light is just enough to release an electron-hole pair. Any photon associated with longer wavelengths will not have sufficient energy associated with it to release an electron and will simply contribute to the heating of the solar cell.

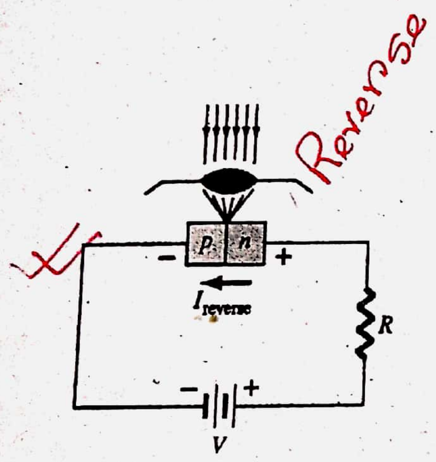
(a)



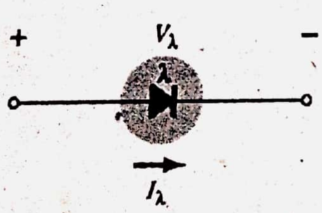
(b)

FIG. 16.18
Solar System: (a) panels on roof of garage; (b) system operation.
(Courtesy of SolarDirect.com)

Thin-film solar cell panels have led to widespread use of solar panels in the home. The solar panels appearing on the roof of the home of Fig. 16.18a are sufficient in power to run an energy-efficient refrigerator for 24 hours a day, while simultaneously running a color TV for 7 hours, a microwave for 15 minutes, a 60-W bulb for 10 hours, and an electric clock for 10 hours. The basic system operates as shown in Fig. 16.18b. The solar panels (1) convert sunlight into dc electric power. An inverter (2) converts the dc power into the standard ac power for use in the home (6). The batteries (3) can store energy from the sun for use if there is insufficient sunlight or a power failure. At night or on dark days when the demand exceeds the solar panel and battery supply, the local utility company (4) can provide power to the appliances (6) through a special hookup in the electrical panel (5). Although there is an initial expense to setting up the system, it is vitally important to realize that the source of energy is free—no monthly bill for sunlight to contend with—and will provide a significant amount of energy for a very long period of time.



(a)



(b)

FIG. 16.19
Photodiode: (a) basic biasing arrangement and construction; (b) symbol.

16.5 PHOTODIODES

The photodiode is a semiconductor p–n junction device whose region of operation is limited to the reverse-bias region. The basic biasing arrangement, construction, and symbol for the device appear in Fig. 16.19.

Recall from Chapter 1 that the reverse saturation current is normally limited to a few microamperes. It is due solely to the thermally generated minority carriers in the n- and p-type materials. The application of light to the junction will result in a transfer of energy from the incident traveling light waves (in the form of photons) to the atomic structure, resulting in an increased number of minority carriers and an increased level of reverse current. This is clearly shown in Fig. 16.20 for different intensity levels. The *dark* current is that current that will exist with no applied illumination. Note that the current will only return to zero with a positive applied bias equal to V_T. In addition, Fig. 16.19a demonstrates the use of a lens to concentrate the light on the junction region. Commercially available photodiodes appear in Fig. 16.21.

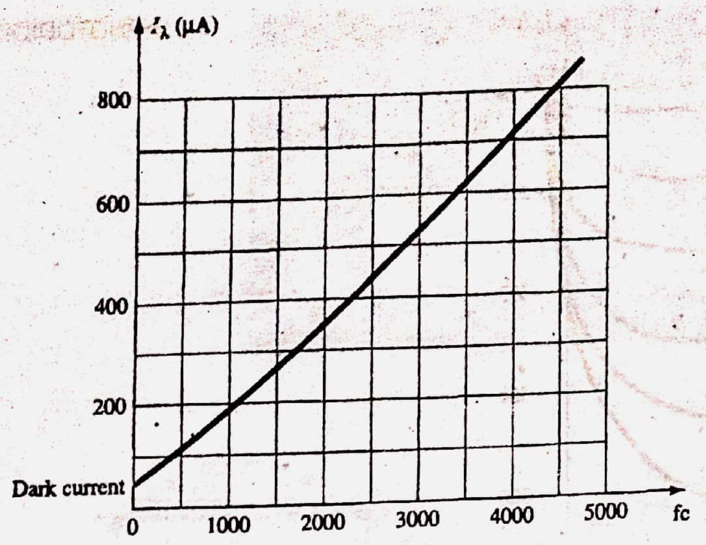


FIG. 16.22
I_λ (μA) versus f_C (at V_λ = 20 V) for the photodiode of Fig. 16.20.

