LIGHT-EMITTING DIODES, DEVICES

Light-emitting diodes (LEDs) are *p-n*-junction devices that emit spontaneous infrared, visible, and ultraviolet radiation. LEDs are the most common compound semiconductor devices. The number of manufactured LEDs exceeds the number of all other compound semiconductor devices. This article is an introduction to the principles of LEDs including the spectral emissive characteristics and human perception of light emitted from LEDs, the efficiency of LEDs, methods to improve efficiency, and novel device concepts.

The number of applications for LEDs is growing rapidly at present. Applications include optical fiber communication, free-space communication, indicator lamps, light sources in the infrared and the visible, and automotive applications. More recently, LEDs have been used in flat panel displays, LED printers, and medical imaging applications.

High-performance light-emitting diodes will approach 100% efficiency and thus be ideal devices for converting electricity to light. These LEDs exhibit lifetimes of more than 10 years of continuous operation and will thus be extremely reliable compared with other light sources. High-volume production will allow for low-cost manufacture of LEDs. Because of these excellent characteristics, LEDs are likely to be the most important light sources of the future. Therefore, the invention of LEDs is as important as the invention of Edison's light bulb.

As background for the detailed theory of LED operation it is important to consider briefly both the fundamental interaction between light and crystalline solids and the basic concepts of current flow in semiconductors.

The interaction between light and matter has captivated scientists for the last few hundred years. During this time the understanding that colors of light correspond to specific wavelengths and energies of an electromagnetic wave emerged. And further, scientists discovered that light interacts with matter via the weakly bound electrons in the solid. The electrons in solids are restricted to characteristic allowed values of energy, unlike electrons in vacuum. For example, in semiconductors at room temperature, the outer valence electrons occupy nearly full allowed energy bands that are separated by forbidden energy "gaps" from nearly empty bands called conduction bands. The allowed and forbidden energy levels in the solid arise as a result of the bonds formed between the atoms in a solid and, in the case of a crystalline solid, these energy levels are further modified as a result of the atomic arrangement symmetry. When these electrons change their energy from conduction electron states to valence electron states they give off light with an energy (or color) that corresponds to the value of the energy "gaps" characteristic of that particular material. This process of generating light is called luminescence.

Another advantage semiconductors have in converting electricity to light is that electrons are mobile in semiconductor crystals and move under the influence of applied voltages, so that low applied voltages effectively move electrons in the material. In order to develop an understanding of electron motion in a semiconductor it is customary to describe the energy of electrons in terms of their velocity, or more precisely crystal-momentum. Typical allowed electron states have increasing energy nearly in proportion to the square of their momentum. The implications for this parabolic relation between energy and momentum, called a dispersion relation, will be discussed in more detail in the following sections.

It is physically convenient to describe the empty spaces in the nearly full valence bands by defining them as a new "particle" called a hole. A hole behaves as if it had a positive charge in response to applied electric fields but is typically less mobile than electrons in the semiconductor.

The process of generating light via recombination of injected electrons and holes is called electroluminescence. In order to inject charge for electroluminescence, it is first necessary to have a substantial supply of mobile charges. One way to achieve this sea of mobile charge is to introduce impurities in the semiconductor to produce regions rich in electrons, called *n*-type, and regions rich in holes, called *p*-type. A *p–n* junction is formed when adjacent regions are *p*- and *n*-type. Charge injection of holes and electrons takes place when a forward biased voltage is applied to the *p–n* junction. Then the injected holes and electrons recombine to give off light. A more detailed and in-depth discussion of charge injection in *p–n* junctions can be found in the article in this encyclopedia entitled DIODES.

Only certain types of semiconductors have the property that allows fundamental excitations in the material to create light rather than heat. These materials are said to have a direct band gap if the fundamental excitation can take place from the highest energy filled states to the lowest energy empty states without involving a thermal vibration of the lattice or other defect. As a result, direct gap materials have a very high internal quantum efficiency.

The most common commercial LEDs are made from III–V semiconductor compounds with direct band gaps. III–V semiconductor materials include compounds made from combinations of In, Ga, Al from the third column of the periodic table of elements and N, P, As, and Sb from the fifth column of the period table of elements. Typically, compounds formed from those smaller species such as N result in bandgaps in the UV through blue and green spectral regions, whereas larger elements such as In, As, and Sb generally result in compounds with their fundamental bandgap in the red to infrared portion of the spectrum. II–VI semiconductor compounds, those with the elements from the second and sixth column of the periodic table of elements, respectively, also typically have a direct bandgap.

RECOMBINATION AND EMISSION LINE SHAPE

The physical mechanism by which semiconductor LEDs emit light is the spontaneous recombination of electron–hole pairs and the simultaneous emission of photons. The spontaneous

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

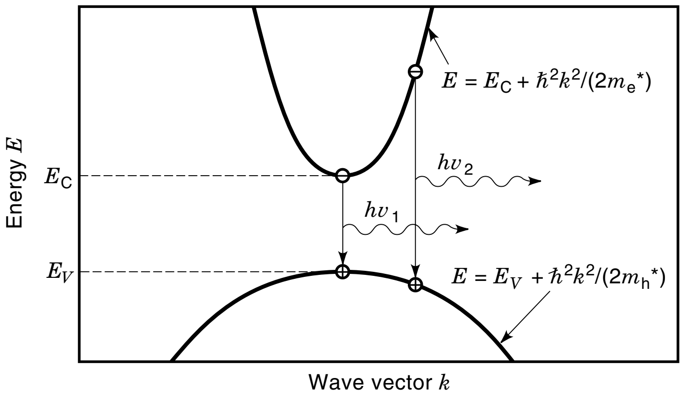

Figure 1. Parabolic electron and hole dispersion relationships showing electron–hole recombination and photon emission.

emission process is contrasted with the stimulated emission processes occurring in semiconductor lasers and superluminescent LEDs. Spontaneous recombination processes have certain characteristics which influence the optical properties of LEDs. The properties of spontaneous emission in LEDs are discussed in this section.

