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Inorganic Semiconductors for Light-emitting Diodes

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1.1

Introduction

During the past 40 years, light-emitting diodes (LEDs) have undergone a significant development. The first LEDs emitting in the visible wavelength region were based on GaAsP compound semiconductors with external efficiencies of only 0.2%. Today, the external efficiencies of red LEDs based on AlGaInP exceed 50%. AlGaInP semiconductors are also capable of emitting at orange, amber, and yellow wavelengths, albeit with lower efficiency. Semiconductors based on AlGaInN compounds can emit efficiently in the UV, violet, blue, cyan, and green wavelength range. Thus, all colors of the visible spectrum are now covered by materials with reasonably high efficiencies. This opens the possibility to use LEDs in areas beyond conventional signage and indicator applications. In particular, LEDs can now be used in high-power applications thereby enabling the replacement of incandescent and fluorescent sources. LED lifetimes exceeding $> 10^5$ h compare favorably with incandescent sources (~ 500 h) and fluorescent sources (~ 5000 h), thereby contributing to the attractiveness of LEDs.

Inorganic LEDs are generally based on p-n junctions. However, in order to achieve high internal quantum efficiencies, free carriers need to be spatially confined. This requirement has led to the development of heterojunction LEDs consisting of different semiconductor alloys and multiple quantum wells embedded in the light-emitting active region. The light-extraction efficiency, which measures the fraction of photons leaving the semiconductor chip, is strongly affected by the device shape and surface structure. For high internal-efficiency active regions, the maximization of the light-extraction efficiency has proven to be the key to high-power LEDs.

This chapter reviews important aspects of inorganic LED structures. Section 1.2 introduces the basic concepts of optical emission. Band diagrams of direct and indirect semiconductors and the spectral shape of spontaneous emission will be discussed along with radiative and nonradiative recombination processes. Spontaneous emission can be controlled by placing the active region in an optical

cavity resulting in a substantial modification of the LED emission characteristics. Theory and experimental results of such resonant-cavity LEDs (RCLEDs) are discussed in Section 1.3. The electrical characteristics of LEDs, to be discussed in Section 1.4, include parasitic voltage drops and current crowding phenomena that result in nonuniform light emission and shortened device lifetimes. Due to total internal reflection at the surfaces of an LED chip, the light-extraction efficiency in standard devices is well below 100 %. Section 1.5 discusses techniques such as chip shaping utilized to increase the extraction efficiency. A particular challenge in achieving efficient LEDs is the minimization of optical absorption processes inside the semiconductor. This can be achieved by covering absorbing regions, such as lower-bandgap substrates, with highly reflective mirrors. Such mirrors should have omnidirectional reflection characteristics and a high angle-integrated, TE-TM averaged reflectivity. A novel electrically conductive omnidirectional reflector is discussed in Section 1.6. Section 1.7 reviews the current state of the art in LED packaging including packages with low thermal resistance.

1.2 Optical Emission Spectra

The physical mechanism by which semiconductor light-emitting diodes (LEDs) emit light is spontaneous recombination of electron-hole pairs and simultaneous emission of photons. The spontaneous emission process is fundamentally different from the stimulated emission process occurring in semiconductor lasers and superluminescent LEDs. The characteristics of spontaneous emission that determine the optical properties of LEDs will be discussed in this section.

The probability that electrons and holes recombine *radiatively* is proportional to the electron and hole concentrations, that is, $R \propto n p$. The recombination rate per unit time per unit volume can be written as

$$R = -\frac{dn}{dt} = -\frac{dp}{dt} = B n p \quad (1.1)$$

where B is the *bimolecular recombination coefficient*, with a typical value of $10^{-10} \text{ cm}^3/\text{s}$ for direct-gap III-V semiconductors.

Electron-hole recombination is illustrated in Fig. 1.1. Electrons in the conduction band and holes in the valence band are assumed to have the parabolic dispersion relations

$$E = E_C + \frac{\hbar^2 k^2}{2 m_e^*} \quad (\text{for electrons}) \quad (1.2)$$

and

$$E = E_V - \frac{\hbar^2 k^2}{2 m_h^*} \quad (\text{for holes}) \quad (1.3)$$

Fig. 1.1 Parabolic electron and hole dispersion relations showing “vertical” electron–hole recombination and photon emission.

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-edge energies, respectively.

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

$$h\nu = E_e - E_h \approx E_g \quad (1.4)$$

The photon energy is approximately equal to the bandgap energy, E_g , if the thermal energy is small compared with the bandgap energy, that is, $kT \ll E_g$. Thus the desired emission wavelength of an LED can be attained by choosing a semiconductor material with appropriate bandgap energy. For example, GaAs has a bandgap energy of 1.42 eV at room temperature resulting in infrared emission of 870 nm.