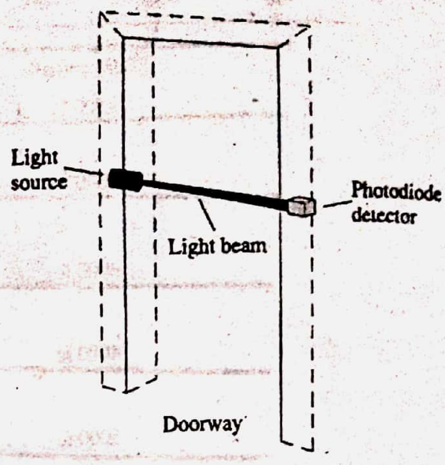


FIG. 16.23
Using a photodiode in an alarm system.

to the dark current level and sounds the alarm. In Fig. 16.24, a photodiode is used to count items on a conveyor belt. As each item passes, the light beam is broken, I_λ drops to the dark current level, and the counter is increased by one.

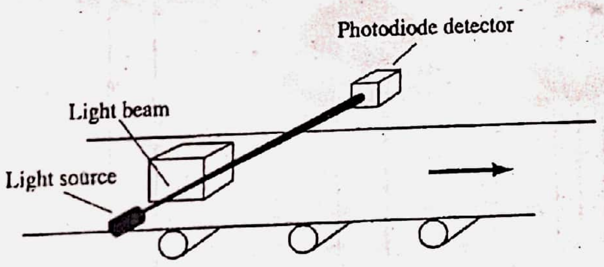


FIG. 16.24
Using a photodiode in a counter operation.

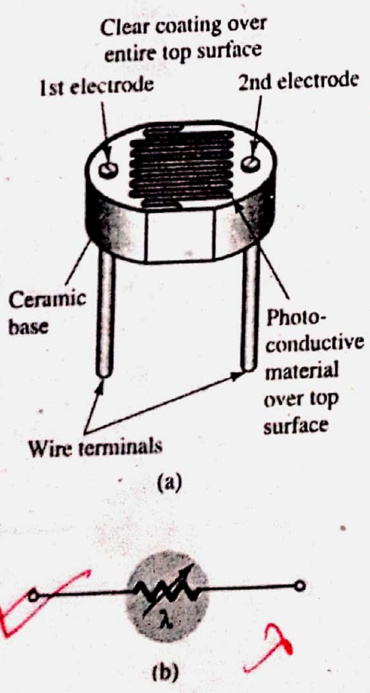


FIG. 16.25
Photoconductive cell: (a) construction; (b) symbol.

16.6 PHOTOCONDUCTIVE CELLS

The photoconductive cell is a two-terminal semiconductor device whose terminal resistance varies (linearly) with the intensity of the incident light. For obvious reasons, it is frequently called a *photoresistive device*. The typical construction of a photoconductive cell is provided in Fig. 16.25 with the most common graphical symbol.

The photoconductive materials most frequently used include cadmium sulfide (CdS) and cadmium selenide (CdSe). The peak spectral response occurs at approximately 5100 Å for CdS and at 6150 Å for CdSe. The response time of CdS units is about 100 ms and of CdSe cells is 10 ms. The photoconductive cell does not have a junction like the photodiode. A thin layer of the material connected between terminals is simply exposed to the incident light energy.

As the illumination on the device increases in intensity, the energy state of a larger number of electrons in the structure will also increase because of the increased availability of the photon packages of energy. The result is an increasing number of relatively "free" electrons in the structure and a decrease in the terminal resistance. The sensitivity curve for a typical photoconductive device appears in Fig. 16.26. Note the linearity (when plotted using a log–log scale) of the resulting curve and the large change in resistance (100 kΩ → 100 Ω) for the indicated change in illumination.

To see the wealth of material available on each device from manufacturers, consider the CdS (cadmium sulfide) photoconductive cell described in Fig. 16.27. Note again the concern with temperature and response time.

