SECTION 9

RADIANT ENERGY SOURCES AND SENSORS

Radiant energy sources include both coherent and noncoherent sources. Noncoherent sources are typically traditional light sources for illuminating applications, but also include light-emitting diodes. Lasers, on the other hand, rely on coherent emission that produces a beam that is highly collimated and highly monochromatic.

Semiconductor laser diodes represent a class of lasers especially useful in optical computing applications, optical sensors, optical disc systems, and materials processing. They are small and highly efficient. When the laser diode is forward biased, incoherent light emission takes place until the drive current reaches a threshold value. Below threshold, the device is similar to a light-emitting diode (LED). Above threshold, lasing takes place and the light output increases rapidly with current. A completely new segment on semiconductor laser diodes begins on p. 9.31.

This section also includes a chapter on cathode-ray tubes and electroluminescent displays, with valuable complementary material on the accompanying CD-ROM covering electro-optics and nonlinear optics, phosphor screens, photoemissive electron tubes, and camera tubes.

Four chapters treat radiant energy sensors. Photoconductive and semiconductor junction detectors convert electromagnetic energy to electric energy. Charge-coupled-device and charge-injection-device image sensors are applicable to high- and low-light-level imaging, spatial character recognition, and facsimile reproduction. Infrared detectors include both thermal detectors and quantum detectors, and often require cryogenic cooling to reduce noise. Solar cells may be used in quantity for power generation or individually as light detectors in applications such as cameras.   D.C.

In This Section:

On the CD-ROM:

Sharp, E. J., “Electro-optics and Nonlinear Optics,” reproduced from the 4th edition of this handbook.

Diakides, N. A., “Phosphor Screens,” from the 4th edition of this handbook, provides a discussion of screens used to convert electron energy into radiant energy in image tubes, cathode-ray tubes, and storage CRTs.

Johnson, C. A., “Photoemissive Electron Tubes, Image Converters, and Intensifiers,” from the 4th edition of this handbook.

Graft, R. D., and R. E. Franseen. “Television Camera Tubes,” from the 4th edition of this handbook, covers theory of operation, construction, materials, and performance.

CHAPTER 9.1

NONCOHERENT RADIANT ENERGY SOURCES

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INTRODUCTION

Glossary

Generation of light. Light is produced by the transition of electrons from states of higher energies to states of lower energies. The law of conservation of energy is satisfied in these transition processes by the emission of a photon, or quantum of light, whose energy corresponds to the difference in energy of the initial and final energy states of the electron.

Blackbody radiation. A blackbody is defined as a body which, if it existed, would absorb all and reflect none of the radiation incident on it. It is thus a perfect absorber and a perfect emitter. The blackbody curves for several values of T are plotted on a logarithmic scale in Fig. 9.1.1.

The total emissivity ϵ of a thermal radiator at a given temperature is the ratio of the total radiation output of that radiator to that of a blackbody of the same temperature.

The spectral emissivity $\epsilon(\lambda)$ of a thermal radiator is defined as the ratio of the output of the source at the wavelength λ to that of a blackbody at the same wavelength and operating temperature.

Graybody radiation. If the emissivity of a thermal radiator is a constant less than 1 for all wavelengths, the radiator is called a graybody.

Selective radiation. A thermal radiator whose spectral emissivity is not constant but is a function of wavelength is called a selective radiator.

The color temperature of a thermal radiator is the temperature of a blackbody chosen such that its output is the closest possible approximation to a perfect color match with the thermal radiator. Figure 9.1.2 shows the spectral distribution of a tungsten filament operating at a color temperature of 3000 K compared with a blackbody of the same temperature and a graybody whose emissivity is the same as tungsten in the visible spectrum.

The candela (cd) is the unit of luminous intensity. Luminous intensity is the amount of luminous flux per unit solid angle in a given direction. This is measured as the luminous flux on a target normal to the direction of incidence divided by the solid angle (measured in steradians, abbreviated sr) subtended by the target as viewed from the source.

The lumen (lm) is the unit of luminous flux. It is equal to the flux in a unit solid angle from a uniform point source of 1 cd intensity.

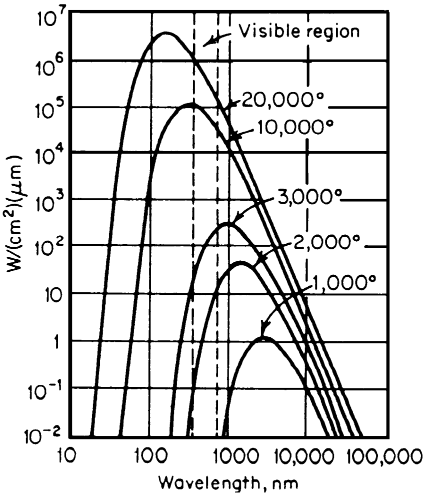

FIGURE 9.1.1 Blackbody distribution curves for several values of temperature in kelvins.