An electron–hole recombination process is schematically illustrated in Fig. 1. Electrons in the conduction band and holes in the valence band are assumed to have the parabolic dispersion relationships

$$E = E_C + \frac{\hbar^2k^2}{2m_e^*} \qquad \text{(for electrons)} \tag{1}$$

$$E = E_V - \frac{\hbar^2k^2}{2m_h^*} \qquad \text{(for holes)} \tag{2}$$

where m_e^* and m_h^* are the electron and hole effective masses, $\hbar$ is Planck's constant divided by 2π, k is the carrier wave number, and E_V and E_C are the valence and conduction band edges, respectively.

The requirement of energy and momentum conservation leads to further insight into the radiative recombination mechanism. The Boltzmann distribution states that electrons and holes have an average kinetic energy kT. Energy conservation requires the photon energy be given by the difference between electron energy E_e and hole energy E_h,

$$h\nu = E_e - E_h \approx E_g \tag{3}$$

The photon energy is approximately equal to the bandgap energy E_g if the thermal energy is small compared to the bandgap energy $kT \ll E_g$. Thus the desired emission wavelength of an LED is attained by choosing a semiconductor material with an appropriate band-gap energy. For example, GaAs has a band-gap energy of 1.4 eV at room temperature, and thus GaAs LEDs emit at the infrared wavelength of 870 nm. GaP has an energy gap of 2.3 eV, and LEDs made with GaP emit at the visible wavelength of 560 nm.

In order to better understand the selection rule conserving momentum in electron–hole recombination, it is helpful to compare the average carrier momentum with the photon momentum. A carrier with kinetic energy kT and effective mass m^* has momentum

$$p = m^*v = \sqrt{2m^*(1/2)m^*v^2} = \sqrt{2m^*kT} \tag{4}$$

The momentum of a photon with energy E_g can be derived from the de Broglie relationship

$$p = \hbar k = \frac{h\nu}{c} = \frac{E_g}{c} \tag{5}$$

Calculation of the carrier momentum (using Eq. 4) and the photon momentum (using Eq. 5) shows that the carrier momentum is orders of magnitude larger than the photon momentum. Therefore the electron momentum cannot change significantly during the transition from the conduction to the valence band. Therefore the transitions are "vertical" as shown in Fig. 1, that is, electrons recombine only with holes that have the same momentum or k value.

Using the requirement that electron and hole moments are the same, the photon energy can be written as the *joint dispersion relationship*

$$h\nu = E_C + \frac{\hbar^2k^2}{2m_e^*} - E_V + \frac{\hbar^2k^2}{2m_h^*} = E_g + \frac{\hbar^2k^2}{2m_r^*} \tag{6}$$

where m_r^* is the reduced mass given by

$$\frac{1}{m_r^*} = \frac{1}{m_e^*} + \frac{1}{m_h^*} \tag{7}$$

Using the joint dispersion relationship, the joint density of states can be calculated and one obtains

$$\rho(E) = \frac{1}{2\pi^2}\left(\frac{2m_r^*}{\hbar^2}\right)^{3/2}\sqrt{E - E_g} \tag{8}$$

The distribution of carriers in the allowed bands is given by the Fermi–Dirac distribution, which can be approximated by the Boltzmann distribution,

$$f_B(E) = e^{-E/(kT)} \tag{9}$$

The *emission intensity* as a function of energy is proportional to the product of Eqs. (8) and (9):

$$I(E) \propto \sqrt{E - E_g}\, e^{-E/(kT)} \tag{10}$$

The line shape of an LED, as given by Eq. (10), is shown in Fig. 2. The maximum emission intensity occurs at

$$E = E_g + \frac{1}{2}kT \tag{11}$$

The full width at half maximum of the emission is given by

$$\Delta E = 1.8\,kT \tag{12}$$

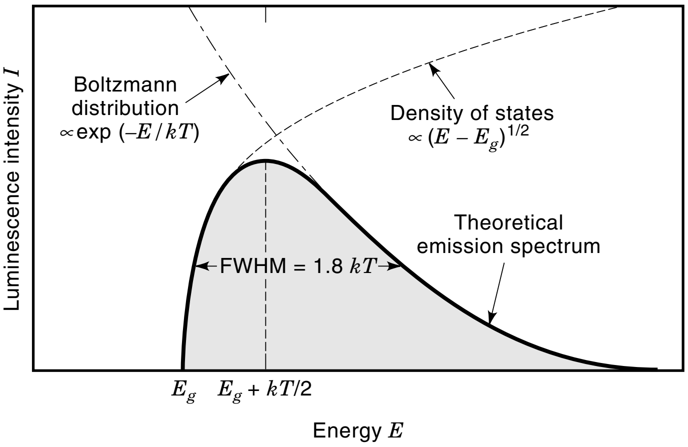

Figure 2. Theoretical emission spectrum of an LED.

