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Light-Emitting Diode Displays

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A light-emitting diode (LED) is a particular solid-state *p–n* junction diode that gives out light upon the application of a bias voltage. The luminescence process in this case is electroluminescence, which is associated with emission wavelengths in the visible and infrared regions of the spectrum. When a forward bias is applied to the *p–n* junction diode, carriers are injected into the depletion region in large numbers. Because of their physical proximity, the electron–hole pairs undergo a recombination that is associated with the emission of energy. Depending on the semiconductor band-gap characteristics, this emitted energy can be in the form of heat (as phonons) or light (as photons).

The solution of the Schrödinger equation for a typical crystal reveals the existence of Brillouin zones. A plot between the energy E of an electron in a solid and its wave vector $\mathbf{k}$ represents the allowed energy bands. It may be noted that the lattice structure affects the motion of an electron when k is close to $n\pi/l$ (where n is any integer and l is the crystal periodicity) and the effect of this constraint is to introduce an energy band gap between the allowed energy bands. Figure 35.1a shows portions of two E vs. k curves for neighboring energy bands within the regions $k = \pi/l$ and $k = -\pi/l$ (also known as the reduced zone).

While the upper band of Figure 35.1 represents the energy of conduction band electrons, the curvature of the lower band can be associated with electrons having negative effective mass. The concept of negative effective mass can readily be identified with the concept of holes in the valence band. While the majority of the electrons are identified with the minima of the upper E–k curve, the majority of the holes are identified with the maxima of the lower E–k curve. The minimum value of the conduction band and the maximum value of the valence band in Figure 35.1a both have identical k values. A semiconductor having such a characteristic is said to have a direct band gap, and the associated recombination in such a semiconductor is referred to as direct.

The *direct recombination* of an electron–hole pair always results in the emission of a photon. In a direct band-gap semiconductor, the emitted photon is not associated with any change in momentum (given by $hk/2\pi$) since $\Delta k = 0$. However, for some semiconducting materials, the E vs. k curve may be somewhat different, as shown in Figure 35.1b. While the minimum conduction band energy can have a nonzero k, the maximum valence band energy can have $k = 0$. The electron–hole recombination in such a semiconductor is referred to as indirect.

An *indirect recombination* process involves a momentum adjustment. Most of the emission energy is thus expended in the form of heat (as phonons). Very little energy is left for the purpose of photon emission, which in most cases is a very slow process. Furthermore, since both photons and phonons are involved in this energy exchange, such transitions are less likely to occur. The interband recombination rate is basically given by

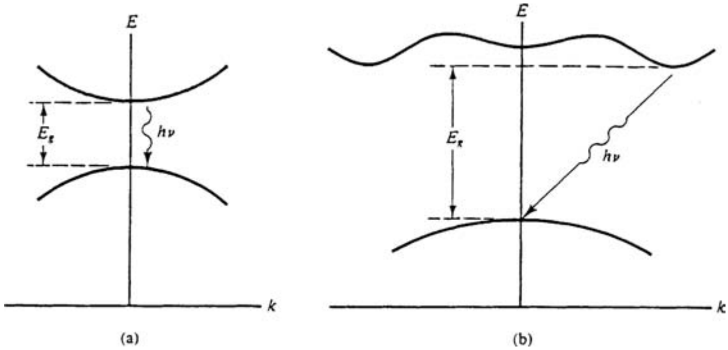

FIGURE 35.1 E vs. k for semiconductors having (a) a direct band gap and (b) an indirect band gap.

$$dn/dt = B_r np \tag{35.1}$$

where B_r is a recombination-dependent constant which for a direct band-gap semiconductor is ~10^6 times larger than that for an indirect band-gap semiconductor. For direct recombination, B_r value ranges from 0.46×10^{-10} to 7.2×10^{-10} cm^3/s.

All semiconductor crystal lattices are alike, being dissimilar only in terms of their band characteristics. Si and Ge both have indirect band transitions, whereas GaAs, for example, is a semiconductor that has a direct band transition. Thus, while Si and Ge are preferred for fabrication of transistors and integrated circuits, GaAs is preferred for the fabrication of LEDs.