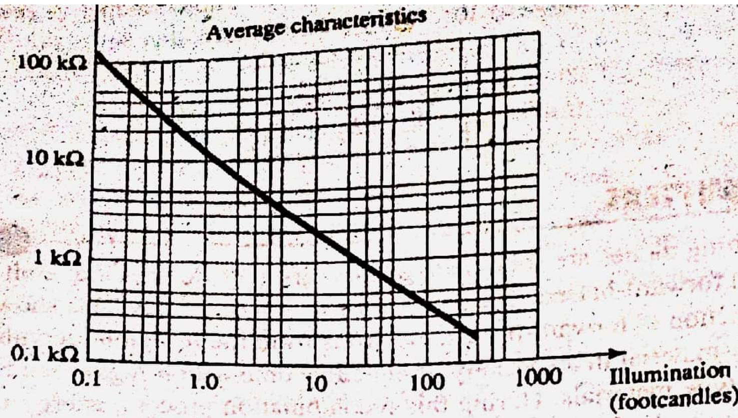
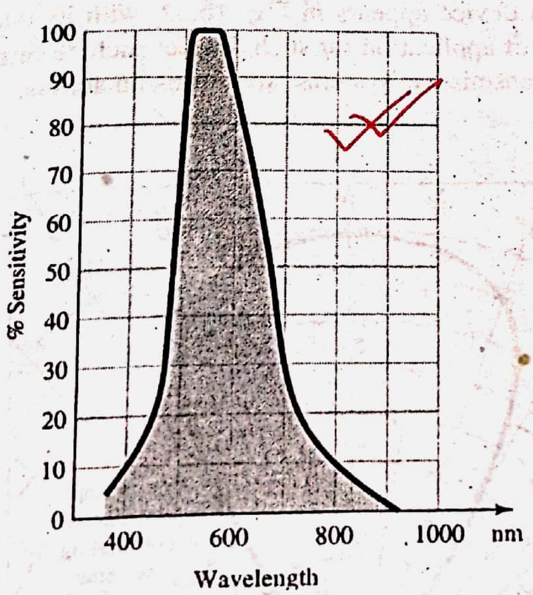


FIG. 16.26
Photoconductive cell-terminal characteristics.



Variation of Conductance with Temperature and Light

Footcandles	*0.01*	*0.1*	*1.0*	*10*	*100*
Temperature			*% Conductance*		
−25°C	103	104	104	102	106
0	98	102	102	100	103
25°C	100	100	100	100	100
50°C	98	102	103	104	99
75°C	90	106	108	109	104

Response Time versus Light

Footcandles	*0.01*	*0.1*	*1.0*	*10*	*100*
Rise (seconds)	0.5	0.095	0.022	0.005	0.002
Decay (seconds)	0.125	0.021	0.005	0.002	0.001

FIG. 16.27
Characteristics of a Clairex CdS photoconductive cell.

Application

One rather simple but interesting application of the device appears in Fig. 16.28. The purpose of the system is to maintain V_o at a fixed level even though V_i may fluctuate from its rated value. As indicated in the figure, the photoconductive cell, bulb, and resistor all form part of this voltage-regulator system. If V_i should drop in magnitude for any of a number of reasons, the brightness of the bulb would also decrease. The decrease in illumination

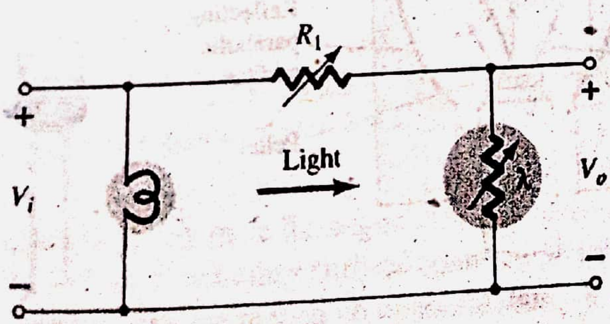


FIG. 16.28
Voltage regulator employing a photoconductive cell.