For example the theoretical room temperature line width of a GaAs LED emitting at 870 nm is $\Delta E = 46$ meV or $\Delta\lambda = 28$ nm.

The spectral line width of LED emission is important in several respects. First, the line width of an LED emitting in the visible is relatively narrow compared with the range of the entire visible spectrum. The red LED emission is particularly narrow as compared to the red color range perception of the human eye. For example, *red* colors range in wavelength from 630 nm to 730 nm, which is much wider than the typical emission spectrum of an LED. Therefore, LED emission is perceived by the human eye as *monochromatic.* This characteristic is important for display applications and will be discussed further as it relates to the chromaticity diagram.

Second, when LEDs are used for fiber optic communications, the spectral width is a crucial parameter. Optical fibers are dispersive, which leads to a range of propagative velocities for an LED light pulse consisting of a range of wavelengths. The material dispersion in optical fibers puts limitations on the bit "*rate* × *distance product*" achievable with LEDs.

The spontaneous lifetime of carriers in LEDs in direct-gap semiconductors is on the order of 1 ns to 100 ns depending on the active region's doping concentration and the material's quality. Thus modulation speeds up to 1 Gbit/s are attainable with LEDs that have a highly doped active region.

EFFICIENCY AND BRIGHTNESS OF LEDs

There are several figures of merit for LEDs including internal efficiency, external efficiency, power efficiency, brightness, and luminosity. Depending on the application, different figures of merit are relevant. For example, the brightness of an LED is important for communication LEDs. The luminosity is relevant for visible LEDs observed by the human eye. The different figures of merit are discussed below.

The *internal quantum efficiency* η_{int} of an LED is defined as the ratio of the number of light quanta (photons) emitted by the active region to the number of charge quanta (electrons) injected into the active region:

$$\eta_{\text{int}} = \frac{\text{number of internally emitted photons}}{\text{number of injected electrons}} \tag{13}$$

A perfect direct-gap semiconductor has an internal quantum efficiency of unity (100%). However, native defects, dislocations, and deep-level impurities reduce η_{int} to lower values because of Shockley–Read recombination processes. In the 1960s and 1970s, typical internal efficiencies of GaAs were less than 1%, at most a few percent (1). This value has increased significantly during the last 15 years, and values exceeding 99% have been reported for OMVPE-grown GaAs (2,3). Clearly all design and growth parameters must be optimized to achieve such high efficiencies.

The *external quantum efficiency* of semiconductors is defined as the ratio of the number of photons emitted from the LED into free space to the number of electrons injected into the active region:

$$\eta_{\text{ext}} = \frac{\text{number of externally emitted photons}}{\text{number of injected electrons}} \tag{14}$$

The highest external efficiency of commercial LEDs exceeds 50% (see, for example, Ref. 4).

The internal and the external efficiency can be very different, that is, photons emitted by the active region may not escape into free space because of reabsorption or total internal reflection at the semiconductor surface. The probability that a photon emitted by the active region leaves the semiconductor is the *escape probability* or *extraction efficiency.* It is the ratio of the external to the internal quantum efficiency;

$$\text{Extraction efficiency} = \eta_{\text{ext}}/\eta_{\text{int}} \tag{15}$$

As discussed later, the extraction efficiency depends strongly on the device's geometry.

For optical fiber applications, the brightness, that is, the optical power emitted per unit solid angle, is more important than the total power because the light needs to be coupled into the small core of an optical fiber. The *brightness efficiency* is defined as

$$\eta_{\text{brightness}} = \frac{\dfrac{P_{\text{opt}}}{\Omega}}{I} \tag{16}$$

where P_{opt} is the optical power emitted into the solid angle Ω and I is the injection current of the device. The brightness efficiency is used to calculate the power that can be coupled into a fiber.

The *power efficiency,* also called the *wall-plug efficiency,* is the ratio of the optical LED output power to the electrical input power. It is related to the external quantum efficiency by

$$\eta_{\text{power}} = \frac{P_{\text{opt}}}{VI} = \eta_{\text{ext}} \left(\frac{hc}{\lambda}\right) \left(\frac{1}{eV}\right) \tag{17}$$

where V and I are the diode voltage and current, respectively. Then the heat power generated inside the LED is given by $VI - P_{\text{opt}}$.

HUMAN EYE SENSITIVITY

The *human eye sensitivity* is a measure of the brightness of a particular light of a certain color and power as perceived by the average person. The human eye sensitivity is shown as a function of wavelength in Fig. 3. The figure reveals that the human eye is sensitive to light in the range 390 nm to 750 nm, and the highest sensitivity is around 500 nm to 600 nm, that is, in the green, yellow, and amber part of the spectrum. Because of the high sensitivity of the human eye, these wavelengths are preferred for low-power, high-intensity signs. A frequently used color for signs along highways is amber. Low power consumption and high intensity of the signs is important because they are usually powered by batteries and located outdoors (5).