The direct recombination (when k = constant) results in a photon emission whose wavelength (in micrometers) is given by

$$\lambda = hc/E_g = 1.24/E_g(\text{eV}) \tag{35.2}$$

where E_g is the band-gap energy. The LEDs under proper forward-biased conditions can operate in the ultraviolet, visible, and infrared regions. For the visible region, however, the spectral luminous efficiency curves of Figure 35.2, which account for the fact that the visual response to any emission is a function of wavelength, should be of concern. It is unfortunate that there is not a single-element semiconductor suitable for fabrication of LEDs, but there are many binary and ternary compounds that can be used for fabrication of LEDs. Table 35.1 lists some of these binary semiconductor materials. The ternary semiconductors include GaAlAs, $CdGeP_2$, and $ZnGeP_2$ for infrared region operation, $CuGaS_2$ and $AgInS_2$ for visible region operation, and $CuAlS_2$ for ultraviolet region operation. Ternary semiconductors are used because their energy gaps can be tuned to a desired emission wavelength by picking appropriate composition.

Of the ternary compounds, gallium arsenide–phosphide (written as $GaAs_{1-x}P_x$) is an example that is basically a combination of two binary semiconductors, namely, GaAs and GaP. The corresponding bandgap energy of the semiconductor can be varied by changing the value of x. For example, when x = 0, E_g = 1.43 eV. E_g increases with increasing x until x = 0.44 and E_g = 1.977 eV, as shown in Figure 35.3. However for $x \geq 0.45$, the band gap is indirect. The most common composition of $GaAs_{1-x}P_x$ used in LEDs has $x = 0.4$ and E_g. 1.3 eV. This band-gap energy corresponds to an emission of red light. Calculators and watches often use this particular composition of $GaAs_{1-x}P_x$.

Interestingly, the indirect band gap of $GaAs_{1-x}P_x$ (with $1 \geq x \geq 0.45$) can be used to output light ranging from yellow through green provided the semiconductor is doped with impurities such as nitrogen. The dopants introduced in the semiconductor replace phosphorus atoms which, in turn, introduce electron trap levels very near the conduction band. For example, if x = 0.5, the doping of nitrogen increases the LED efficiency from 0.01 to 1%, as shown in Figure 35.4. It must be noted, however, that nitrogen doping

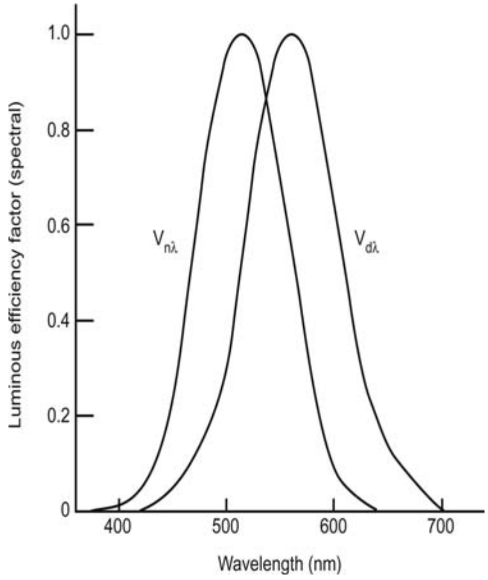

FIGURE 35.2 Spectral luminous efficiency curves. The photopic curve $V_{d\lambda}$ corresponds to the daylight-adapted case while the scotopic curve $V_{n\lambda}$ corresponds to the night-adapted case. (From Boyd, R.W., *Radiometry and the Detection of Optical Radiation,* John Wiley & Sons, New York, 1983. With permission.)

TABLE 35.1 Binary Semiconductors Suitable for LED Fabrication

	Material	E_g (eV)	Emission Type
III–V	GaN	3.5	UV
II–VI	ZnS	3.8	UV
II–VI	SnO_2	3.5	UV
II–VI	ZnO	3.2	UV
III–VII	CuCl	3.1	UV
II–VI	BeTe	2.8	UV
III–VII	CuBr	2.9	UV — visible
II–VI	ZnSe	2.7	Visible
III–VI	In_2O_3	2.7	Visible
II–VI	CdS	2.52	Visible
II–VI	ZnTe	2.3	Visible
III–V	GaAs	1.45	IR
II–VI	CdSe	1.75	IR — Visible
II–VI	CdTe	1.5	IR
III–VI	GaSe	2.1	Visible

shifts the peak emission wavelength toward the red. The shift is comparatively larger at and around $x = 0.05$ than $x = 1.0$. The energy emission in nitrogen-doped $GaAs_{1-x}P_x$ devices is a function of both x and the nitrogen concentration.