It is helpful to compare the average carrier momentum with the photon momentum. A carrier with kinetic energy kT and effective mass m^* has the momentum

$$p = m^* v = \sqrt{2 m^* \frac{1}{2} m^* v^2} = \sqrt{2 m^* kT} \quad (1.5)$$

The momentum of a photon with energy E_g can be obtained from the de Broglie relation

$$p = \hbar k = h\nu / c = E_g / c \quad (1.6)$$

Calculation of the carrier momentum (using Eq. (1.5)) and the photon momentum (using Eq. (1.6)) yields that the carrier momentum is *orders of magnitude lar-*

ger than the photon momentum. Therefore the electron momentum must not change significantly during the transition. The transitions are therefore “vertical” as shown in Fig. 1.1, i. e. electrons recombine with only those holes that have the same momentum or k value.

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

$$\hbar \nu = E_C + \frac{\hbar^2 k^2}{2 m_e^*} - E_V + \frac{\hbar^2 k^2}{2 m_h^*} = E_g + \frac{\hbar^2 k^2}{2 m_r^*} \quad (1.7)$$

where m_r^* is the reduced mass given by

$$\frac{1}{m_r^*} = \frac{1}{m_e^*} + \frac{1}{m_h^*} \quad (1.8)$$

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

$$\rho(E) = \frac{1}{2\pi^2} \left(\frac{2 m_r^*}{\hbar^2} \right)^{3/2} \sqrt{E - E_g} \quad (1.9)$$

The distribution of carriers in the allowed bands is given by the Boltzmann distribution, i. e.

$$f_B(E) = e^{-E/(kT)} \quad (1.10)$$

The *emission intensity* as a function of energy is proportional to the product of Eqs. (1.9) and (1.10),

$$I(E) \propto \sqrt{E - E_g} e^{-E/(kT)} \quad (1.11)$$

The emission lineshape of an LED, as given by Eq. (1.11), is shown in Fig. 1.2. The maximum emission intensity occurs at

$$E = E_g + \frac{1}{2} kT \quad (1.12)$$

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

$$\Delta E = 1.8 kT \quad (1.13)$$

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

The spectral linewidth of LED emission is important in several respects. *First*, the linewidth of an LED emitting in the visible range is relatively narrow compared with the range of the entire visible spectrum. The LED emission is even narrower than the spectral width of a single color as perceived by the human eye. For example, *red* colors range from 625 to 730 nm, which is much wider

Fig. 1.2 Theoretical emission spectrum of an LED. The full width at half maximum (FWHM) of the emission line is $1.8 kT$.

than the typical emission spectrum of an LED. Therefore, LED emission is perceived by the human eye as *monochromatic*.

Secondly, optical fibers are dispersive, which leads to a range of propagation velocities for a light pulse comprising a range of wavelengths. The material dispersion in optical fibers limits the “*bit rate $\times$ distance product*” achievable with LEDs. The spontaneous lifetime of carriers in LEDs in direct-gap semiconductors typically is of the order of 1–100 ns depending on the active region doping concentration (or carrier concentrations) and the material quality. Thus, modulation speeds up to 1 Gbit/s are attainable with LEDs.

A spectral width of $1.8kT$ is expected for the thermally broadened emission. However, due to other broadening mechanisms, such as *alloy broadening* (i.e. the statistical fluctuation of the active region alloy composition), the spectral width at room temperature in III-V nitride LEDs can be broader, typically (3 to 8) kT . Experimental evidence shown in Fig. 1.3 supports the use of a Gaussian function to describe the spectral power density function of an LED. Therefore,

$$P(\lambda) = P \frac{1}{\sigma\sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{\lambda - \lambda_{\text{peak}}}{\sigma} \right)^2 \right] \quad (1.14)$$

where P is the total optical power emitted by the LED. Inspection of Fig. 1.3 indeed reveals that the Gaussian curve is a very good match for the experimental emission spectrum. Giving the line widths in terms of units of kT is very useful as it allows for convenient comparison with the theoretical line width of $1.8kT$.

The emission spectra of an AlGaInP red, a GaInN green, and a GaInN blue LED are shown in Fig. 1.4. The LEDs shown in Fig. 1.4 have an active region comprised of a ternary or quaternary alloy, e.g. $\text{Ga}_{1-x}\text{In}_x\text{N}$. In this case, alloy broadening leads to spectral broadening that goes beyond $1.8kT$. Alloy broadening due to inhomogeneous distribution of In in the active region of green $\text{Ga}_{1-x}\text{In}_x\text{N}$ LEDs

Fig. 1.3 Theoretical emission spectrum of a semiconductor exhibiting substantial alloy broadening. The full width at half maximum (FWHM) is related to the standard deviation (σ) by the equation shown in the figure.

