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Light Emitting Diodes (LEDs)

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Overview

LEDs have been around for more than 30 years. They have found application in nearly every consumer-electronic device:
TV sets, VCRs, telephones, car electronics, and many others. They are used in fiber-optic communications, mostly because of their small size and long life. However, their low intensity, poor beam focus, low-modulation bandwidth, and incoherent radiation—in comparison with laser diodes, that is—restrict their usage to a specific sector of communications technology: relatively short-distance and low-bandwidth networks. Local area networks are the largest application area for transmitters based on LEDs. Since fiber-optic LANs is a booming technology today, LEDs are in wide use. Thus, we need to take a thorough look at light-emitting diodes.

Light Radiation by a Semiconductor

Energy-band diagram

You are probably familiar with semiconductor materials through your study of electronic devices such as diodes and transistors. Such background should help you to understand the workings of LEDs because an LED is, after all, *a semiconductor diode*. However, we'll discuss an LED's principle of operation on the assumption that you are unfamiliar with it or have forgotten much of what you learned some time ago.

First, you'll recall from Chapter 2 that all materials consist of atoms, which are nuclei surrounded by electrons rotating at stationary orbits. Each orbit corresponds to a certain energy value; thus, these atoms may possess only discrete energy values. We represent this idea through an energy-level diagram (Figure 2.8).

Semiconductors are solid-state materials consisting of tightly packed atoms. Atoms, in turn, are bonded by interatomic forces into a lattice structure. Each atom includes many electrons, but a material's properties are determined by its outermost electrons.

The important fact is that in semiconductors (and in solids in general) the possible energy levels are still discrete, but they are so close to one another that we depict them as an energy band rather than a set of separate levels. We think of an energy band as a wide, *continuous* region of energy, but if you had a magic magnifier to look at this band closely, you would see the discrete energy levels that make up the band. Figure 9.1(a) shows this. It should be noted that the vertical axis in Figure 9.1 represents an electron's energy, while the horizontal axis serves merely as a visual aid.

In semiconductors we distinguish two *energy bands: valence* (lower, meaning less energy) and *conduction* (upper, meaning higher energy). They are separated by an *energy gap*, E_g, where no energy levels (that is, no electrons) are allowed. In other words, electrons can be either at the valence band or at the conduction band but cannot be in between—at the energy gap.

An energy band consists of allowed, or possible, energy levels, which means the electrons may occupy them.

When the absolute temperature is zero and no external electric field is applied, all electrons are concentrated at the valence band and there are no electrons at the conduction band. This is because none of the electrons possess enough extra energy to jump over the energy gap. But when some external energy—either through temperature or by an external electric field—is provided to the electrons at the valence band, some of them acquire enough energy to leap over the energy gap and occupy energy levels at the conduction band. We say these electrons are "excited." These excited electrons leave *holes* (positive charge carriers) at the valence band, as Figure 9.1(b) shows.

Light radiation—energy bands

Recall again our discussion in Chapter 2 of how light is radiated: When an excited electron falls from an upper energy level to a lower one, it releases a quantum of energy called a photon. The relationship among ΔE_l, E_p, and λ. is given by: $\Delta E = E_p = hf = hc/\lambda$, where ΔE is the difference between the two energy levels, E_p is the photon's energy, and λ is the wavelength.

The same idea holds for semiconductors. If an excited electron falls from a conduction band to a valence band, it releases a photon whose energy, E_p, is equal to or greater than the energy gap, E_g. Since not just one but many energy levels at the conduction and valence bands can participate in the radiation process, many close wavelengths, λ_i, can be radiated. This is why we said that $E_p \geq E_g$, which has another form: $\lambda_i \leq hc/E_g$. (If you measure E_g in electron volts, eV, and λ in nanometers, nm, then λ_i 1248/E_g—see Formula 2.8.) The result of this multiwavelength radiation is a wide spectral width, $\Delta\lambda$, of light emitted by the semiconductor. This explanation is depicted in Figure 9.2.

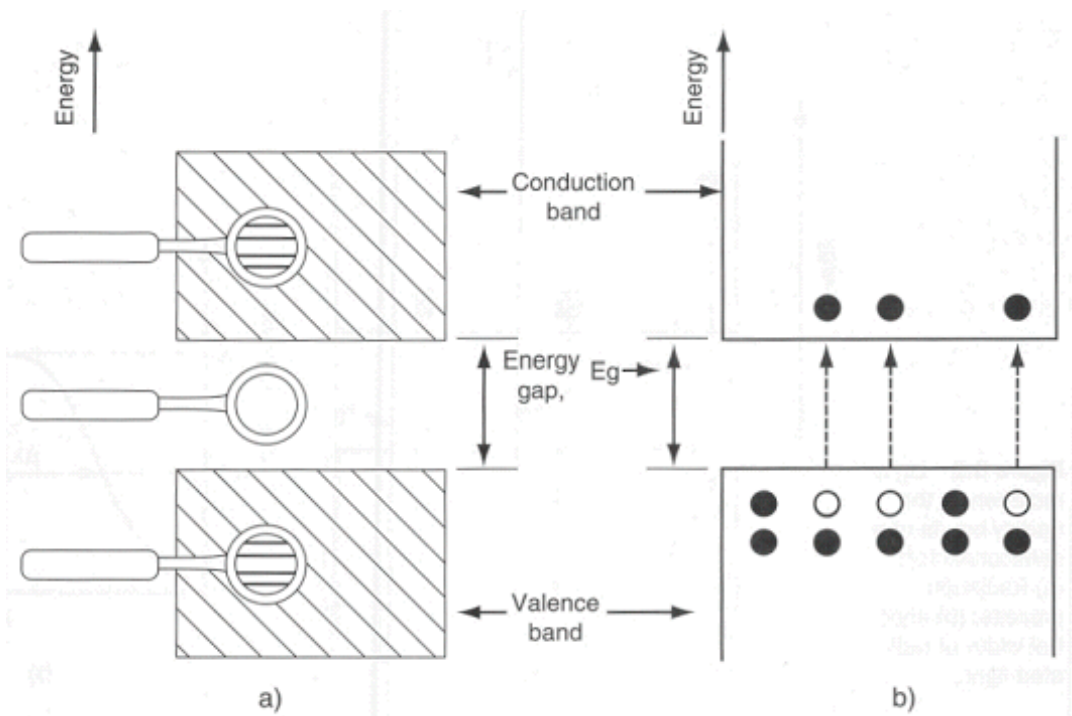

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Figure 9.1 Energy bands of an intrinsic semiconductor: (a) General representation; (b) for finite temperature.

Thus, to make a semiconductor radiate, it is necessary to excite a significant number of electrons at the conduction band. This can be done by providing external energy to the material. The most suitable form of this external energy is electric current flowing through a semiconductor.