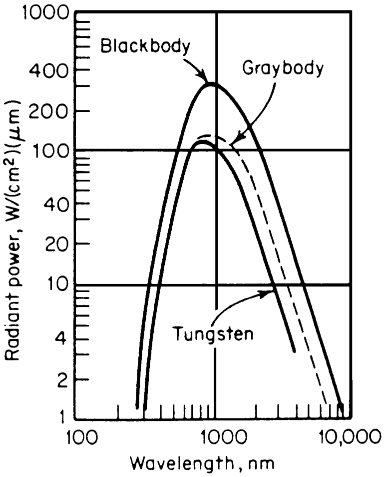

FIGURE 9.1.2 Spectral distribution of tungsten at a color temperature compared with blackbody and graybody of the same temperature.

The luminous efficacy of a light source is the measure of light-producing efficiency of the source. It is the ratio of the total luminous flux output to the total input power of the source. Luminous efficacy is measured in lumens per watt.

Radiative efficiency of a light source is the ratio (in percent) of total output power of the source measured in watts to the input power to the source.

Incandescence. Emission of radiation relating to the temperature of the source.

Luminescence. Emission of radiation relating to causes other than temperature of the source.

Fluorescence. Luminescence stimulated by radiation, not continuing more than about 10^{-8} s after the stimulating radiation is cut off.

The most commonly used light sources are the tungsten filament, electric discharge and electroluminescent lamps, and solid-state or light-emitting diodes. The first source is incandescent; the others are luminescent.

Tungsten-Filament Lamps

Filament. The higher the operating temperature of a solid filament, the higher the percentage of its radiation that falls in the visible portion of the electromagnetic spectrum. Tungsten, with its high melting point (3653 K), low vapor pressure, and other favorable characteristics, is the most frequently used filament material. In higher-power incandescent lamps (generally above 40 W) an inert gas instead of vacuum surrounds the filament to reduce the evaporation rate of the tungsten.

Lamp Types. Tungsten filament lamps are divided into the following categories: general-service lamps; high- and low-voltage lamps; series-burning lamps; projector and reflector lamps; showcase lamps; spotlight, floodlight, and projection lamps; halogen-cycle lamps; and infrared lamps.

Tungsten halogen-cycle lamps have a quartz envelope and use a halogen fill, usually iodine, to keep the bulb clean by chemical reaction with sublimated tungsten. This reaction provides a high-lumen maintenance

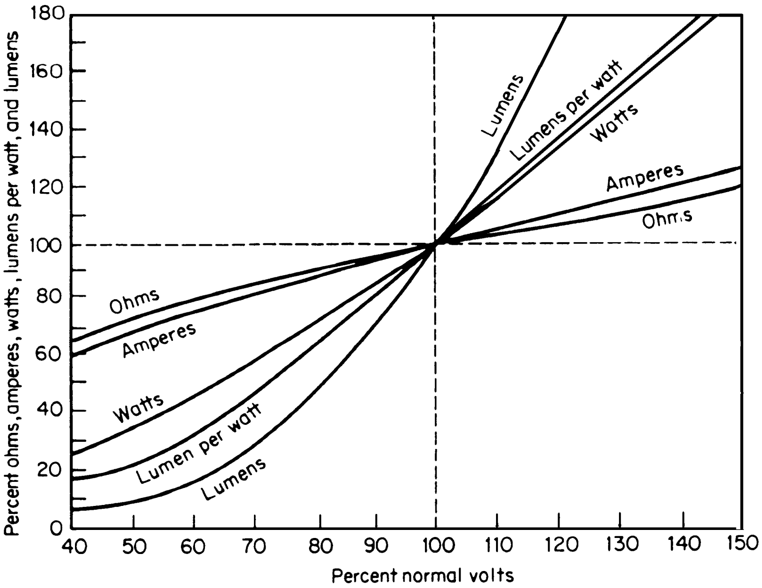

FIGURE 9.1.3 Interrelation of lamp parameters for large tungsten-filament lamps. (*General Electric Co.*)

throughout the life of the lamp by redepositing evaporated tungsten on the filament instead of on the bulb. *Infrared lamps* are tungsten-filament lamps that operate at low filament temperature.

Lamp Parameters. The quantities voltage, current, resistance, temperature, watts, light output, efficacy, and life of a filament lamp are interrelated, and one cannot be changed without changing the others. Figure 9.1.3 shows how these quantities change typically as a function of the voltage for large gas-filled lamps.