Nitrogen is a different type of impurity from those commonly encountered in extrinsic semiconductors. Nitrogen, like arsenic and phosphorus, has five valence electrons, but it introduces no net charge carriers in the lattice. It provides active radiative recombination centers in the indirect band-gap materials. For an electron, a recombination center is an empty state in the band gap into which an electron falls and, thereafter, falls into the valence band by recombining with a hole. For example, while a GaP LED emits green light (2.23 eV), a nitrogen-doped GaP LED emits yellowish green light (2.19 eV), and a heavily nitrogen-doped GaP LED emits yellow light (2.1 eV).

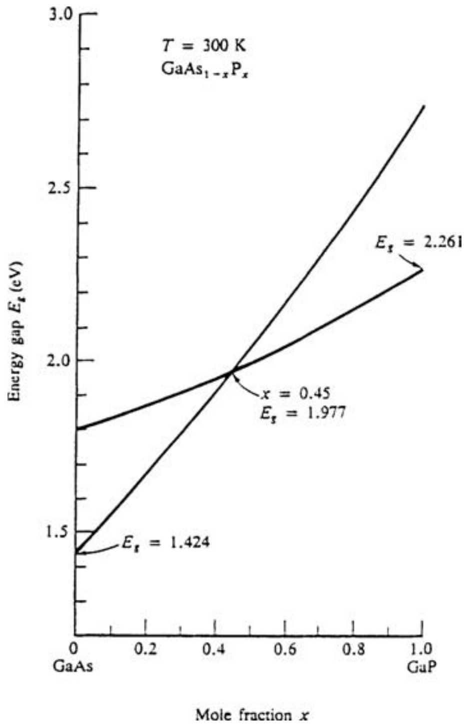

FIGURE 35.3 Band-gap energy vs. x in $GaAs_{1-x}P_x$. (From Casey, H.J., Jr. and Parish, M.B., Eds., *Heterostructure Lasers,* Academic Press, New York, 1978. With permission.)

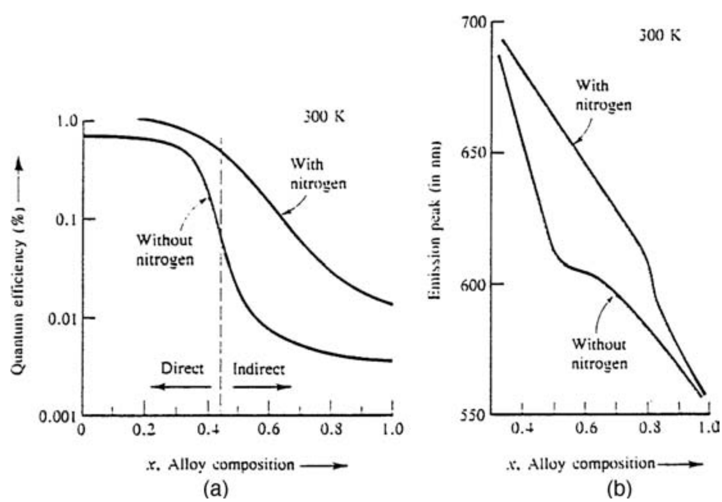

FIGURE 35.4 The effects of nitrogen doping in $GaAs_{1-x}P_x$: (a) quantum efficiency vs. x and (b) peak emission wavelength vs. x.