Light radiation—The p-n junction

We can insert atoms of another material into a semiconductor so that either a majority of electrons (negative charge carriers) or a majority of holes (positive charge carriers) will be created. The former semiconductor is called the *n* type, where *n* stands for negative, and the latter is called the *p* type, where *p* stands for positive. We call these *n* type and *p* type *doped*, or *extrinsic*, semiconductors in contrast to a *pure*, or *intrinsic*, semiconductor, which consists of atoms of one material. The inserted foreign materials are called *dopants*. (Sound familiar? See Section 7.1, where the word *dopant* was used in the same sense but there applied to a fiber-fabrication process.)

When an *n*-type semiconductor is brought into physical contact with a *p* type, a *p-n* junction is created. At the boundary of the junction, electrons from the *n* side diffuse to the *p* side and recombine with holes and, at the same time, holes from the *p* side diffuse to the *n* side and recom bine with electrons. Thus, a finite width zone, called the *depletion region*, forms. Here, there are no mobile electrons or holes. Since positive ions at the *n* side and negative ions at the *p* side within the depletion region are left without electrons or holes, these ions create an internal electric field called a *contact potential*. We characterize this field by *depletion voltage*, V_D. Figure 9.3(a) illustrates this explanation.

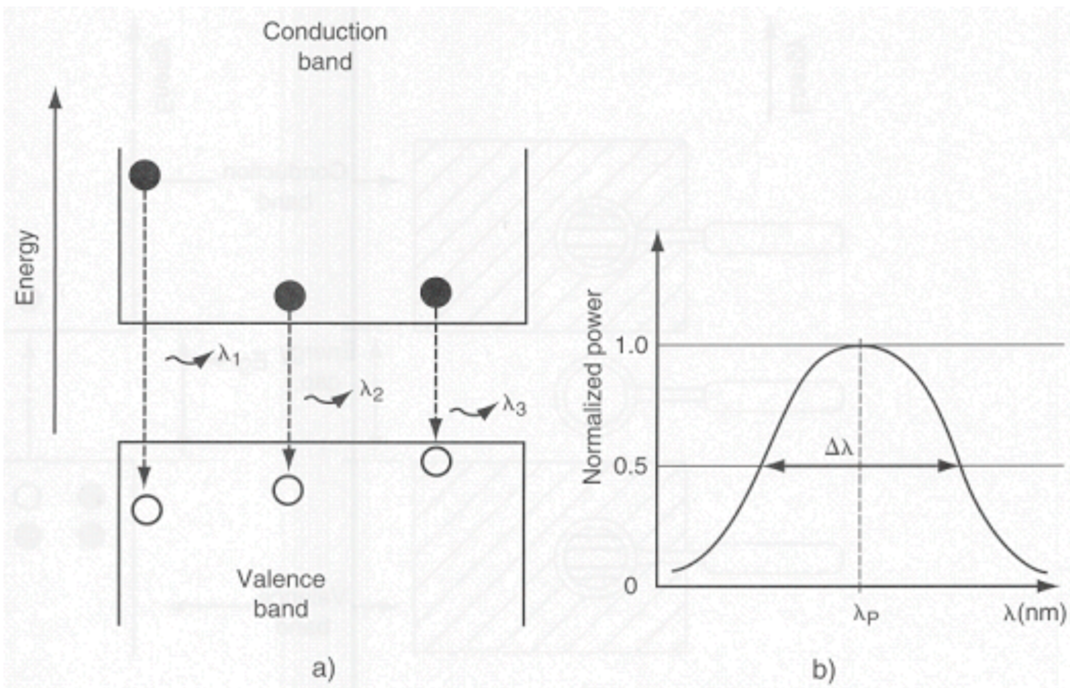

Figure 9.2 Light radiation by the energy bands of a semiconductor: (a) Radiation process; (b) spectral width of radiated light.

The most important point to keep in mind is this: *An electron-hole recombination releases a quantum of energy—a photon*. In other words, to make a semiconductor radiate, it is necessary to sustain electron-hole recombinations. But the depletion voltage prevents electrons and holes from penetrating into a depletion region; therefore, external energy must be supplied to overcome this voltage barrier. This external voltage, called *forward biasing voltage*, V, is shown in Figure 9.3(b). Obviously, V must be greater than V_D.

To achieve permanent light radiation, the following dynamic process must occur: Mobile electrons from the *n* side, attracted by the positive terminal of V, enter the depletion region. Simultaneously, mobile holes from the *p* side, attracted by the negative terminal of V, enter the same depletion region. Electron-hole recombinations within a depletion region produce light. Electric charges return through a biasing circuit.

(*Note:* In semiconductors, electrons are much more mobile than holes. This is why, when a dynamic process is described, it is customary to refer to electrons entering the active region and to ignore the movement of the holes. But holes are present even though they aren't mentioned explicitly and, again, only the electron-hole recombination produces light.)

LED: Principle of action

A light-emitting diode, LED, is a semiconductor *diode* made by creation of a junction of *n*-type and *p*-type materials. Thus, the principle of an LED's action works precisely the same way that we described the creation of permanent light radiation: The forward-biasing voltage, V, causes electrons and holes to enter the depletion region and recombine (Figure 9.3[b]). Alternatively, we can say that the external energy provided by V excites electrons at the conduction band. From there, they fall to the valence band and recombine with holes (Figure 9.2[a]). Whatever point of view you prefer, the net result is light radiation by a semiconductor diode.

This concept is displayed by the circuit of an LED (Figure 9.4[a]). If you are familiar with a semiconductor forward-biased diode, you will immediately recognize this circuit.

In fact, if you are at all familiar with electronics, you may even say, "Wait a minute. Electron-hole recombination is the process that occurs in regular diodes and transistors too. What's the difference between an LED and a regular diode?" The difference is that in a regular diode these recombinations release energy in the thermal—rather than the visible—portion of the spectrum. This is why these electronic devices are always warm when you turn them on. In an LED, however, these recombinations result in the release of radiation in the visible, or light, part of the spectrum. We call the first type of recombination *nonradiative*, while the second type is called *radiative* recombination. In reality, both types of recombination occur in a diode, when a majority of recombinations are radiative, we have an LED.