Some useful exponential relations frequently applied to incandescent filament lamps, where capital letters indicate normal-rated values, are

$$\frac{\text{life}}{\text{LIFE}} = \left(\frac{\text{VOLTS}}{\text{volts}}\right)^d \qquad \frac{\text{lumens}}{\text{LUMENS}} = \left(\frac{\text{volts}}{\text{VOLTS}}\right)^k$$

$$\frac{\text{LM/W}}{\text{lm/w}} = \left(\frac{\text{VOLTS}}{\text{volts}}\right)^g \qquad \frac{\text{watts}}{\text{WATTS}} = \left(\frac{\text{volts}}{\text{VOLTS}}\right)^n$$

For approximate calculations the following average exponents may be used: $d = 13$, $g = 1.9$, $k = 3.4$, and $n = 1.6$.

Electric-Discharge Lamps

Fluorescent Lamps. Fluorescent lamps are electric-discharge lamps in which light is produced through the excitation of phosphors by the ultraviolet energy from a mercury arc. The lamp usually consists of a phosphor-coated tubular bulb with electrodes sealed into each end and containing mercury vapor at low pressure along with an inert starting gas such as argon or an argon-neon mixture. Various colors, grades of white light, and even black light (near ultraviolet) are obtained by the choice of available phosphors. Cool white is the most widely used white-light fluorescent tube.

Lamp types. Fluorescent lamps are classified as *hot-cathode* or *cold-cathode* type. There are three classes of hot-cathode fluorescent lamps: *preheat, instant-start*, and *rapid-start*. Preheat lamps allow preheating of the cathodes for a few seconds before striking the mercury arc. Instant-start lamps require no preheat because sufficient voltage is applied between the electrodes to strike the arc very quickly. Rapid-start lamps have continuously heated cathodes requiring a lower voltage than instant-start lamps. This feature also allows dimming and flashing of the lamp.

Mercury Lamps. Mercury vapor discharge lamps of the wall-stabilized variety are used primarily for general lighting. Mercury lamps with additives such as the metal halide lamp and sodium vapor lamp and mercury compact arcs are treated in separate succeeding paragraphs. Most mercury vapor lamps have two bulbs. The inner bulb, called the *arc tube*, contains the arc and the electrodes between which the arc burns. The outer bulb protects the arc tube from drafts and stabilizes the operating temperature. Mercury lamps for general lighting are available in input power sizes from 50 to 3000 W.

In addition to mercury in the arc tube, an easily ionized inert gas such as argon is present to facilitate starting. The arc is generally ignited through use of a starting electrode and current-limiting starting resistor. An arc is first struck between the starting electrode and the adjacent main electrode. The heating and additional ionization resulting from this arc allow the large arc to form between the main electrodes.

Electrical and radiation characteristics. The color-rendering properties of a clear mercury lamp are only fair, owing to the line structure in the blue end of the spectrum. A clear mercury lamp of 1000 W input power has a typical initial luminous efficacy of 56 lm/W.

Metal Halide-Mercury Vapor Lamps. Metal halide-mercury vapor lamps are very nearly the same as regular mercury lamps except that additives such as the iodides of sodium, thallium, and indium are contained in the arc tube for the purpose of improving color rendition and efficiency. The typical initial luminous efficacy of a metal halide-mercury lamp of 1000 W input power is 90 lm/W.

High-Pressure Sodium Vapor Lamps. High-pressure sodium vapor lamps are presently the most efficient source of artificial light. A typical 1000-W high-pressure sodium lamp has an initial luminous efficacy of 140 lm/W. The theoretical efficiency of white light in the visible region, assuming 100 percent conversion of power into a continuum output, is 220 lm/W. Typical life of high-pressure sodium lamps is 12,000 to 20,000 h.

High-pressure sodium lamps require a high-transmission ceramic envelope such as alumina to contain the alkali metal at high temperature and an alkali-resistant high-temperature metal seal. The corrosive effects of sodium at high operating temperature prohibit the use of quartz and other glasses as an arc-tube material. Xenon is used as the readily ionized starting gas. When the xenon starting gas is ionized, the arc is struck, producing heat, and the vapor pressure starts to rise.

Arc-Light Sources. (a) *Short-arc or compact-arc lamps* are of the enclosed-bulb type. Most are made for dc operation, which results in long life and good arc stability. They have high operating pressure, a comparatively short arc gap, and very high luminance (photometric brightness). The arc length may vary from about $^1/_3$ to 17 mm. Since these lamps have the highest luminance of any continuous-operation light source and provide maintenance-free, clean operation, they have replaced the carbon arc in many applications.

Mercury short-arc lamps contain a low pressure of inert gas such as argon for starting. After the arc is struck, the lamp warms up and the mercury vapor reaches full operating pressure within a few minutes. Warmup time is reduced to approximately one-half of that of the mercury arc if xenon at 1 atm or more pressure is added. The spectra of mercury and mercury-xenon lamps are essentially the same. The luminous efficacy of these lamps is about 50 lm/W for a 1000-W lamp. These lamps are available in a power range from 30 to 5000 W.