The injected excess carriers in a semiconductor may recombine either radiatively or nonradiatively. Whereas nonradiative recombination generates phonons, radiative recombination produces photons. Consequently, the internal quantum efficiency η, defined as the ratio of the radiative recombination rate R_r to the total recombination rate, is given by

$$\eta = R_r / (R_r + R_{nr}) \tag{35.3}$$

where R_{nr} is the nonradiative recombination rate. However, the injected excess carrier densities return to their value exponentially as

$$\Delta p = \Delta n = \Delta n_0 e^{-t/\tau} \tag{35.4}$$

where τ is the carrier lifetime and Δn_0 is the excess electron density at equilibrium. Since $\Delta n/R_r$ and $\Delta n/R_{nr}$ are, respectively, equivalent to the radiative recombination lifetime τ_r and the nonradiative recombination lifetime τ_{nr}, we can obtain the effective minority carrier bulk recombination time τ as

$$(1/\tau) = (1/\tau_r) + (1/\tau_{nr}) \tag{35.5}$$

such that $\eta = \tau/\tau_r$. The reason that a fast recombination time is crucial is that the longer the carrier remains in an excited state, the larger the probability that it will give out energy nonradiatively. In order for the internal quantum efficiency to be high, the radiative lifetime τ_r needs to be small. For indirect band-gap semiconductors, $\tau_r \gg \tau_{nr}$ so that very little light is generated, and for direct band-gap semiconductors, τ_r increases with temperature so that the internal quantum efficiency deteriorates with the temperature.

As long as the LEDs are used as display devices, it is not too important to have fast response characteristics. However, LEDs are also used for the purpose of optical communications, and for those applications it is appropriate to study their time response characteristics. For example, an LED can be used in conjunction with a photodetector for transmitting optical information between two points. The LED light output can be modulated to convey optical information by varying the diode current. Most often, the transmission of optical signals is facilitated by introducing an optical fiber between the LED and the photodetector.

There can be two different types of capacitances in diodes that can influence the behavior of the minority carriers. One of these is the *junction capacitance*, which is caused by the variation of majority charge in the depletion layer. While it is inversely proportional to the square root of bias voltage in the case of an abrupt junction, it is inversely proportional to the cube root of bias voltage in the case of a linearly graded junction. The second type of capacitance, known as the *diffusion capacitance*, is caused by the minority carriers.

Consider an LED that is forward biased with a dc voltage. Consider further that the bias is perturbed by a small sinusoidal signal. When the bias is withdrawn or reduced, charge begins to diffuse from the junction as a result of recombination until an equilibrium condition is achieved. Consequently, as a response to the signal voltage, the minority carrier distribution contributes to a signal current.

Consider a one-dimensional p-type semiconducting material of cross-sectional area A whose excess minority carrier density is given by

$$\delta \Delta n_p / \delta t = D_n \delta^2 \Delta n_p / \delta x^2 - \Delta n_p / \tau \tag{35.6}$$

As a direct consequence of the applied sinusoidal signal, the excess electron distribution fluctuates about its dc value. In fact, we may assume excess minority carrier density to have a time-varying component as described by

$$\Delta n_p(x,t) = \langle \Delta n_p(x) \rangle + n'_p(x) e^{j\omega t} \tag{35.7}$$

where $\langle \Delta n_p(x) \rangle$ is a time-invariant quantity. By introducing Equation 35.7 into Equation 35.6, we get two separate differential equations:

$$\delta^2/\delta x^2 \left(\langle \Delta n_p(x) \rangle \right) = \langle \Delta n_p(x) \rangle / (L_n)^2 \tag{35.8a}$$

and

$$\delta^2/\delta x^2\left[\Delta n_{\mathrm{p}}'(x)\right] = \Delta n_{\mathrm{p}}'(x)\Big/\left[L_{\mathrm{n}}^*\right]^2 \tag{35.8b}$$

where

$$L_{\mathrm{n}}^* = L_{\mathrm{n}}\Big/\left(1 + j\omega\tau\right)^{1/2} \tag{35.9a}$$

and

$$L_{\mathrm{n}} = \left(D_{\mathrm{n}}\tau\right)^{1/2} \tag{35.9b}$$

The dc solution of Equation 35.8a is well known. Again, the form of Equation 35.8b is similar to that of Equation 35.8a and, therefore, its solution is given by

$$\Delta n_{\mathrm{p}}'(x) = \Delta n_{\mathrm{p}}'(0)e^{-x/L} \tag{35.10}$$

Since the frequency-dependent current $I(\omega)$ is simply a product of eAD_{n} and the concentration gradient, we find that

$$\begin{aligned} I(\omega) &= \left|eAD_{\mathrm{n}}\mathrm{d}n_{\mathrm{p}}'(x)/\mathrm{d}x\right|_{x=0} \\ &= I(0)\Big/\left(1+\omega^2\tau^2\right)^{1/2} \end{aligned} \tag{35.11}$$

where $I(0)$ is the intensity emitted at zero modulation frequency. We can determine the admittance next by dividing the current by the perturbing voltage. The real part of the admittance, in this case, will be equivalent to the diode conductance, whereas its imaginary part will correspond to the diffusion capacitive susceptance.