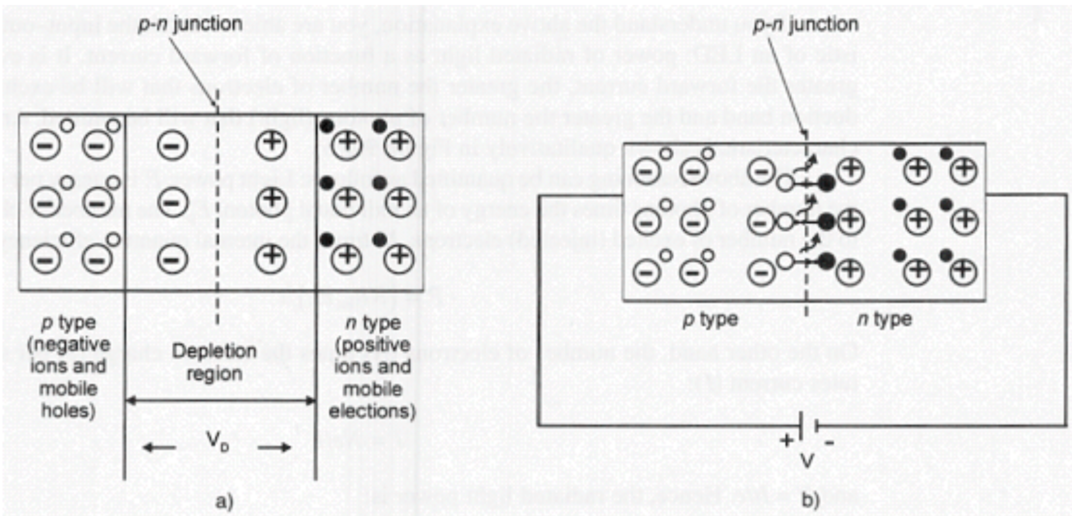

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Figure 9.3 Light radiation by the *p-n* junction of a semiconductor: (a) Depletion region and depletion voltage, V_D; (b) light radiation as the result of electron-hole recombinations.

The forward current injects electrons into the depletion region, where they recombine with holes in radiative and nonradiative ways. Thus, nonradiative recombinations take excited electrons from useful, radiative recombinations and decrease the efficiency of the process. We characterize this by the *internal quantum efficiency*, η_{int}, which shows what fraction of the total number of excited (injected) electrons produces photons.

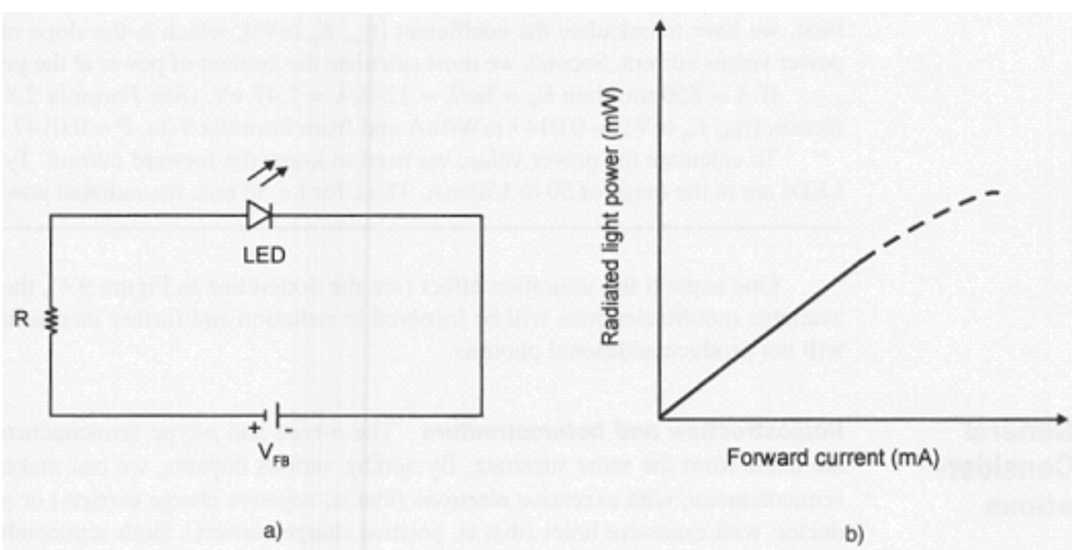

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Figure 9.4 An LED's principle of operation: (a) Electronic circuit; (b) an input-output characteristic.

If you understand the above explanation, you are able to sketch the input-output characteristic of an LED: power of radiated light as a function of forward current. It is evident that the greater the forward current, the greater the number of electrons that will be excited at the con duction band and the greater the number of photons (light) that will be emitted. An input-output characteristic is shown qualitatively in Figure 9.4(b).

The above reasoning can be quantified as follows: Light power, P, is energy per second, that is, the number of photons times the energy of an individual photon, E_p. The number of photons is equal to the number of excited (injected) electrons, N, times the internal quantum efficiency, η_{int}. Thus,

$$P = (N\eta_{int}E_P)/t \quad (9.1)$$

On the other hand, the number of electrons (N) times the electron charge (e) per second constitutes current (I):

$$I = Ne/t \quad (9.2)$$

and $N = It/e$. Hence, the radiated light power is:

$$P = (It/e)(\eta_{int}E_P)/t = [(\eta_{int}E_P)/e]I \quad (9.3)$$

Here, E_P is measured in joules. If you measure E_p, in electron volts, eV, and I in mA, then

$$P(\text{mW}) = [\eta_{int}E_p(eV)]I(\text{mA}) \quad (9.3a)$$

In sum, an LED's light power is proportional to the forward current, as Figure 9.4(b) shows.

Example 9.1.1

Problem:

What power is radiated by an LED if its quantum efficiency is 1% and the peak wavelength is 850 nm?

Solution:

The key to solving this problem is given by Formulas 9.3 or 9.3a. Thus, we need to take two steps. First, we have to calculate the coefficient [η_{int} E_P (eV)], which is the slope of the graph showing power versus current. Second, we must calculate the amount of power at the given forward current.

If λ = 850nm, then E_P = he/λ, = 1248/λ, = 1.47 eV. (See Formula 2.8 and Example 2.2.) Hence, [η_{int} E_P (eV)] = 0.0147 mW/mA and from Formula 9.3a, P = 0.0147 I.

To calculate the power value, we need to know the forward current. Typical values of I for LEDs are in the range of 50 to 150 mA. Thus, for I = 50 mA, the radiated power is P = 0.735 mW.

One expects the saturation effect (see the dotted line in Figure 9.4), the point where all the available mobile electrons will be involved in radiation and further increasing the current value, will not produce additional photons.

General Considerations

Homostructure and heterostructure

The *n*-type and *p*-type semiconductors discussed above are made from the same substrate. By adding various dopants, we can make either an *n* type of semiconductor, with excessive electrons (that is, negative charge carriers) or a *p* type of semiconductor, with excessive holes (that is, positive charge carriers). Both semiconductor types have the same energy gap. The *p-n* junction of such semiconductors becomes what's known as a homojunction. The possible structures of an LED made from such a semiconductor—homostructures—are shown in Figures 9.5(a) and 9.5(b).

There are two basic arrangements of an LED: surface emitting (SLED) and edge emitting (ELED). The depletion region and surrounding area, where electron-hole recombinations take place, are known as an *active region*. Light produced by these recombinations radiates in all di rections, but only a transparent window of the upper electrode (Figure 9.5[a]) or an open edge (Figure 9.5[b]) allows light to escape from the semiconductor structure. All other possible directions (in the case of SLED) and the opposite edge (in the case of ELED) are blocked from light by the LED's packages.