A quantitative measure for the LED brightness perceived by humans is the *luminosity* which is measured in *lumens* (lm). The luminosity used exclusively for LEDs emitting in the visible wavelength range, is a measure of the subjective intensity experienced by humans. The sensitivity of the human eye peaks in the green at $\lambda = 555$ nm. The *relative eye sensitivity* $V(\lambda)$ is defined as unity at the highest sensitivity wavelength, that is, $V(\lambda = 555\text{ nm}) = 1$ lm/W. The luminosity and the relative eye sensitivity are related by

$$L = 680\,V(\lambda)\,P_{\text{opt}} \tag{18}$$

where P_{opt} is the optical power emitted by the light source. Thus an LED that emits 1 mW at 555 nm has a luminosity of 0.680 lm. The *luminous efficiency* is obtained by dividing the luminosity by the electrical input power to the LED. The unit of luminous efficiency is lm/W. Luminosity is used for LEDs emitting in the visible wavelength range, and radiometric units (mW) are used for IR and UV LEDs.

The human eye has three different receptors which are sensitive in the red, green, and blue parts of the spectrum. The chromaticity diagram shown in Fig. 4 allows expressing the colors in terms of the two parameters x and y (5). Light sources that emit *white light* are located in the center of the chromaticity diagram, as indicated in Fig. 4. White light sources include sunlight and high-temperature tungsten filament light sources. *Pure colors* are located on the perimeter of the chromaticity diagram. For example, the LEDs in Fig. 4 that emit in red, red-orange, orange, and amber emit very pure colors, that is, their emission line is narrow. In contrast, the green and blue–green LEDs shown in Fig. 4 do not emit pure colors, and therefore the points that represent them on the chromaticity diagram are removed from the perimeter of the diagram. The physical reason is that the InGaN-based LEDs do not have the material quality comparable to the other LEDs. The InGaN-based LEDs have broader emission lines, which is probably caused by compositional fluctuations (alloy broadening) of the ternary semiconductor. Therefore the optical properties of InGaN LEDs can still be improved. The blue InGaN LED shown in Fig. 4 is much closer to the perimeter of the chromaticity diagram. This LED contains less indium, and therefore it is likely to exhibit less alloy broadening, that is, it is spectrally purer than the LEDs with a greater mole fraction of indium.

Unusually broad GaN luminescence spectra were published by Iliopolos and Moustakis (6). The spectra were more than a factor of two wider than state-of-the-art material. Such broad linewidths are indicative of low-quality material with high defect and impurity concentrations. The authors found compensation ratios as high as and exceeding a factor of five, confirming the poor quality of their GaN.

If LEDs are used for display applications, the three LEDs emitting in the red, green, and blue should be located as close

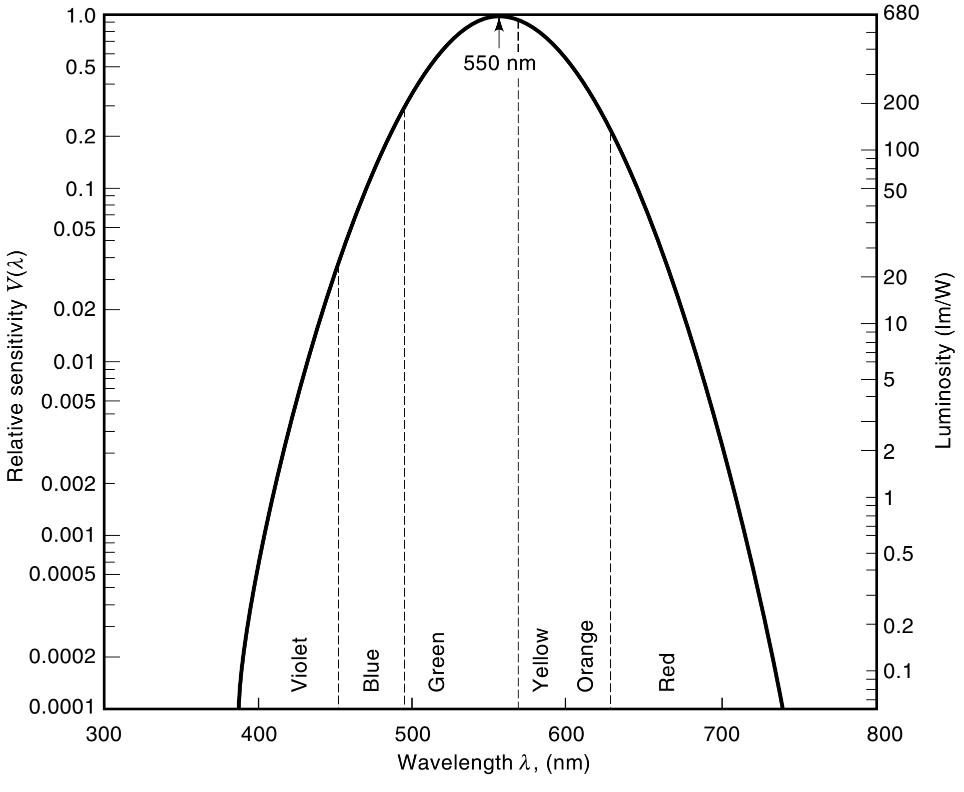

Figure 3. Relative human eye sensitivity and luminosity as defined by the Comission Internationale de l'Eclairage (CIE) for normal photopic vision.