Fig. 1.4 Emission spectrum of AlGaInP/GaAs red, GaInN/GaN green, GaInN/GaN blue, GaInN/GaN UV, and AlGaInP/GaAs deep UV LEDs at room temperature (adopted from refs. [3–5]).

can cause linewidths as wide as $10kT$ at room temperature [1]. It should be noted, however, that a recent study found inhomogeneous strain distribution in GaInN quantum wells as a result of electron damage during TEM experiments [2]. It was concluded that the damage might lead to a “false” detection of In-rich clusters in a homogeneous quantum-well structure.

Efficient recombination occurs in direct-gap semiconductors. The recombination probability is much lower in indirect-gap semiconductors because a phonon is required to satisfy momentum conservation. The radiative efficiency of indirect-gap semiconductors can be increased by isoelectronic impurities, e.g. N in GaP. Isoelectronic impurities can form an optically active deep level that is localized in real space (small Δx) but, as a result of the uncertainty relation, delocalized in k space (large Δk), so that recombination via the impurity satisfies momentum conservation.

During *nonradiative* recombination, the electron energy is converted to vibrational energy of lattice atoms, i.e. phonons. There are several physical mechan-

isms by which nonradiative recombination can occur with the most common ones being recombination at point defects (impurities, vacancies, interstitials, antisite defects, and impurity complexes) and at spatially extended defects (screw and edge dislocations, cluster defects). The defects act as efficient recombination centers (Shockley–Read recombination centers) in particular, if the energy level is close to the middle of the gap.

1.3

Resonant-cavity-enhanced Structures

Spontaneous emission implies the notion that the recombination process occurs *spontaneously*, that is without a means to influence this process. In fact, spontaneous emission has long been believed to be uncontrollable. However, research in microscopic optical resonators, where spatial dimensions are of the order of the wavelength of light, showed the possibility of controlling the spontaneous emission properties of a light-emitting medium. The changes of the emission properties include the spontaneous emission rate, spectral purity, and emission pattern. These changes can be employed to make more efficient, faster, and brighter semiconductor devices. The changes in spontaneous emission characteristics in resonant-cavity (RC) and photonic-crystal (PC) structures were reviewed by Joannopoulos et al. [6].

Resonant-microcavity structures have been demonstrated with different active media and different microcavity structures. The first resonant-cavity structure was proposed by Purcell (1946) for emission frequencies in the radio frequency (rf) regime [7]. Small metallic spheres were proposed as the resonator medium. However, no experimental reports followed Purcell's theoretical publication. In the 1980s and 1990s, several resonant cavity structures have been realized with different types of optically active media. The active media included organic dyes [8, 9], semiconductors [10, 11], rare-earth atoms [12, 13], and organic polymers [14, 15]. In these publications, clear changes in spontaneous emission were demonstrated including changes in spectral, spatial, and temporal emission characteristics.

The simplest form of an optical cavity consists of two coplanar mirrors separated by a distance L_{cav} as shown in Fig. 1.5. About one century ago, Fabry and Perot were the first to build and analyze optical cavities with coplanar reflectors

Fig. 1.5 Schematic illustration of a resonant cavity consisting of two metal mirrors with reflectivity R_1 and R_2 . The active region has a thickness L_{active} and an absorption coefficient a . Also shown is the standing optical wave. The cavity length is L_{cav} is equal to $\lambda / 2$.

Fig. 1.6 (a) Schematic structure of a substrate-emitting GaInAs/GaAs RCLED consisting of a metal top reflector and a bottom distributed Bragg reflector (DBR). The RCLED emits at 930 nm. The reflectors are an AlAs/GaAs DBR and a Ag top reflector. (b) Picture of the first RCLED (after ref. [20]).

[16]. These cavities had a large separation between the two reflectors, i. e. $L_{\text{cav}} \gg \lambda$. However, if the distance between the two reflectors is of the order of the wavelength, $L_{\text{cav}} \approx \lambda$, new physical phenomena occur, including the enhancement of the optical emission from an active material inside the cavity.

At the beginning of the 1990s, the *resonant-cavity light-emitting diode* (RCLED) was demonstrated, initially in the GaAs material system [17], shown in Fig. 1.6, and subsequently in organic light-emitting materials [14]. Both publications reported an emission line narrowing due to the resonant cavities. RCLEDs have many advantageous properties when compared with conventional LEDs, including higher brightness, increased spectral purity, and higher efficiency. For example, the RCLED spectral power density at the resonance wavelength was shown to be enhanced by more than one order of magnitude [18, 19].