A homostructured LED has two major drawbacks. First, its active region is too diffuse, which makes the device's efficiency very low. This is because electron-hole recombinations take place in various locations, that is, over a large area, a situation that requires high current density to support the desired level of radiated power. (Remember, we are talking about the dimensions of a few microns, so the word *large* is relative here.) Second, this type of LED radiates a broad light beam. This makes the coupling of this light into an optical fiber extremely inefficient and is the reason why you cannot find an LED with a homojunction in practical applications.

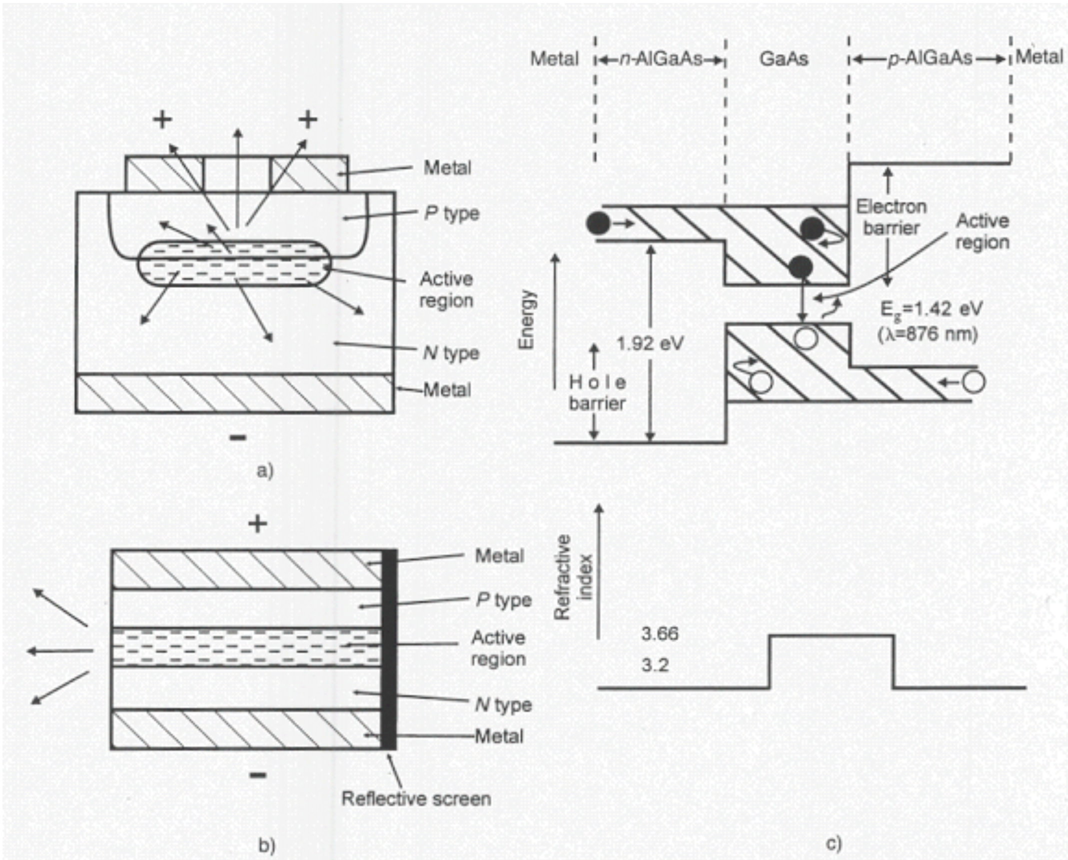

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Figure 9.5 LED structures: (a) Homostructure of a surface LED (SLED); (b) homostructure of an edge-emitting LED (ELED); (c) double heterostructure.

Commercially manufactured LEDs that radiate well-directed light with acceptable efficiency use heterojunctions. Heterostructured LEDs are made from different types of semiconductor materials, each type having a different energy gap. Figure 9.5(c) shows a heterostructure made from two different semiconductors.

Two basic concepts are introduced with this heterostructure: the confinement of electron-hole recombinations within a highly restricted active region and the conduction of radiated light in one direction.

The first is achieved by placing a semiconductor with a small energy gap between the two layers of the substrate semiconductor with the larger energy gap. Figure 9.5(c) shows that gallium arsenide (GaAs), whose E_g = 1.42 eV, is placed between the aluminum gallium arsenide (AlGaAs) layers, whose E_g = 1.92 eV. As one can see from Figure 9.5(c) electrons injected from *n*-type AlGaAs confront an energy barrier at the junction where GaAs and *p*-type AlGaAs meet and are reflected back into the active region. The same mechanism works for holes.

The conduction of light in one direction is achieved because the GaAs semiconductor has a higher refractive index (here, 3.66) than the substrate semiconductor (here, 3.2). Thus, the active region works as a waveguide similar to the way a fiber traps light within the core using the core cladding interface. The same concept is implemented for another popular heterostructure, indium phosphide-indium gallium arsenide phosphide (InP-InGaAsP) [1].

Such a structure is also called a *double heterostructure (DH).* Most commercial LEDs use not two but three different types of semiconductors to increase the light-radiation efficiency and to confine radiated light better.

Radiant patterns—Spatial patterns of radiation

Two basic types of light-emitting diodes—surface-emitting LED (SLED) and edge-emitting LED (ELED)—have different spatial-radiation patterns, as Figure 9.6 shows. SLED radiates light as a *Lambertian* source (named after Johann Lambert, an eighteenth-century German scientist). Its power distribution is described by the following formula:

$$P = P_0 \cos \theta, \quad (9.4)$$

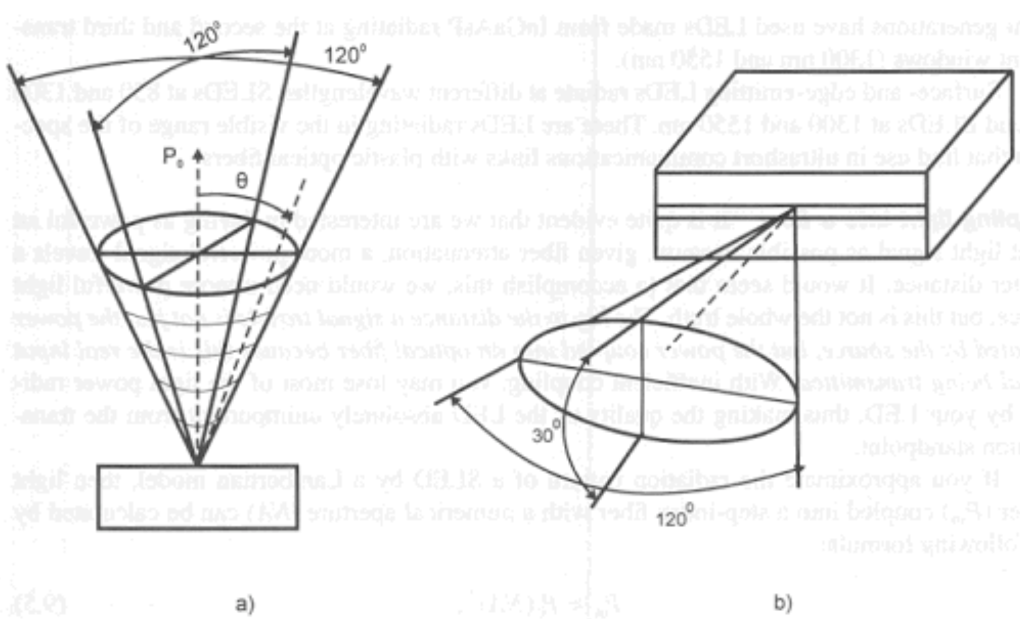
where θ is the angle between the direction of observation and the line orthogonal to the radiating surface; thus, $P = P_0$ when $\theta = 0°$. Half of the power of the Lambertian source is concentrated in a 120° cone.