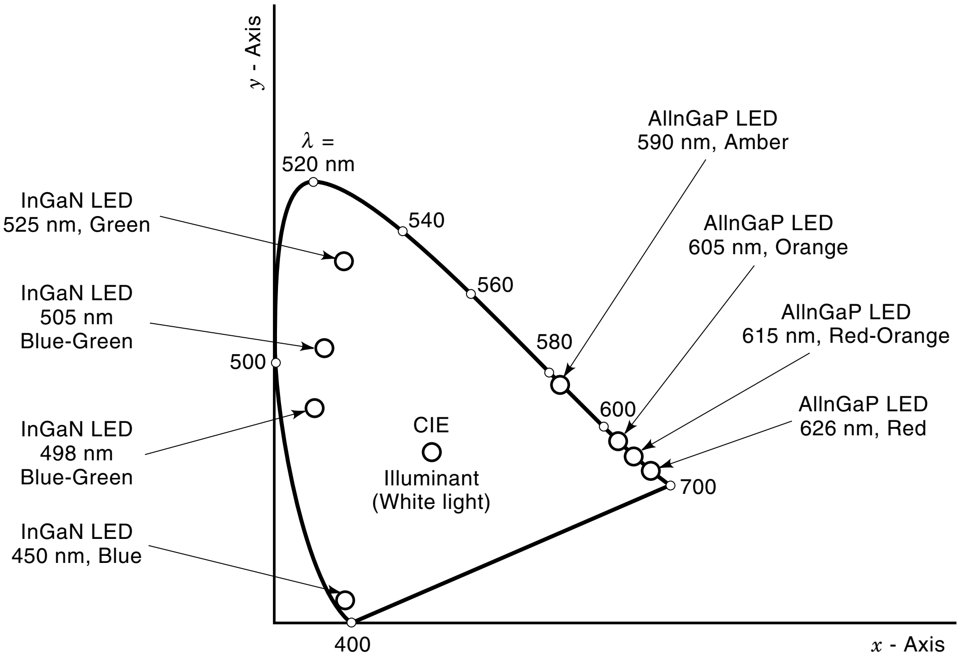

Figure 4. Chromaticity diagram as defined by the Comission Internationale de l'Eclairage (CIE) describing all visible colors by the parameters x and y. Saturated colors, that is, pure colors, are located on the perimeter of the chromaticity diagram. White light is located in the center of the diagram. The locations of several LEDs are also shown (after Ref. 5).

as possible to the perimeter of the chromaticity diagram so that the displayed picture attains the greatest brilliance and can use the millions of colors which the human eye can differentiate.

LIGHT-ESCAPE PROBLEM

The device structure and fabrication process of semiconductor LEDs strongly influence the escape probability of photons. To illustrate this fact, consider a point-like active region located below a planar semiconductor–air interface. Consider further that the active region emits photons in an isotropic pattern. Such a configuration is shown in Fig. 5. Light emitted along the normal direction with respect to the semiconductor–air interface can escape from the semiconductor and the transmittance is given by the Fresnel coefficients. If the angle of the light incident on the semiconductor surface exceeds the angle of total internal reflection, then the light is reflected back into the semiconductor. The solid angle of the light-escape cone is given by

$$\Omega = 2\pi(1 - \cos\Theta_c) \tag{19}$$

where Θ_c = arc $\sin(n_2/n_1)$ is the critical angle of total internal reflection and n_1 and n_2 are the refractive indices of the semiconductor and air, respectively. For example, one obtains $\Theta_c = 16.6°$ for GaAs. The light-escape problem strongly reduces the light output for materials of high refractive index, such as GaAs. (The light-escape problem is less relevant in LEDs made from organic polymers. Such polymers have low refractive indexes ($n \approx 1.5$), thus allowing most light generated inside a polymer LED to be transmitted through the polymer–air interface.)

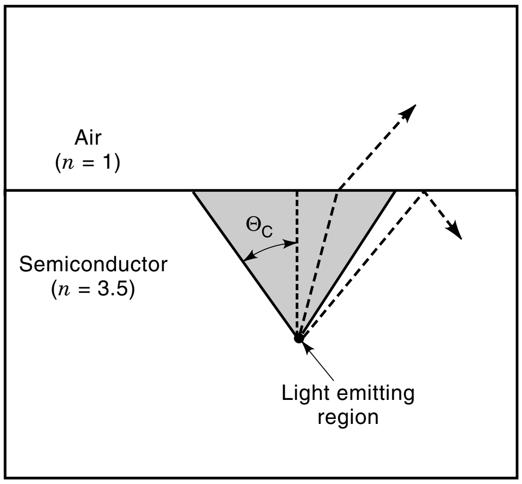

Figure 5. Light-escape cone defined by the angle of total internal reflection of the semiconductor–air interface.

The total fraction of light that can escape from the semiconductor can be calculated by dividing Eq. (19) by the solid angle of the unit sphere (4 π):

$$\frac{\Omega}{4\pi} = \frac{1}{2}\left[1 - \cos\left(\arcsin\frac{n_2}{n_1}\right)\right] \tag{20}$$

If the semiconductor is not coated with an optical antireflective layer, Fresnel reflection losses need to be taken into account. For large refractive index differences ($n_1 \gg n_2$), the angle of incidence at the semiconductor–air interface is near the surface normal. Including the Fresnel coefficients for normal incidence yields

$$\frac{\Omega}{4\pi} = \frac{1}{2}\left[1 - \cos\left(\arcsin\frac{n_2}{n_1}\right)\right]\left[1 - \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2}\right] \tag{21}$$