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16.8 LIQUID-CRYSTAL DISPLAYS

(Read)

The liquid-crystal display (LCD) has the distinct advantage of having a lower power requirement than the LED, typically on the order of microwatts for the display, compared to the order of milliwatts for LEDs. It does, however, require an external or internal light source, and is limited to a temperature range of about 0°C to 60°C. Lifetime is an area of concern because LCDs can chemically degrade. The types of unit of major interest are field-effect and dynamic-scattering units. Each will be covered in some detail in this section.

A liquid crystal is a material (normally organic for LCDs) that flows like a liquid but whose molecular structure has some properties normally associated with solids. For light-scattering units, the greatest interest is in *nematic liquid crystal,* which has the crystal structure shown in Fig. 16.33. The individual molecules have a rodlike appearance as shown in the figure. The indium oxide conducting surface is transparent, and under the condition shown in the figure, incident light will simply pass through and the liquid-crystal structure will appear clear. If a voltage (for commercial units the threshold level is usually between 6 V and 20 V) is applied across the conducting surfaces, as shown in Fig. 16.34, the molecular arrangement is disturbed, with the result that regions are established with different indices of refraction. The incident light is therefore reflected in different directions at the interface between regions of different indices of refraction (referred to as *dynamic scattering*—first studied by RCA in 1968), with the result that the scattered light has a frosted-glass appearance. Note in Fig. 16.34, however, that the frosted look occurs only where the conducting surfaces are opposite each other; the remaining areas remain translucent.

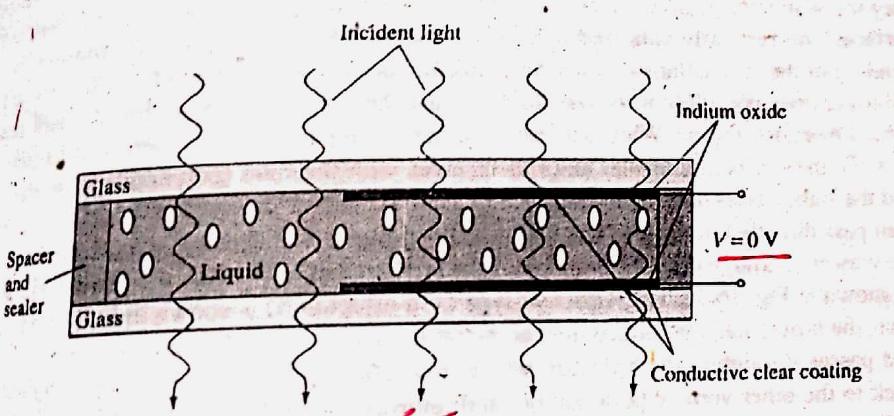


FIG. 16.33
Nematic liquid crystal with no applied bias.

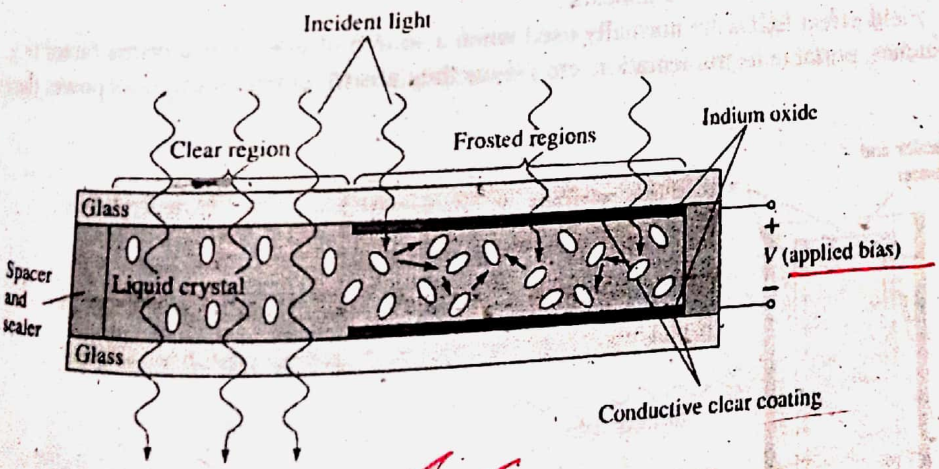


FIG. 16.34
Nematic liquid crystal with applied bias.

FIG. 16.35
LCD eight-segment digit display.