Xenon short-arc lamps are filled to a cold pressure of several atmospheres with high-purity xenon gas. Operating pressure is roughly double the cold pressure. These lamps do not have as long a warmup time as the metal vapor types; 80 percent of the light output is obtained within 1 s of startup. Xenon has excellent color-rendering characteristics because of its continuous spectrum in the visible region. Luminous efficacy at 5000 W is approximately 45 lm/W.

(b) *Carbon arcs* are of three basic types: the low-intensity arc, the flame arc, and the high-intensity arc.

The *low-intensity arc* has as its source of light the incandescent tip of the positive carbon, which is maintained near the sublimation point of carbon (3700°C). The heat supplied to the positive carbon is from high-current-density electron bombardment originating from the negative carbon.

The *flame arc* is obtained by enlarging the core of the electrodes of a low-intensity arc and replacing the removed material with compounds of rare-earth elements such as cerium.

The *high-intensity arc* is obtained from the flame arc by increasing the core size and the current density so that the anode spot spreads over the entire tip of the carbon. A crater is formed, and this becomes the primary source of light.

Flashtubes. Flashtubes are designed to produce high-luminance flashes of light of very short duration. They are used in optical pumping of lasers, stroboscopic work, photographic applications, and many other purposes requiring flashing lights.

Lamp construction. The flashtube consists of a glass or quartz tube filled with gas and containing two or more electrodes. The fill gas preferred for most flashtube applications is xenon because of its high output of white light. Other gases, including argon, neon, krypton, and hydrogen, are frequently used.

Driving circuit. Energy for flashing the tube is usually stored in a capacitor. This energy is determined by the equation $E = CV^2/2$, where E = energy (J), C = capacitance (μF), and V = voltage on capacitor (kV). The duration of the flash usually depends on the resistance of the discharge and the capacitance of the storage capacitor, the duration being approximately $3RC$, with R in ohms and C in farads. For short pulses of 1 μs or less duration, frequently the inductance of the tube or circuit is the dominant factor over the resistance in determining pulse length.

Many circuits have been used to flash lamps. One basic method is to hold off a voltage higher than the self-breakdown voltage of the lamp with an electronic switch, such as a thyratron, silicon-controlled rectifier, or spark gap, and trigger the switch when a flash is desired.

Electroluminescent Lamps

An electroluminescent lamp is a thin flat source in which light is produced through excitation of a phosphor by an alternating electric field. The lamp basically consists of a capacitor with a phosphor embedded in the dielectric material sandwiched between two conducting plates. The front plate is a transparent sheet of either plastic, glass, or ceramic with a thin transparent conductive film on it. The back conductive plate may be a metal sheet or film or a transparent material like the front plate.

LIGHT-EMITTING DIODES

Mark Hodapp, David L. Evans, David O'Brien, Jason Yorks

Pn Junction Injection Electroluminescence

The emission of light (photons) from a naturally occurring *pn* junction was first noted by Lassew in 1923. In 1962, studies of GaAs (gallium arsenide) revealed the feasibility of high-level electroluminescent emissions from *pn* junctions (see Holonyak, 1962). The same year, an intensive development program was begun at Hewlett-Packard and elsewhere to produce a useful manufacturable, visible-light-emitting *pn* junction device. The result was the light-emitting diode (LED). LEDs benefit from: (1) useful light output at low currents and voltages; (2) the accuracy with which the light-emitting area can be defined through the use of semiconductor photolithographic processes; (3) the high speed at which the devices can be switched; (4) a lifetime far in excess of an incandescent light source; and (5) the ability to withstand high degrees of shock and vibration.

Operating Mechanism

Light-emitting diode lamps operate much like a silicon or germanium diode. Although they both rectify current, neither silicon nor germanium emits light. When an LED is forward biased, photons are emitted in all directions; however, not all of these photons emerge from the lamps as useful light. The amount of emitted light is dependent upon the material, the geometry of the package, how many photons are absorbed, reflected, refracted, and finally emitted from the lamp.

LED Materials

There are numerous elements and elemental compounds that have bandgap energies capable of producing photon emissions ranging from ultraviolet to infrared. Very few of these materials, however, are practical for LED devices. Some of them are not useful because they cannot be easily doped to form a *pn* junction, some do not emit photons at a useful wavelength, and some have too low a conversion efficiency. Most commercially available LED devices are manufactured from Type 3 elements in the periodic table (A1, Ga, In) and Type 5 elements in the periodic table (N, P, As, Sb); however, a small number of LEDs use Type 4 elements (SiC) and Type 2 (Zn) and Type 6 (Se). Most commercial LED devices use the binary compounds GaAs, GaP, SiC, ternary compounds $GaAs_{1-x} P_x$, $Al_x Ga_{1-x} As$, or quaternary compounds $(Al_xG_{1-x})_{0.5} In_{0.5} P$.