The modulation response as given by Equation 35.11 is, however, limited by the carrier recombination time. Often an LED is characterized by its modulation bandwidth, which is defined as the frequency band over which signal power (proportional to $I^2(\omega)$) is half of that at $\omega = 0$. Using Equation 35.11, the 3-dB modulation bandwidth is given by

$$\Delta\omega \approx 1/\tau_{\mathrm{r}} \tag{35.12}$$

where the bulk lifetime has been approximated by the radiative lifetime. Sometimes the 3-dB bandwidth of the LED is given by $I(\omega) = ½I(0)$, but this simplification contributes to an erroneous increase in the bandwidth by a factor of 1.732.

Under conditions of thermal equilibrium, the recombination rate is proportional to the product of initial carrier concentrations, n_0 and p_0. Then, under nonequilibrium conditions, additional carriers $\Delta n = \Delta p$ are injected into the material. Consequently, the recombination rate of injected excess carrier densities is given by initial carrier concentrations and injected carrier densities as

$$\begin{aligned} R_{\Delta\mathrm{r}} &= \left[B_{\mathrm{r}}\left(n_{\mathrm{o}} + \Delta n\right)\left(p_{\mathrm{o}} + \Delta p\right) - B_{\mathrm{r}}n_{\mathrm{o}}p_{\mathrm{o}}\right] \\ &= B_{\mathrm{r}}\left(n_{\mathrm{o}} + p_{\mathrm{o}} + \Delta n\right)\Delta n \end{aligned} \tag{35.13}$$

where B_{r} is the same constant introduced in Equation 35.1. For *p*-type GaAs, for example, $B_{\mathrm{r}} = 1.7 \times 10^{-10}$ cm³/s when $p_0 = 2.4 \times 10^{18}$ holes/cm³. Equation 35.13 is used to define the radiative carrier recombination lifetime by

$$\tau_r = \Delta n / R_{\Delta r} = \left[B_r\left(n_o + p_o + \Delta n\right)\right]^{-1} \tag{35.14}$$

In the steady-state condition, the excess carrier density can be calculated in terms of the active region width d by

$$\Delta n = J\tau_r / ed \tag{35.15}$$

where J is the injection current density.

The radiative recombination lifetime is found by solving Equation 35.14 after having eliminated Δn from it using Equation 35.15:

$$\tau_r = \left[\left\{\left(n_o + p_o\right)^2 + \left(4J/B_r ed\right)\right\}^{1/2} - \left(n_o + p_o\right)\right] \Big/ \left(2J/ed\right) \tag{35.16}$$

Thus, while for the low carrier injection (i.e., $n_o + p_o \gg \Delta n$), Equation 35.16 reduces to

$$\tau_r \approx \left[B_r\left(n_o + p_o\right)\right]^{1/2} \tag{35.17a}$$

for the high carrier injection (i.e., $n_o + p_o \ll \Delta n$), it reduces to

$$\tau_r \approx \left(ed/JB_r\right)^{1/2} \tag{35.17b}$$

Equation 35.17a indicates that in highly doped semiconductors, τ_r is small. But the doping process has its own problem, since in many of the binary LED compounds higher doping may introduce nonradiative traps just below the conduction band, thus nullifying Equation 35.12. In comparison to Equation 35.17a, Equation 35.17b provides a better alternative whereby τ_r can be reduced by decreasing the active region width or by increasing the current density. For the case of p-type GaAs, the radiative lifetimes vary between 2.6 and 0.35 ns, respectively, when p_0 varies between 1.0×10^{18} holes/cm^3 and 1.5×10^{19} holes/cm^3.

Usually, LEDs are operated at low current ($\geqslant$10 mA) and low voltages ($\geqslant$1.5 V), and they can be switched on and off in the order of 10 ns. In addition, because of their small sizes, they can be reasonably treated as point sources. It is, therefore, not surprising that they are highly preferred over other light sources for applications in fiber-optic data links.