ELED radiates as a Lambertian source in the plane parallel to the edge and produces a much narrower beam in the plane perpendicular to the edge, as Figure 9.6(b) shows.

A Lambertian source is simply a reference model that describes in a general way a homostructured SLED. In reality, a heterostructured LED radiates a much better directed beam. Figure 9.6(c) depicts a sample of a real spatial pattern of radiation. Because of the form of its radiant pattern, a SLED is more suitable to use with a multimode fiber, while an ELED can be used with a singlemode fiber.

Radiating wavelengths

A radiating wavelength is determined by the energy gap of a semiconductor, as discussed above. We cannot change an energy gap just as we cannot change energy levels of a given material; therefore, to obtain another wavelength, we have to choose another material. In the case of semiconductors, a desired energy gap, E_g, is created by using compound semiconductors consisting of several components. For example, the energy gap for GaAs is equal to 1.42 eV, but if you use the composition AlGaAs, you obtain an energy gap from 1.42 eV to 1.92 eV. The value of the energy gap attainable depends on the ratio of the ingredients making up the composition. In our example, if the semiconductor is composed of 37% AlAs and 63% GaAs, E_g equals 1.92 eV. If a smaller amount of AlAs is incorporated, the energy gap narrows. Table 9.1 displays the energy gaps and wavelengths of some popular semiconductors used for LED fabrication.



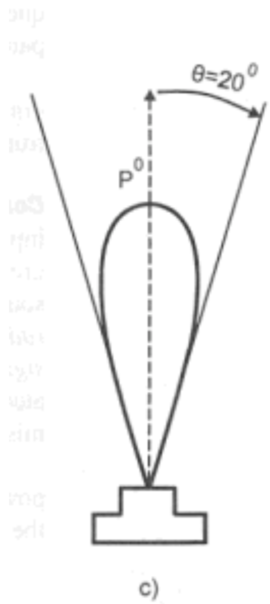


Figure 9.6 LED radiant pattern: (a) Surface-emitting LED (Lambertian source); (b) edge-emitting LED; (c) real radiant pattern.

The first generation of fiber-optic communications systems used LEDs made from AlGaAs, which radiate at around 850 nm at the first transparent window. The second and subsequent generations have used LEDs made from InGaAsP radiating at the second and third transparent windows (1300 nm and 1550 nm).

Table 9.1 Energy gaps and wavelengths (T = 300k) of popular semiconductors used for LED fabrication

Material	Energy gap, *E*g (eV)	Wavelengths (nm)
Si	1.17	1067
Ge	0.775	1610
GaAs	1.424	876
InP	1.35	924

Sources: Joseph Palais, *Fiber Optic Communication*, 4th ed., Englewood Cliffs, N.J.: Prentice Hall, 1998.

Rajiv Ramaswami and Kumar Sivarajan, *Optical Networks: A Practical Perspective*, San Francisco: Morgan Kaufman, 1998.
Tien Pei Lee, C.A. Burrus, Jr., and R.H. Saul, "Light-Emitting Diodes for Telecommunication," in *Optical Fiber Telecommunications-II*, ed.by S.E. Miller and I.P. Kaminow, Boston: Academic Press, 1988, pp. 467–508.

Surface- and edge-emitting LEDs radiate at different wavelengths: SLEDs at 850 and 1300 nm and ELEDs at 1300 and 1550 nm. There are LEDs radiating in the visible range of the spectrum that find use in ultrashort communications links with plastic optical fibers.

Coupling light into a fiber

It is quite evident that we are interested in having as powerful an input light signal as possible because, given fiber attenuation, a more powerful signal travels a greater distance. It would seem that to accomplish this, we would need a more powerful light source, but this is not the whole truth. *The key to the distance a signal travels is not just the power radiated by the source, but the power coupled into an optical fiber because this is the real input signal being transmitted*. With inefficient coupling, you may lose most of the light power radiated by your LED, thus making the quality of the LED absolutely unimportant from the transmission standpoint.

If you approximate the radiation pattern of a SLED by a Lambertian model, then light power (P_{in}) coupled into a step-index fiber with a numerical aperture (*NA*) can be calculated by the following formula:

$$P_{in} = P_0(NA)^2, \quad (9.5)$$

where P_0 is determined by Formula 9.4.

Example 9.1.2

Problem:

What is the power coupled into a step-index multimode fiber whose n_1 = 1.48 and whose n_2 = 1.46 if the SLED radiates 100 μW?

Solution:

From Example 3.1.4, you know that for this fiber the *NA* = 0.2425. Therefore,

$$P_{in} = P_0 (NA)^2 = 100\ \mu W \times 0.0588 = 5.88\ \mu W.$$

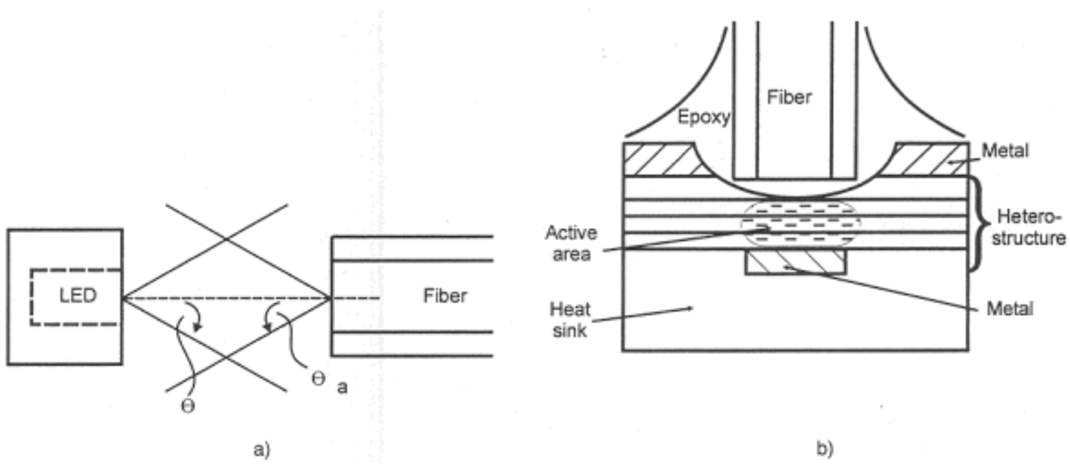
It is useful to calculate the power launched into a graded-index fiber. Even though, strictly speaking, Formula 9.5 is applied to a step-index fiber, we can extend its application to a graded-index fiber. We need bear in mind only that the result of our calculations gives us the order of magnitude, not the precise value.