Table 9.1.1 lists a few of the materials available for LEDs, their associated bandgaps, emission wavelengths, and transition types. In a direct transition, the electrons in the conduction band and the holes in the valence band both have zero momentum at the point where the energy bandgap between two bands is the smallest. Electrons can easily drop across the bandgap and emit a photon while conserving momentum.

In an indirect transition, the momenta are different at the narrowest point between the bands. To conserve momentum, a phonon (quantum of heat) is either generated or absorbed by the crystal structure. The addition of this extra component reduces the likelihood of recombination, resulting in a less efficient LED. The maximum possible energy of the emitted photon is determined by the bandgap energy of the solid in which the *pn* junction is formed.

Efficiency of LED Devices

The efficiency with which an electroluminescent material converts current flow into detectable photon emission determines whether usable devices can be manufactured from the material. The percentage of current flow, which results in recombination's yielding photons of the desired wavelength, is a measure of the internal conversion efficiency (n_{int}) of the diode, sometimes referred to as internal quantum efficiency (see Craford,

TABLE 9.1.1 LED Semiconductor Materials

Material	Band GaP Energy (eV)	Peak Wavelength (nm)	Transition Type
GaAs	1.43	910	Direct
$GaAs_{0.6}P_{0.4}$	1.91	650	Direct
$GaAs_{0.35}P_{0.65}$	2.09	635	Indirect
$GaAs_{0.20}P_{0.80}$	2.16	600	Indirect
$GaAs_{0.10}P_{0.90}$	2.21	583	Indirect
GaP:N	2.26	568	Indirect
GaP	2.26	555	Indirect
$Al_{0.35}Ga_{0.65}As$	1.93	645	Direct
$(Al_{0.08}Ga_{0.92})_{0.5}In_{0.5}P$	1.99	622	Direct
$(Al_{0.12}Ga_{0.88})_{0.5}In_{0.5}P$	2.02	615	Direct
$(Al_{0.27}Ga_{0.73})_{0.5}In_{0.5}P$	2.10	590	Direct
SiC	2.99	480	Indirect

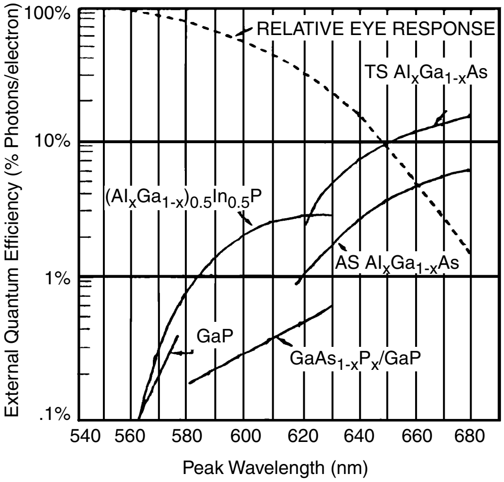

FIGURE 9.1.4 External quantum efficiency of LED materials.

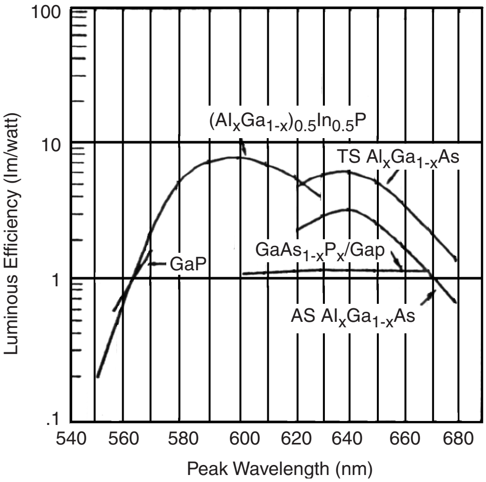

FIGURE 9.1.5 Luminous efficiency of LED materials.

1992). A material that has n_{int} of 100 percent may not be useful if the emitted photons cannot be efficiently coupled from the device.

Two major factors control the internal (n_{int}) to external coupling coefficient (n_{ext}). One factor is direct reabsorption of the emitted photon in the bulk material (basically a measure of the opacity of the material). The other factor is *internal reflection* at the crystal/air interface, causing the photon to be reflected back into the crystal and reabsorbed.

Figure 9.1.4 shows the external quantum efficiency (photons/electron) for a number of LED materials. $GaAs_{1-x}P_x$ grown on a GaP substrate has an external quantum efficiency of about 1 percent. $Al_{0.35}Ga_{0.65}As$ has an external quantum efficiency of 5 to 10 percent depending on whether the substrate is transparent or opaque. $(Al_x Ga_{1-x})_{0.5} In_{0.5} P$ has an external quantum efficiency of about 6 percent in the red and orange spectrum.

It is desirable to optimize the total coupling efficiency between the emitting device's input signal and the detecting device's output. A standard emitter is matched to the human eye by picking the wavelength at which the product of the relative response of the eye and the relative efficiency of the diode is largest.