Two particular LED designs are popular: *surface emitters* and *edge emitters*. They are shown in Figure 35.5. In the former, the direction of major emission is normal to the plane of the active region, whereas in the latter the direction of major emission is in the plane of the active region. The emission pattern of the surface emitters is very much isotropic, whereas that of the edge emitters is highly directional.

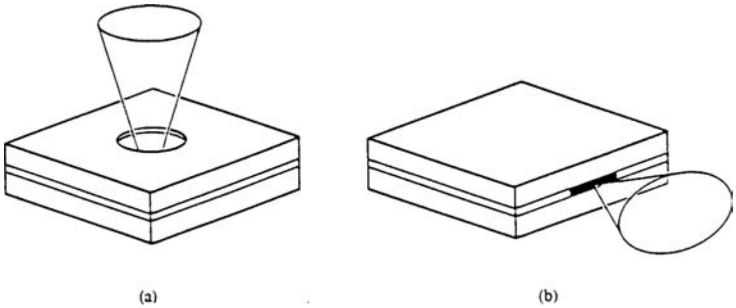

FIGURE 35.5 LED type: (a) surface emitter and (b) edge emitter.

As the LED light originating from a medium of refractive index n_1 goes to another medium of refractive index $n_2(n_2 < n_1)$, only a portion of incident light is transmitted. In particular, the portion of the emitted light corresponds to only that which originates from within a cone of semiapex angle θ_c, such that

$$\theta_c = \sin^{-1}(n_2/n_1) \tag{35.18}$$

In the case of an LED, n_1 corresponds to the refractive index of the LED medium and n_2 corresponds to that of air (or vacuum). Light originating from *beyond* angle θ_c undergoes a total internal reflection. However, the light directed from *within* the cone of the semiapex angle θ_c will be subjected to Fresnels loss. Thus, the overall transmittance T is given by

$$T = 1 - \{(n_1 - n_2)/(n_1 + n_2)\}^2 \tag{35.19}$$

Accordingly, the total electrical-to-optical conversion efficiency in LEDs is given by

$$\begin{aligned}\eta_{\text{LED}} &= T[(\text{solid angle within the cone})/(4\pi)] \\ &= (T/2)(1 - \cos\theta_c) \\ &= (T/4)\sin^2\theta_c \\ &= (1/4)(n_2/n_1)^2\left[1 - \{(n_1 - n_2)/(n_1 + n_2)\}^2\right]\end{aligned} \tag{35.20}$$

Only two schemes increase the electrical-to-optical conversion efficiency in an LED. The first technique involves guaranteeing that most of the incident rays strike the glass-to-air interface at angles less than θ_c. It is accomplished by making the semiconductor–air interface hemispherical. The second method involves schemes whereby the LED is encapsulated in an almost transparent medium of high refractive index. The latter means is comparatively less expensive. If a glass of refractive index 1.5 is used for encapsulation, the LED efficiency can be increased by a factor of 3. Two of the possible encapsulation arrangements and the corresponding radiation patterns are illustrated in Figure 35.6.

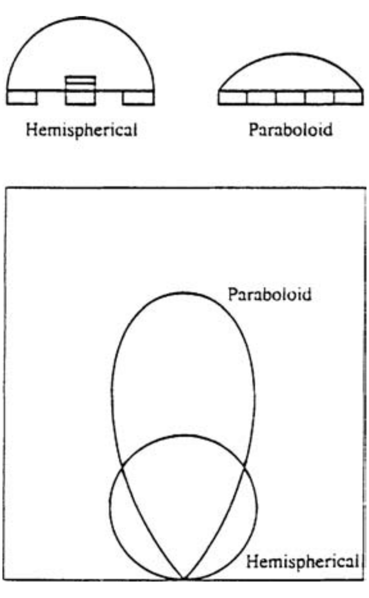

FIGURE 35.6 LED encapsulation geometries and their radiation patterns.