For semiconductors with a large refractive index (e.g., GaAs), it is $n_1 \gg n_2$. Using this inequality and neglecting Fresnel losses, Eq. (20) can be approximated by

$$\frac{\Omega}{4\pi} \approx \frac{1}{4}\left(\frac{n_2}{n_1}\right)^2 \tag{22}$$

This equation shows that a large difference in refractive index is an impediment to realizing high-efficiency LEDs. As an example, we consider a point-like light source located below a planar GaAs surface and calculate the fraction of light that can escape from the semiconductor. Using $n_1 = 3.5$ and $n_2 = 1$, Eq. (20) yields $\Omega/(4\pi) \approx 2\%$. This result illustrates a fundamental problem of LEDs made from materials of high refractive index, namely, the difficulty of coupling the light out of the semiconductor. Photons reflected back into the semiconductor are likely to be lost for external emission because of reabsorptive processes, for example, in the substrate. The inherently high defect density of substrates makes nonradiative recombination the dominant recombination process in substrate materials, that is, reabsorption of photons in the substrate decreases the external quantum efficiency.

The ideal LED structure consists of a point-like active region in the center of a spherically shaped semiconductor coated with an antireflective coating. This geometry ensures that light emitted from the active region would strike the semiconductor surface at an angle of 90°, resulting in the absence of total internal reflective losses (7). However, such spherical LEDs are incompatible with today's planar semiconductor fabrication technology.

LED STRUCTURES AND FABRICATION

There are a number of methods for improving the escape probability beyond the mere 2% calculated previously. These methods include (1) multiple escape cones, (2) mesa structures, (3) transparent epitaxial layers and substrates, (4) lensed structures, (5) reflective contacts, (6) transparent contacts, (7) antireflective coatings, and (8) epoxy domes. These structures and fabrication methods are discussed in detail here.

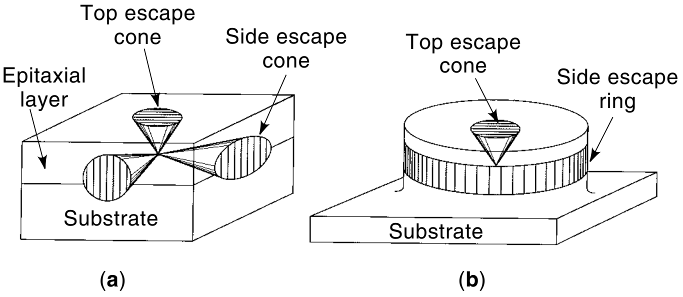

Figure 6. (a) Light-escape cones of a cubicle-shaped LED. (b) Top light-escape cone and side escape ring of a cylindrical LED.

1. *Multiple escape cones* allow more efficient extraction of light from a high index semiconductor. The principle of multiple escape cones is illustrated in Fig. 6(a) which shows a cubicle-shaped LED with a point-like light-emitting region in the center of the epitaxial layer. Light escapes through cones directed toward the top, four sides, and the substrate. Three of the six cones are shown in Fig. 6(a). The escape probability is increased by a factor of six compared to a planar LED.
2. *Mesa-etched* structures, shown in Fig. 6(b), further increase the light-escape probability. It is evident from geometric optics that a cylindrical mesa has the optimum shape. For such a circular mesa, the four discrete escape cones are merged into a single escape ring, shown in Fig. 6(b). Further improvement results if a hemispherical structure is used. The fabrication of hemispherical structures by a photochemical etching processes was reported by Ostermeyer et al. (8).
3. *Transparent epitaxial layers* and *transparent substrates* reduce reabsorption losses in the epitaxial layers and the substrate. For emission wavelengths $\lambda < 870$ nm (e.g., LEDs with $Al_xGa_{1-x}As$, $(AlGa)_{0.5}In_{0.5}P$ or GaAsP active regions), the emitted light is reabsorbed in GaAs buffer layers and in the GaAs substrate. Because of the low radiative efficiency of substrates, absorbed photons are not reemitted.

   Transparency or near-transparency of the epitaxial layers is achieved by avoiding the growth of semiconductors with a band gap lower than the active light-emitting region or by keeping the absorbing layers very thin. Transparent substrates can be also obtained by removing the absorbing GaAs substrates. In this process, which is also called *epitaxial liftoff,* the substrate is removed, and the fragile epitaxial film is subsequently bonded to another substrate by means of Van der Waals bonds (9,10). GaP, glass, and sapphire are suitable transparent substrate materials for GaAs LEDs.

   Another alternative for achieving transparent substrates is growing very thick layers of GaP on the GaAs substrate and subsequently removing the original GaAs substrate (11). If the GaP is sufficiently thick (>100 μm), it has enough mechanical stability to serve as a transparent substrate. The capability of high growth rates make vapor-phase epitaxy (VPE) a suitable technique for growing thick GaP.
4. *Lenses* were employed to increase the brightness of communication LEDs (8). The lenses were made by illuminating the sample, located in a photosensitive etching solution, with a certain intensity pattern. Lenses on GaAs LEDs have also been used to generate collimated beams for free-space optical interconnects (12).
5. *Reflective contacts* have been used to reflect the light emanating from the active region to the direction of interest. For a 100% reflective mirror, a doubling of the LED brightness can be achieved. Two types of reflectors have been employed, namely, metallic reflectors (13) and distributed Bragg reflectors (14).
6. *Transparent ohmic contacts* can be made from semiconducting oxides, in particular InSnO and CdSnO (15). Absorption in metallic contacts is thereby avoided. However, even semiconducting oxides do have some absorption, although the absorption is small.
7. *Antireflective* (*AR*) *coatings* are used on communication LEDs to reduce Fresnel losses. For normal incidence, the reflectivity of an uncoated GaAs–air interface is ap-