For diodes having shorter peak-emitting wavelengths, such as *n*-doped GaAsP emitters at 565 nm (green) and 585 nm (yellow), the relative sensitivity of the diode is substantially lower but the relative efficiency of the eye is higher. For visible applications, the efficiency of LEDs is usually specified in terms of lumens per watt or lumens per amp. The numerator, lumens, is a measurement of the total optical flux generated, scaled by the human eye response. The denominator, watts or amps, is the electrical power or current applied to the LED.

Figure 9.1.5 shows the luminous efficiency (lumens per watt) for a number of LED materials. $GaAs_{1-x}P_x$ grown on a GaP substrate has a luminous efficiency of about 1 lm/W. $Al_x Ga_{1-x} As$ has a luminous efficiency that peaks at 8 lm/W in the red region. (This corresponds to the wavelength of $Al_{0.35} Ga_{0.65} As$. $(–Al_x Ga_{1-x})_{0.5}$. $In_{0.5} P$ has a luminous efficiency of about 8 lm/W in the red and orange regions. (For the sake of comparison, a red filtered incandescent bulb in an auto tail light has a luminous efficiency of about 6 lm/W.)

Real Versus Ideal LEDs

A *pn* junction in GaAsP material exhibits numerous discrepancies between the ideal and the real. Surface recombination, tunneling phenomena, space charge recombination, current crowding, and bulk recombination because of anomalous impurities tend to reduce the efficiency of an LED. The relative effects of these nonradiative phenomena tend to be dependent on the current density J (amps per square centimeter of junction area),

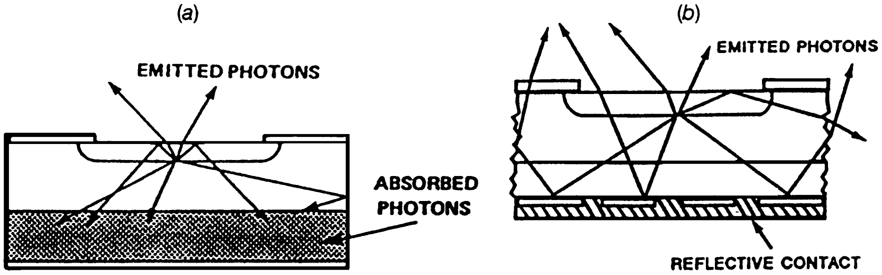

FIGURE 9.1.6 Cross sections of (*a*) GaAsP on opaque GaAs substrate; (*b*) GaAsP or GaP on transparent GaP substrate.

and the perimeter to area ratio of the diode. At low current (< 1A/cm^2) nearly all the current in a diode may result from one of these nonideal mechanisms.

The net effect of nonideal mechanisms is that an LED has its peak operating efficiency at a current that is dependent on the area and geometry of the junction and the size of the electrical contact. A doubling of current at low current densities may lead to a light output increase of two to three times, whereas a doubling of current at high current densities may result in slightly less than a doubling of light output.

Transparent Versus Opaque Substrates

The photons generated at the junction of a *pn* electroluminescent diode are emitted in all directions. If the diode substrate is opaque, as is the case with GaAs, only those photons that are emitted upward within a critical angle defined by Snell's law will be emitted as useful light. All other photons emitted into or reflected into the crystal will be absorbed. This phenomenon is illustrated in Fig. 9.1.6*a*.

When compared to GaAs, GaP is nearly transparent. Diodes formed by an epitaxial layer grown on a GaP substrate will exhibit improved efficiency because of the emission of photons that would have been absorbed in the GaAs substrate. The resulting structure is shown in Fig. 9.1.6*b*.

Similar considerations exist for AlGaAs and AlInGaP LEDs. In the case of DH AlGaAs LEDs, the AlGaAs is grown on an opaque GaAs substrate. For the TS AlGaAs LEDs, the GaAs substrate is removed. The bottom layer of the $Al_{0.6}Ga_{0.4}As$ is transparent to the light emitted in the junction. This is the reason that TS AlGaAs LEDs have twice the luminous efficiency of DH AlGaAs LEDs. The present AlInGaP LEDs use an opaque GaAs substrate. If the substrate was removed, an additional factor of 2 in luminous efficiency could be achieved.

Temperature Effects on LED Parameters

Absolute temperature variation affects an LED's parameters. Those of greatest interest to the user are forward voltage, quantum efficiency, and emitted wavelength. These are discussed in some detail in Hewlett-Packard Application Note, "LED Theory" (see Evans, 1993).