Typical graded-index 62.5/125 μm fiber has an *NA* of 0.275. Let's take this number for our calculations. The result:

$$P_{in} = P_0 (NA)^2 = 100\ (\mu W) \times 0.0756 = 7.56\ \mu W$$

In other words, less than 10% of radiated power is coupled into a multimode fiber.

Formula 9.5 allows you to approximate the amount of power coupled, but by no means does it give you precise numbers. This is because of the inherent nature of the Lambertian model itself. Nevertheless, this formula underscores the basic idea: The amount of light power coupled into a fiber depends on the fiber's numerical aperture. Recalling that $NA = \sin \Theta_a$, where Θ_a is the fiber's acceptance angle (see Formula 3.4), you will appreciate the general coupling diagram in Figure 9.7(a).



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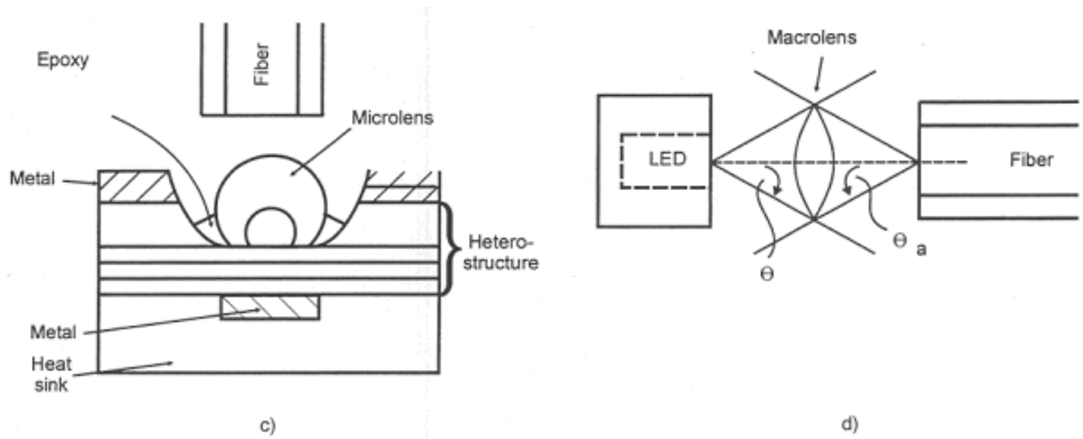

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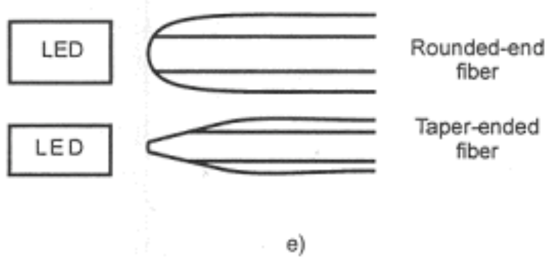


Figure 9.7 Coupling light form an LED into an optical fiber: (a) General diagram; (b) Burrus SLED; (c) microlens coupling; (d) macrolens coupling; (e) rounded-end and taper-ended fibers. *([b] and [c] reprinted from C.A. Burrus and B.J. Miller, "Small-Area Double Heterostructure AlGaAs Electroluminescent Diode Source for Optical-Fiber Transmission Lines,"* Optics Communications*, vol. 4, 1971, pp. 307–309, with permission from Elsevier Science.)*

Any of several coupling techniques can be employed to improve coupling efficiency. The most popular one is direct coupling. A common example is the so-called Burrus SLED, developed by C. A. Burrus, Jr., at the Bell Telephone Laboratories in 1971. Here, a multimode fiber is inserted directly into a semiconductor structure in order to place the fiber end as close to an active area as possible. This arrangement is sketched in Figure 9.7(b). It is interesting to note that this SLED, commonly referred to as an example of good coupling design, was one of the first commercially successful GaAs/AlGaAs LED heterostructures. A novel feature of this design is its placement of an active layer very close to the surface, thus increasing the efficiency of the optical output by minimizing the absorption of radiated photons.

To improve coupling efficiency, various lensing techniques are also used. We can distinguish between the microlens and macrolens approaches. An example of the microlens technique is given in Figure 9.7(c), while the macrolens approach is illustrated in Figure 9.4(d). We have to keep in mind that a lens cannot improve the radiation property of an LED, but it can match the output angle of a light source to the acceptance angle of the optical fiber [2].

Many other lensing schemes—such as a double-lens optical system—are used to improve coupling efficiency. (See, for example, [3] and [4].) It is worth mentioning that rounded and taper-ended shapes of fiber ends (Figure 9.7[e]) are also effective means to achieving this goal.

Most of the techniques mentioned above are employed with SLEDs. Surface-emitting LEDs are used with multimode fibers but, without employing some coupling technique, the radiation from SLEDS would not fit into even the relatively large *NA*s of these fibers.

Reading Data Sheets—Characteristics of LEDs

We will read the data sheets of LEDs in an unusual manner. First, we'll discuss the physics underlying each characteristic. Second, we'll consider not only the given specifications but also typical characteristics of other commercially available LEDs. We do this because modern LEDs come with a variety of characteristics that cannot be shown on one data sheet. Figure 9.8 displays the data sheet of a 1.3-μm SLED and ELED manufactured by AMP Inc.

Packages

Packages are shown in the photos in Figure 9.8. The basic package of an LED is the transistor-outline-style metallic *header* (case or can) shown in Figures 9.8(a) and 9.8(b). This case is usually hermetically sealed and may have a flat or lensed window cap. A SLED is packed with a variety of *connectors*, which is the typical packaging style for a surface-emitting LED. Packing LEDs with connectors guarantees a certain coupling efficiency because the user does not need to mount a fiber onto an LED; he or she need only connect the fiber through one of the standard connectors.

ELEDs are packed not only with a connector, as Figure 9.8(b) shows, but also in *pigtail* style. (See Figure 1.5.) This is because ELEDs are used not only with multimode fibers but also with singlemode fibers, which require much more accurate coupling. A factory-assembled pigtail package guarantees the maximum coupling efficiency and minimum insertion loss. (Connecting a pigtailed LED entails simply splicing a pigtail and a transmission fiber. You'll recall from Chapter 8 that the typical fusion-splicing loss is 0.01 dB, while the loss from a good connector is not less than 0.1 dB.)

Keep in mind, too, that an LED package includes a *heat-sink component*. As pointed out above, there are nonradiative recombinations that release a lot of heat in an active layer. This heat changes the junction temperature and thus the parameters of the light-conversion process. Therefore, a heat sink is a crucial component supporting an LED's operation.