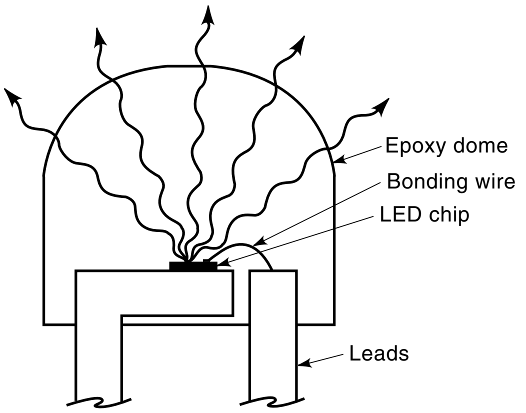

Figure 7. Typical LED structure with a hemispherical epoxy dome.

proximately 30%. Antireflective coatings $\lambda/4$ thick and refractive index $n_{\mathrm{AR}} = (n_{\mathrm{GaAs}})^{1/2}$ reduce the reflectivity to zero at the wavelength of interest.

8. *Epoxy domes,* as shown in Fig. 7, are used on all commercial LEDs. The epoxy refractive index ($n \approx 1.5$) reduces the index contrast and, according to Eq. (22), increases the size of the light-escape cone. Total internal reflection at the epoxy–air interface does not occur because of the hemispherical shape of the epoxy dome and the resulting perpendicular angle of incidence at the epoxy–air interface.

Surface-emitting and edge-emitting LEDs are employed for *communication applications. Surface-emitting LEDs* (13) have diameters of the light-emitting area ranging from 20 μm to 50 μm. These diameters are suited to efficiently couple light into the core of multimode optical fibers whose typical core diameters are 62.5 μm. Single-mode fibers whose core diameters are 5 μm require much smaller light-emitting regions. Using edge-emitting LEDs is advantageous for single-mode fibers.

The structure of *edge-emitting LEDs* (13) is similar to that of edge-emitting semiconductor lasers including the double heterostructure active region which serves as a waveguide. However, edge-emitting LEDs lack at least one of the two reflectors of a Fabry–Perot cavity laser. The lack of a cavity prevents edge-emitting LEDs from lasing. When the devices are driven to transparency, the heterostructures guide the light emitted into waveguiding modes all the way to the LED edge. Thus the light intensity is proportional to the length of the device. The size of the light-emitting area at the LED edge is given by the thickness and width of the waveguide. These dimensions can be very small (e.g., 0.5 μm × 5 μm). The high intensity and the small emissive area of edge-emitting LEDs make them well suited for efficiently coupling the output light into single-mode fibers.

Super-luminescent LEDs (13), also called *superradiant LEDs,* are pumped beyond transparency and use stimulated emission and optical gain to further increase the light intensity. The light intensity increases *superlinearly* with increasing injection current because of stimulated emissive processes. Only the absence of reflectors prevents superluminescent LEDs from lasing. The advantages of superluminescent LEDs are their simplicity of fabrication and the higher reliability compared to lasers. However, superluminescent LEDs, just as lasers, are more temperature-sensitive than regular LEDs.

NOVEL DEVICE CONCEPTS

During recent years, many new LED device concepts have been demonstrated or proposed which can significantly increase LED performance. Several new concepts are discussed here, namely the resonant-cavity LED, the photon-recycling LED, the single-mode LED, and a concept based on photonic crystals.

Resonant-cavity light-emitting diodes (RCLEDs) have more than 10 times the brightness achievable with conventional LEDs (16–18). RCLEDs employ enhanced spontaneous emission achievable by placing the active region into a resonant microcavity. The structure of a GaInAs/GaAs/AlGaAs RCLED, shown in Fig. 8, consists of a GaInAs/GaAs strained pseudomorphic quantum-well active region located between an Ag reflector and an AlAs/GaAs distributed Bragg reflector (DBR). These two reflectors define the optical cavity of the device. The fundamental optical mode of the cavity is in resonance with the emissive wavelength of the active region. In the case of resonance, the spontaneous emission along the axis of the cavity is strongly enhanced (17). RCLEDs have been realized in the wavelength range 850–950 nm (16,17,19–23) and in the visible wavelength range (24,25).

The light power versus current (LI) characteristic of an RCLED is shown in Fig. 9(a) (17). Also shown are the typical range of LI curves for the best conventional LEDs (shaded area) and the LI curve of an idealized theoretical device denoted as the *ideal isotropic emitter.* It is assumed that this planar device has an isotropically emitting, 100% internal quantum efficiency active region. Comparison reveals that the intensity of the RCLED exceeds the intensity of the ideal isotropic emitter and of the best conventional LEDs. (The ODL50 is a commercial Lucent data-link product.) The enhanced spontaneous emission along the cavity axis makes the RCLED well suited for communication applications (23).