Lamp Packaging

Figure 9.1.7 shows the cross section of a typical LED lamp. The light emitting element consists of a small chip of LED material about 0.010 in. on a side by 0.006 in., mounted in a reflective metal dish. The bottom of the LED is attached to the reflector using an electrically conducting epoxy. The top of the LED is bonded to the second pin of the package with a gold wire. The LED die and lead frame are cast in an epoxy housing. The epoxy package secures the pins of the lamp and contributes to the optical properties of the lamp. A wide range of optical properties can be created by using different lens shapes and positions of the reflector dish in the package, and by adding diffusant to the epoxy.

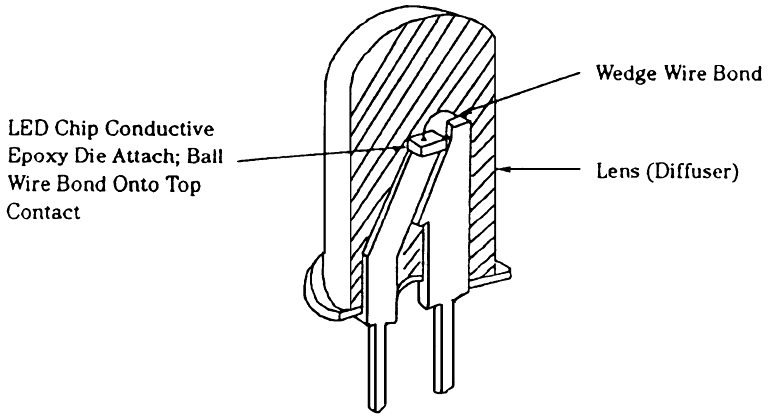

FIGURE 9.1.7 Cross section showing LED lamp construction.

The mechanical properties of the LED lamp are typically limited by the epoxy package rather than the LED die. The LED die, die attach material, and wire bond are very rugged and can withstand mechanical shock and vibration that would destroy a tungsten filament. However, the epoxy material typically has a higher temperature expansion coefficient than the rest of the lamp, so that temperature cycling at extremely high temperatures can put excessive stresses on the gold wire and wire bond. Today's LEDs are capable of withstanding hundreds of temperature cycles from –55/100°C; however, at temperatures above 100°C, the number of survivable temperature cycles is significantly reduced. Consequently most LED lamps recommend a maximum junction temperature of 110°C. The availability of higher temperature epoxies is expected to raise this limit to at least 125°C.

LED Drive Circuits

The LED lamp typically has an electrical characteristic shown in Fig. 9.1.8. Light is generated only when the *pn* junction is forward biased and current flows through the junction. This occurs at the turn-on voltage. At higher voltages, the current increases very quickly. The light output is a function of the current through the LED.

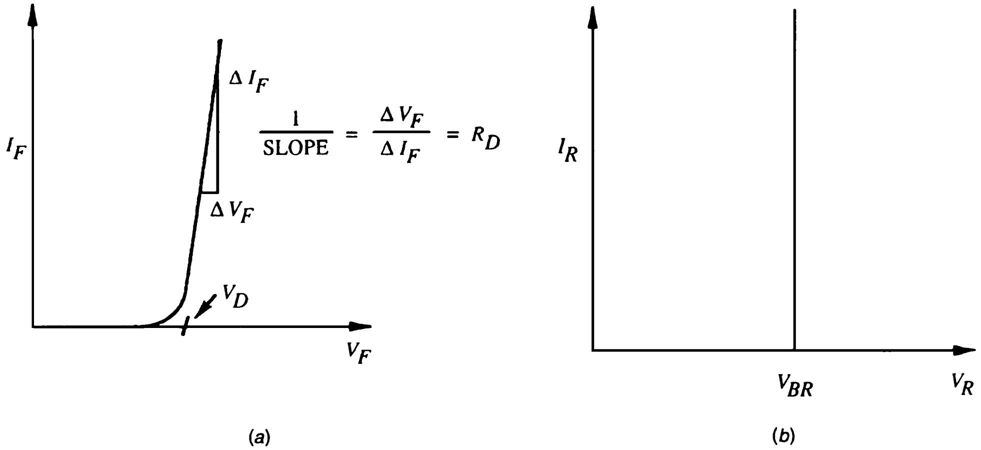

FIGURE 9.1.8 (*a*) Forward and (*b*) reverse characteristics of LED lamp.

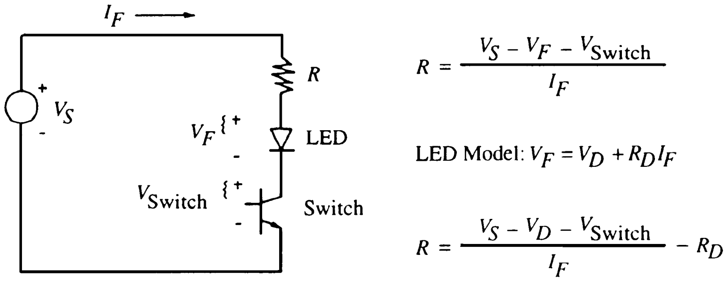

FIGURE 9.1.9 Typical resistive drive circuit for LED.