A numeral on an LCD display may have the segmented appearance shown in Fig. 16.35. The black area is actually a clear conducting surface connected to the terminals below for external control. Two similar masks are placed on opposite sides of a sealed, thick layer of liquid-crystal material. If the number 2 were required, the terminals 8, 7, 3, 4, and 5 would

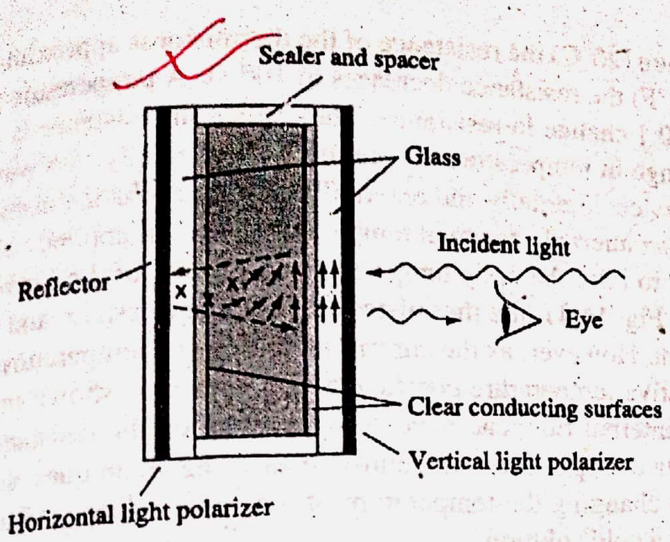


FIG. 16.38
Reflective field-effect LCD with no applied bias.

FIG. 16.39
Transmissive-type LCD.

Application write.

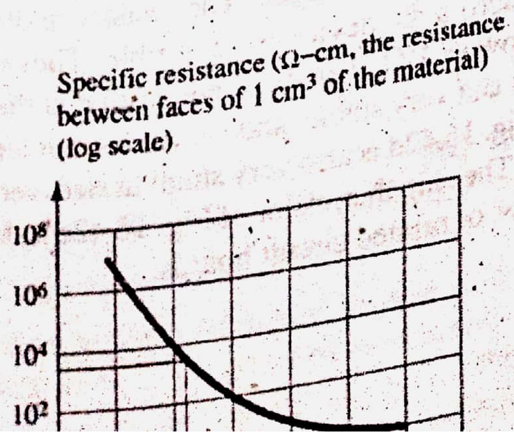
light-scattering types—the microwatt range compared to the low-milliwatt range. The cost is typically higher for field-effect units, and their height is limited to about 2 in., whereas light-scattering units are available up to 8 in. in height.

A further consideration in displays is turn-on and turn-off time. LCDs are characteristically much slower than LEDs. LCDs typically have response times in the range 100 ms to 300 ms, whereas LEDs are available with response times below 100 ns. However, there are numerous applications, such as in a watch, where the difference between 100 ns and 100 ms ($\frac{1}{10}$ of a second) is of little consequence. For such applications, the lower power demand of LCDs is a very attractive characteristic. The lifetime of LCD units is steadily increasing beyond the 10,000+-hour limit. Since the color generated by LCD units is dependent on the source of illumination, there is a greater range of color choice.

16.9 THERMISTORS

The thermistor is, as the name implies, a temperature-sensitive resistor; that is, its terminal resistance is related to its body temperature. It is not a junction device and is constructed of germanium, silicon, or a mixture of oxides of cobalt, nickel, strontium, or manganese. The compound employed determines whether the device has a positive or a negative temperature coefficient.

The characteristics of a typical thermistor with a negative temperature coefficient are provided in Fig. 16.40, which also shows the commonly used symbol for the device. Note in



(b)

FIG. 1.49
Zener terminal identification and symbols.

The terminal identification and the casing for a variety of Zener diodes appear in Fig. 1.49. Their appearance is similar in many ways to that of the standard diode. Some areas of application for the Zener diode will be examined in Chapter 2.

1.16 LIGHT-EMITTING DIODES

The increasing use of digital displays in calculators, watches, and all forms of instrumentation has contributed to an extensive interest in structures that emit light when properly biased. The two types in common use to perform this function are the light-emitting diode (LED) and the liquid-crystal display (LCD). Since the LED falls within the family of *p–n* junction devices and will appear in some of the networks of the next few chapters, it will be introduced in this chapter. The LCD display is described in Chapter 16.