Output and coupled power

The values of *coupled power* are given in the table of specifications and shown in the graph "Coupled Power vs. Drive Current" (Figure 9.8). Coupled power, obviously, depends on the type of fiber and on the LED's package. The typical power coupled into 62.5/125-μm multimode fiber by an AMP SLED is 75 μW. The typical power coupled into a singlemode fiber by an AMP ELED is 15 μW.

Since a Lambertian source, by which we model a SLED, couples only a fraction of the output power, these data allow us to calculate output power. In the simplest approach, given by Formula 9.5, we have $P_0 = P_{in} /(NA)^2$. If the typical *NA* for a multimode fiber is 0.275, then P_0 = 13.2 P_{in}. Actually, this coefficient may be as much as two times less, which means a much larger portion of radiated power is coupled into a fiber.

Absolute numbers of output power range from units to tenths of milliwatts. To increase output power, one has to increase the current (more precisely, the current density) in the active area. This raises the number of nonradiative transitions, thus decreasing quantum efficiency and increasing the temperature of the junction. This, in turn, leads to a decrease in output power [5]. Thus, there is a limit to an LED's output power.

Most manufacturers prefer to specify not output power and radiant patterns but the net result: coupled power. This is what an end-user really wants to know: how much light is at the optical fiber's input. Values of coupled power range from units to hundreds of microwatts for SLEDs. ELEDs can couple into a singlemode fiber as little as 5 μW of light power and they need a cooled package to have more than 50 μW of coupled power.

The graph depicting light power versus driving current—*P-I* or *L-I*—shows one of the most important characteristics of LEDs. (See Figure 9.8.)

Pay particular attention to the nonlinearity of the curves in Figure 9.8.

The graph "Coupled Power vs. Temperature" shows a very important effect: Power decreases as temperature increases, with the slope approximately 2 dB per 65°C. Thus, if ambient temperature increases from 25°C to 90°C, coupled power drops to 79% of the original number; that is, P_{in} (90°C) = 0.79 P_{in} (25°C) because 2 dB = –20 log(0.79). This slope is given as a coefficient ($\Delta P_{out}/\Delta T$ = –0.03 dB°C) in the table of specifications. The coupled power of an ELED decreases with temperature even more steeply than a SLED's power does. (See Figure 9.8[b].)

Wavelength and spectral width

Radiated *wavelength*, often referred to as a peak wavelength, λ_p, is determined by an energy gap, *E*. Manufacturers usually specify minimum and maximum values of λ_p. For AMP's SLED, these numbers are 1290 nm and 1350 nm; for the ELED, they are 1270 nm and 1330 nm. Even though it doesn't show in Figure 9.8, λ_p shifts to the longer wavelengths with increasing current and temperature but stays within a specified range.

A *spectral width*, $\Delta\lambda$, is measured as full width at half maximum, FWHM, as Figure 9.8(b) shows in the graph "Spectral Width." (Also see Figure 9.2[b].) For AMP's SLED, the spectral width is very wide: 170 nm. It is much narrower for the ELED: 65 nm. (In comparison, a laser diode's $\Delta\lambda$ is around 1 nm and less.) These values of $\Delta\lambda$ are typical for modern LEDs. They are much less for LEDs radiating at peak wavelength, around 850 nm, where the typical $\Delta\lambda$ is about 50 nm.

Spectral width depends on temperature, as the graph "SLED FWHM over Temperature" (Figure 9.8[a]) shows. In the range between 25°C and 90°C, spectral width increases from 155 nm to 180 nm; that is, the slope is 0.38 nm/°C. You can find this number in the table of specifications in Figure 9.8(a). The FWHM width also increases with the rise of forward (drive) current, with the slope equaling approximately 0.69 nm/mA.

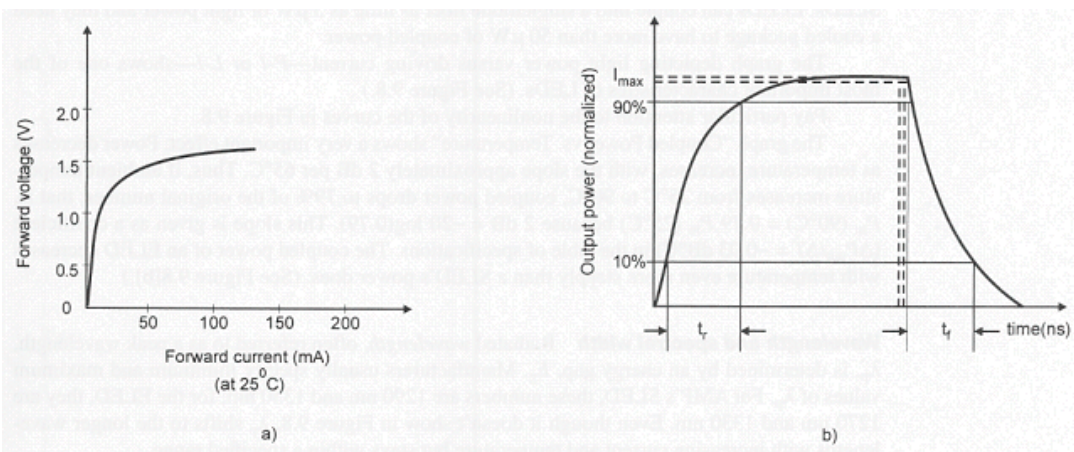
You will recall that spectral width is the critical parameter that determines the chromatic dispersion—and, hence, bandwidth—of an optical fiber. Chromatic dispersion is proportional to both spectral width and distance (see Formula 3.19); therefore, these LEDs can be used for narrow-bandwidth, short-distance applications.

Electrical characteristics

The electrical characteristics—forward voltage, capacitance, and leakage current—are common to any electronic diode. Manufacturers sometimes specify the *forward voltage versus forward current* characteristic, which, typically, has a form shown in Figure 9.9(a). The value of the forward voltage usually does not exceed 2 volts.

Capacitance, *C*, specified in the data sheet, is inherent in an LED. There are two sources of *C*: (a) charge capacitance, associated with the *p-n* junction, and (b) diffusion capacitance, associated with carrier lifetime at the active region [5]. An LED's capacitance limits its practical modulation ability and, thus, restricts its bandwidth. For example, one manufacturer specifies a capacitance of 20 pF for a SLED whose bandwidth is 200 MHz (at a peak wavelength of 865 nm) and 200 pF for a SLED whose bandwidth is 125 MHz (at a peak wavelength of 1320 nm) [4]. This is the typical range of an LED's capacitance.

Leakage current is caused by the flow of minority charge carriers (electrons in the *p* region and holes in the *n* region). These charge carriers are created by thermal energy, which excites electrons even in the *p* region. This current is measured at some reverse-bias voltage (2 volts in Figure 9.8 [a]).