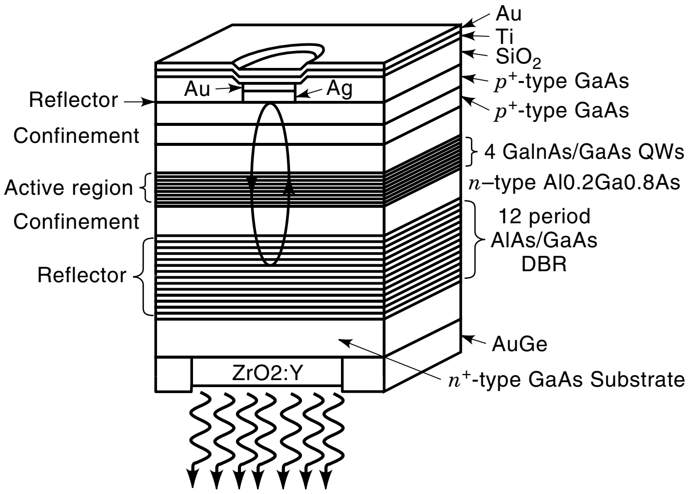

Figure 8. Structure of a GaAs-based resonant-cavity light-emitting diode (RCLED).

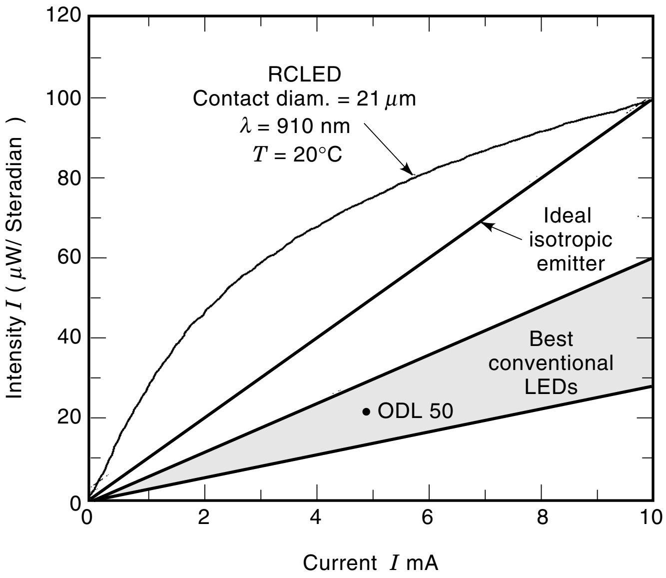

Figure 9. Light intensity versus current of an RCLED, of the *ideal isotropic emitter,* and of the best conventional LEDs.

Quantum efficiencies as high as 16% have been achieved with RCLEDs in display applications (20).

Photon-recycling LEDs employ photon recycling to increase the LED efficiency. The physical principle of the device is shown in Fig. 10. Photons emitted into the escape cone are emitted into free space. All other photons are reflected back into the semiconductor and, if the semiconductor does not have any optical losses, are eventually reabsorbed by the active region. If the internal efficiency of the active material is 100%, all reabsorbed photons eventually escape from the semiconductor. Figure 10 schematically shows the principle of photon recycling. Photons either escape after the first emission process or after one or several total internal reflective/absorptive/reemissive ("recycling") processes. The physics of photon recycling in optoelectronic devices was first discussed by Stern and Woodall (26). Schnitzer et al. (2,3) showed that high external quantum efficiencies are achieved by photon recycling in optically pumped structures. Numai et al. (27) used Au-coated semiconductor micropillars to enhance photon recycling in vertical-cavity structures.

Single-mode LEDs are based on an optical resonator structure which has only one single optical mode resonating with the optically active medium. In this case, the entire radiation couples to that particular optical mode. If such a device would have 100% internal quantum efficiency, the L vs. I characteristic of the device would be indistinguishable from that of a laser with a zero threshold current (28). Therefore, the device has also been termed *zero-threshold laser* (27). The simplest structure of a single-mode LED would be a semiconductor micropillar, whose cavity quality factor Q could be enhanced by highly reflective coatings. Even though the zero-threshold laser would have a laser-like L vs. I characteristic, the noise properties would be similar to that of an LED.

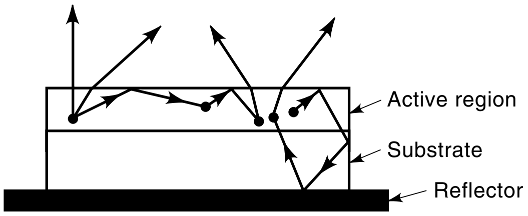

Figure 10. Illustration of photon-recycling processes consisting of emission, total internal reflection, reabsorption, and reemission.

The single-mode LED is inherently a low-current device. A low optical mode density implies that the total volume of the device is very small (i.e., volume $\approx \lambda^3$). Because the current density in a cw operated device is limited to the kA/cm^2 range (e.g., 20 kA/cm^2), the maximum current injected into the device will also be limited. Furthermore, because of the small size of the device, problems associated with the high surface recombination velocity of GaAs need to be addressed.

Recently, Fan et al. (29) proposed a new *photonic-bandgap structure* with very high extraction efficiency. A thin slab of a two-dimensional photonic crystal drastically alters the radiation pattern of spontaneous emission. All guided modes of the thin slab were eliminated at the transition frequency so that the spontaneous emission is entirely coupled into free-space modes and results in greatly enhanced extraction efficiency. This and the other previously mentioned structures will be used in future LED structures that will be the most efficient light sources available.

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