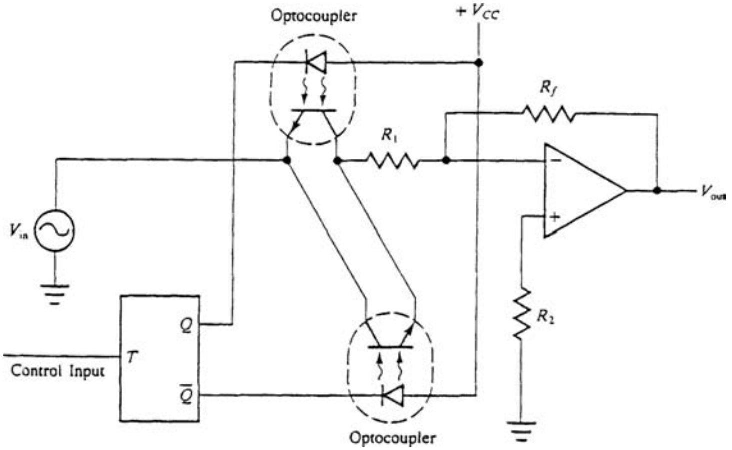

FIGURE 35.7 A chopping circuit with an amplifier.

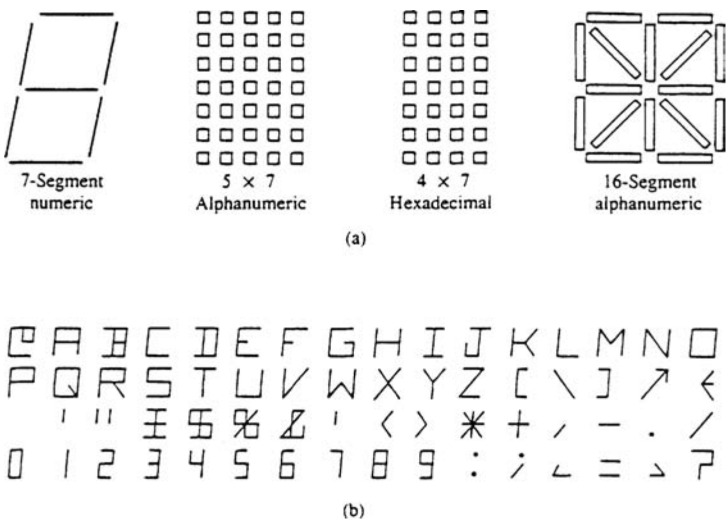

FIGURE 35.8 (a) LED display formats; and (b) displayed alphanumeric characters using 16-segment displays.

LEDs are often used in conjunction with a phototransistor to function as an optocoupler. The optocouplers are used in circumstances when it is desirable to have a transmission of signals between electrically isolated circuits. They are used to achieve noise separation by eliminating the necessity of having a common ground between the two systems. Depending on the type of coupling material, these miniature devices can provide both noise isolation as well as high voltage isolation. Figure 35.7 shows a typical case where two optocouplers are used to attain a chopper circuit. The two optocouplers chop either the positive or the negative portion of the input signals with a frequency of one half that of the control signal that is introduced at the *T* flip-flop. The operational amplifier provides an amplified version of the chopped output waveform. In comparison, a chopper circuit that uses simple bipolar transistors produces noise spikes in the output because of its inherent capacitive coupling.

The visible LEDs are best known for their uses in displays and indicator lamps. In applications where more than a single source of light is required, an LED array can be utilized. An LED array is a device consisting of a row of discrete LEDs connected together within or without a common reflector cavity. Figure 35.8a shows different LED arrangements for displaying hexadecimal numeric and alphanumeric characters, whereas Figure 35.8b shows, for example, the possible alphanumeric characters using 16-segment displays. In digital systems, the binary codes equivalent to these characters are usually decoded and, consequently, a specific combination of LED segments are turned on to display the desired alphanumeric character.

The dot matrix display provides the most desirable display font. It gives more flexibility in shaping characters and has a lower probability of being misinterpreted in case of a display failure. However, these displays involve a large number of wires and increased circuit complexity. LED displays, in general, have an excellent viewing angle, high resonance speed ($\geqslant$10 ns), long life, and superior interface capability with electronics with almost no duty cycle limitation. LEDs with blue emission are not available commercially. When compared with passive displays, LED displays consume more power and involve complicated wiring with at least one wire per display element.

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