[+] Enlarge Image

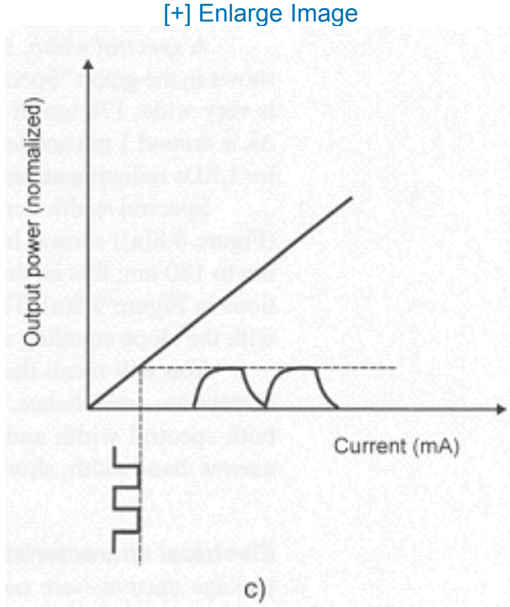


Figure 9.9 Characteristics of an LED: (a) Typical graph of a forward voltage versus current; (b) rise, t_r, and fall, t_f, time; (c) modulation of an LED.

Lifetime, rise/fall time, and bandwidth

Lifetime, τ, of the charge carriers is the time between the moment they are excited (injected into a depletion region) and the moment they are recombined. It is sometimes called *recombination lifetime* and it ranges from nanoseconds to milliseconds. We distinguish between radiative, τ_r and nonradiative, τ_{nr} combination lifetimes so that the total carrier lifetime, τ, is equal to [5]:

$$1/\tau = 1/\tau_r + 1/\tau_{nr} \quad (9.6)$$

Incidentally, internal quantum efficiency, η_{int}, which shows how many photons are radiated with respect to a specific number of injected electrons, can be quantified by the following formula:

$$\eta_{int} = \tau/\tau_r \quad (9.7)$$

Rise/fall time, t_r, is defined as 10 to 90% of the maximum value of the pulse, as Figure 9.9(b) shows. For an LED, this characteristic shows how an output light pulse follows the electrical-modulating input pulse. (See Figure 9.9[c].) An ideal step pulse is shown as two dotted lines in Figure 9.9(b). This enables you to visualize the pulse distortion caused by the rise/fall time.

Rise/fall time is determined by an LED's capacitance (*C*), input step current with amplitude(I_p), and the total recombination lifetime (τ) so that [3]:

$$t_r = 2.2[\tau + (1.7 \times 10^{-4} \times T°K \times C)/I_p], \quad (9.8)$$

where *T°K* is absolute temperature in kelvin (0°C = 273°K).

This formula is important because it discloses the parameters on which rise time depends. With a high I_p, the second term on the right side of Formula 9.8 becomes negligible and *rise time is ultimately determined by the recombination lifetime*.

Manufacturers prefer to measure, not calculate, rise time, and typical values that can be found in data sheets range from 2 to 4 ns.

Modulation bandwidth, *BW*, is the range of modulating frequencies within which detected electric power declines at –3 dB. (See Figure 3.17.) In electronics, the general relationship between bandwidth and rise time is given by the well-known formula

$$BW = 0.35/t_r \quad (9.9)$$

This formula stems from the exponential response of an RC circuit to a step-input pulse. But if you plug into Formula 9.9 the value t_r = 2.5 ns (from the data given in Figure 9.8[a]), you will not get *BW* = 115 MHz, as given by this specification sheet. (You will, rather, obtain 140 MHz.)

This discrepancy occurs because if the forward current is modulated at angular frequency, ω, an LED's output light intensity, $I(\omega)$, will vary as follows [5]:

$$I(\omega) = I(0) / \sqrt{[1+(\omega\tau)^2]} \quad (9.10)$$

where $I(0)$ is the LED's light intensity at constant current and τ is a carrier lifetime, as before. Detected electric power is proportional to I^2. (See our discussion of electrical and optical bandwidth in Section 4.6.) Taking $I^2(\omega)/I^2(0) = ½$, which is a –3 dB decline, one can find from Formula 9.10 that

$$BW = \Delta\omega = 1/\tau \quad (9.11)$$

This yields a very important principle: *An LED's modulation bandwidth is limited by the recombination lifetime of the charge carriers*. The physics governing this result is as follows: Suppose you excite an electron at the conduction band. It takes τ ns for this electron to fall to the valence band and recombine. During this interval you cannot change its status, so that if you turn off the forward current, you must wait τ ns until radiation will actually cease. This τ ns interval is necessary to allow a charge carrier to reach its destination. In other words, you cannot stop an excited electron that is on its way from the conduction band to the valence band. Thus, *lifetime τ puts a fundamental limit on the modulation bandwidth of an LED*. (You can repeat this reasoning using a *p-n* junction model: While an electron is moving through an active region, you cannot stop it; that is, you cannot change its status until this electron recombines.)

Table 9.2 Typical characteristics of LEDs

Active Material	Type	Radiating wavelength λ (nm)	Spectral width $\Delta\lambda$ (nm)	Output power into fiber (μW)	Forward current (mA)	Rise/fall time (ns)
AlGaAs	SLED	660	20	190–1350	20(min)	13/10
	ELED	850	35–65	10–80	60–100	2/2–6.5/6.5
GaAs	SLED	850	40	80–140	100	—
	ELED	850	35	10–32	100	6.5/6.5
InGaAsP	SLED	1300	110	10–50	100	3/3
	ELED	1300	25	10–150	30–100	1.5/2.5
	ELED	1550	40–70	1000–7500	200–500	0.4/0.4–12/12

Source: *Lightwave 1999 Worldwide Directory of Fiber-Optic Communications Products and Services*, March 31, 1999, pp. 58-61.

This is why LEDs are restricted by bandwidth in the range of hundreds of MHz. Such restrictions determine their applications in local area and other low-bandwidth networks.

Power-bandwidth product is another important characteristic of an LED. It appears that the product of an LED's optical output power and its modulation bandwidth is constant:

$$BW \times P = \text{constant} \quad (9.12)$$

In other words, you can increase an LED's bandwidth but only at the expense of its output power. Alternatively, you can increase output power but then bandwidth decreases.

Reliability is one of the major advantages of an LED. The table of SLED specifications in Figure 9.8 shows that the mean time to failure is more than a hundred million hours. It's hard to imagine more impressive numbers describing the reliability of an opto-electronic device. (To characterize reliability, the industry determines the average time to failure of an LED, which it refers to as mean time to failure, or MTTF.)

As we have mentioned several times already, LEDs find their applications in LANs as Token-Rings, 100 Mbit/s Ethernets, Fibre Channels, FDDIs, and other datacom networks; they are also used in intraoffice telecom networks.

In conclusion, we have summarized in Table 9.2 the typical characteristics of LEDs. These numbers give you a general idea of what today's LEDs look like.