As the name implies, the light-emitting diode is a diode that gives off visible or invisible (infrared) light when energized. In any forward-biased *p–n* junction there is, within the structure and primarily close to the junction, a recombination of holes and electrons. This recombination requires that the energy possessed by the unbound free electrons be transferred to another state. In all semiconductor *p–n* junctions some of this energy is given off in the form of heat and some in the form of photons.

In Si and Ge diodes the greater percentage of the energy converted during recombination at the junction is dissipated in the form of heat within the structure, and the emitted light is insignificant.

For this reason, silicon and germanium are not used in the construction of LED devices. On the other hand:

Diodes constructed of GaAs emit light in the infrared (invisible) zone during the recombination process at the p–n junction.

Even though the light is not visible, infrared LEDs have numerous applications where visible light is not a desirable effect. These include security systems, industrial processing, optical coupling, safety controls such as on garage door openers, and in home entertainment centers, where the infrared light of the remote control is the controlling element.

Through other combinations of elements a coherent visible light can be generated. Table 1.9 provides a list of common compound semiconductors and the light they generate. In addition, the typical range of forward bias potentials for each is listed.

The basic construction of an LED appears in Fig. 1.50 with the standard symbol used for the device. The external metallic conducting surface connected to the *p*-type material is smaller to permit the emergence of the maximum number of photons of light energy when the device is forward-biased. Note in the figure that the recombination of the injected carriers due to the forward-biased junction results in emitted light at the site of the recombination.

TABLE 1.9
Light-Emitting Diodes

Color	Construction	Typical Forward Voltage (V)
Amber	AlInGaP	2.1
Blue	GaN	5.0
Green	GaP	2.2
Orange	GaAsP	2.0
Red	GaAsP	1.8
White	GaN	4.1
Yellow	AlInGaP	2.1

There will, of course, be some absorption of the packages of photon energy in the structure itself, but a very large percentage can leave, as shown in the figure.

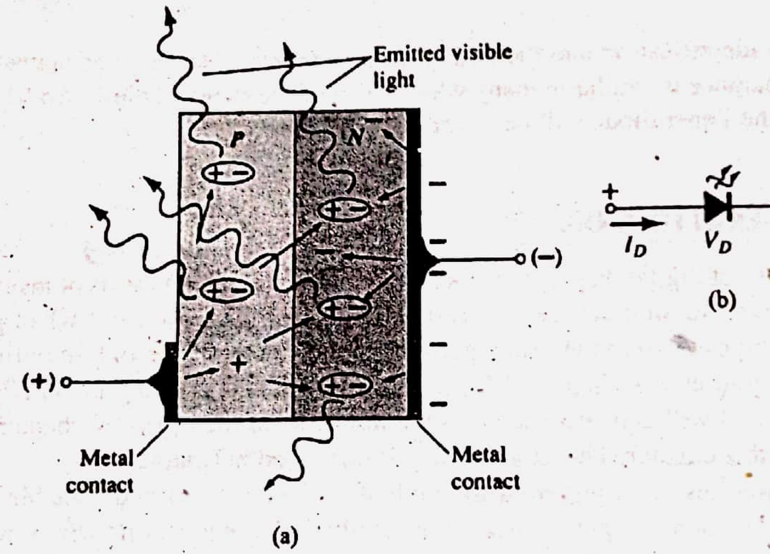


FIG. 1.50
(a) Process of electroluminescence in the LED; (b) graphic symbol.

Just as different sounds have different frequency spectra (high-pitched sounds generally have high-frequency components, and low sounds have a variety of low-frequency components), the same is true for different light emissions.

The frequency spectrum for infrared light extends from about 100 THz (T = tera = 10^{12}) to 400 THz, with the visible light spectrum extending from about 400 to 750 THz.

It is interesting to note that invisible light has a lower frequency spectrum than visible light.

In general, when one talks about the response of electroluminescent devices, one references their wavelength rather than their frequency.

The two quantities are related by the following equation:

$$\boxed{\lambda = \frac{c}{f}} \quad \text{(m)} \tag{1.15}$$

where $c = 3 \times 10^8$ m/s (the speed of light in a vacuum)
f = frequency in Hertz
λ = wavelength in meters.