Under reverse bias conditions, negligible current flows through the LED until the breakdown voltage is exceeded. Higher negative voltages will force a current through the *pn* junction. This breakdown voltage depends on the doping of the *pn* junction and the type of LED materials technology used. Typically, the reverse breakdown voltage is greater than 10 V. If the current is not externally limited, the *pn* junction can be damaged by localized heating within the diode junction.

Most LED drive schemes use a resistor is series with the LED lamp (or string of LED lamps) as shown in Figure 9.1.9. The resistor sets the current to the LED lamp (or string). Most LEDs can be modeled in the forward direction as a resistor in series with a constant voltage, or by the equation described below:

$$V_F = V_D + I_F R_D$$

where V_F = voltage applied to the LED
V_D = turn-on voltage of the LED
R_D = reciprocal of the slope of the I-V characteristics
I_F = current flowing through the LED

For most LEDs, V_D is in the range of 1.7 to 3.0 V, depending on the color of light generated. R_D typically varies from 1 to 20 Ω, depending on the LED material used.

Then, the current through the LED can be calculated as follows:

$$\begin{aligned} I_F &= (V_S - V_{\text{SWITCH}} - nV_F)/R \\ &= (V_S - V_{\text{SWITCH}} - nV_D)/(R + nR_D) \end{aligned}$$

where I_F = current flowing through the LED
V_S = power supply voltage
V_{SWITCH} = voltage across transistor switch
V_F = voltage across the LED
R = external resistance
n = number of LED lamps in series

For most LEDs of a given materials technology, V_D is generally very well controlled. This means that the current through the circuit is determined primarily by R and R_D. If R is much larger than nR_D, then the current is controlled primarily by the value of the external resistance R.

LEDs can be driven by a number of other drive circuits including constant current drivers and a variety of pulsed drive circuits (see Hodapp, 1994).

Segmented Displays and Multi-indicator Applications

LED displays and individual lamps are commonly used as information or status indication devices. These products are typically categorized as intelligent or nonintelligent. An intelligent LED display is one that has an

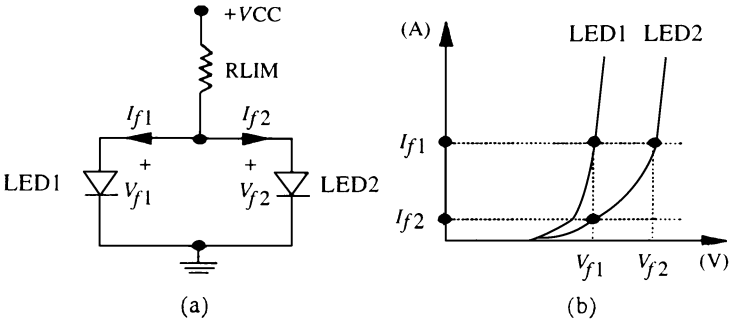

FIGURE 9.1.10 Application circuit: (a) two LEDs in parallel share one current limiting resistor; (b) forward voltage vs. forward current characteristics for the LEDs.

on-board IC integrated with the LEDs, where all the electro-optical biasing of the discrete LEDs has already been provided to the end user. The user varies the brightness of the LEDs by simply changing a combination of 1s and 0s in the control register of the IC. The active semiconductor chips have already been matched by the OEM and thus uniformity is provided. However, a nonintelligent display or individual lamp is made up of semiconductor chip(s), contact wires, and some packaging to provide mechanical stability, environmental protection, and optical lensing. These products are seven and sixteen segment displays, light bars, and discrete lamps. These nonintelligent devices require the designer to determine the electro-optical biasing configuration to achieve a desired brightness and uniformity.

There are important precautions in designing biasing circuits for nonintelligent applications. For example, in an application that requires the use of two or more LEDs of the same color, and luminous uniformity is required, it is recommended that the designer *not* place the LEDs in parallel with each other and in series with the same current limiting resistor (RLIM). Figure 9.1.10 depicts this situation. The mismatched LEDs can result in a discernible difference in brightness between the two. In this case LED 1 will appear to be brighter than LED 2 if the current ratio is greater than 2 to 1. This and other problems related to variations in the V_f versus I_f characteristics of a given LED are treated in the literature (see York, 1994).

LEDs and Light Guides

A light guide is a device designed to transport light from a light source to a point at some distance with minimal loss. Light is transmitted through a light guide by means of total internal reflection. Light guides are usually made of optical grade materials such as acrylic resin, polycarbonate, epoxies, and glass. A light guide can be used to transmit light from an LED lamp on a pc board to a front panel for use as status indication, can be used to collect and direct light to backlight an LCD display or legend, and can be used as the means to illuminate a grid pattern on a see-through window (see Evans, 1993).

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