The enhancement of spontaneous emission can be calculated based on the changes of the *optical mode density* in a one-dimensional (1D) resonator, i. e. a coplanar Fabry–Perot cavity. We first discuss the basic physics causing the changes of the spontaneous emission from an optically active medium located inside a microcavity and give analytical formulas for the spectral and integrated emission enhancement. The spontaneous radiative transition rate in an optically active, homogeneous medium is given by (see, for example, ref. [21])

$$W_{\text{spont}} = \tau_{\text{spont}}^{-1} = \int_0^\infty W_{\text{spont}}^{(\ell)} \rho(\nu_\ell) d\nu_\ell \quad (1.15)$$

where $W_{\text{spont}}^{(\ell)}$ is the spontaneous transition rate into the optical mode ℓ and $\varrho(\nu_\ell)$ is the optical mode density. Assuming that the optical medium is homogeneous, the spontaneous emission lifetime, τ_{spont} , is the inverse of the spontaneous emission rate. However, if the optical mode density in the device depends on the spatial direction, as in the case of a cavity structure, then the emission rate given in Eq. (1.15) depends on the direction. Equation (1.15) can be applied to some small range of solid angle along a certain direction, for example the direction perpendicular to the reflectors of a Fabry–Perot cavity. Thus, Eq. (1.15) can be used to calculate the emission rate along a specific direction, in particular the optical axis of a cavity.

The spontaneous emission rate into the optical mode ℓ , $W_{\text{spont}}^{(\ell)}$, contains the dipole matrix element of the two electronic states involved in the transition [21]. Thus $W_{\text{spont}}^{(\ell)}$ will *not* be changed by placing the optically active medium inside an optical cavity. However, the optical mode density, $\varrho(\nu_\ell)$, is strongly modified by the cavity. Next, the changes in optical mode density will be used to calculate the changes in spontaneous emission rate.

We first compare the optical mode density in free space with the optical mode density in a cavity. For simplicity, we restrict our considerations to the one-dimensional case, i.e. to the case of a coplanar Fabry–Perot cavity. Furthermore, we restrict our considerations to the emission along the optical axis of the cavity.

In a one-dimensional homogeneous medium, the density of optical modes per unit length per unit frequency is given by

$$\rho^{1D}(\nu) = \frac{2n}{c} \quad (1.16)$$

where n is the refractive index of the medium. Equation (1.16) can be derived using a similar formalism commonly used for the derivation of the mode density in free space. The constant optical mode density given by Eq. (1.16) is shown in Fig. 1.7.

In planar cavities, the optical modes are discrete and the frequencies of these modes are integer multiples of the fundamental mode frequency, as shown schematically in Fig. 1.7. The fundamental and first excited mode occur at frequencies of ν_0 and $2\nu_0$, respectively. For a cavity with two metallic reflectors (no distributed Bragg reflectors) and a π phase shift of the optical wave upon reflection, the fundamental frequency is given by $\nu_0 = c / 2nL_{\text{cav}}$, where c is the velocity of light in vacuum and L_{cav} is the length of the cavity. In a *resonant cavity*, the emission frequency of an optically active medium located inside the cavity equals the frequency of one of the cavity modes.

The optical mode density along the cavity axis can be derived using the relation between the mode density in the cavity and the optical transmittance through the cavity, $T(\nu)$,

$$\rho(\nu) = K T(\nu) \quad (1.17)$$

Fig. 1.7
(a) Optical mode density of a one-dimensional planar microcavity (solid line) and of homogeneous one-dimensional space. (b) Theoretical shape of the luminescence spectrum of bulk semiconductors.

where K is a constant. The value of K can be determined by a normalization condition, i.e. by considering a single optical mode. The transmittance through a Fabry–Perot cavity can be written as

$$T(\nu) = \frac{T_1 T_2}{1 + R_1 R_2 - 2\sqrt{R_1 R_2} \cos(4\pi\bar{n} L_{\text{cav}} \nu/c)} \quad (1.18)$$

The transmittance has maxima at $\nu = 0, \nu_0, 2\nu_0, \dots$, and minima at $\nu = \nu_0/2, 3\nu_0/2, 5\nu_0/2, \dots$.

The optical mode density of a one-dimensional cavity for emission along the cavity axis is given by

$$\rho(\nu) = \frac{(R_1 R_2)^{3/4}}{T_1 T_2} \frac{4n}{c} (1 - \sqrt{R_1 R_2}) T(\nu) \quad (1.19)$$

This equation allows one to calculate the density of optical modes at the maxima and minima. At the *maxima*, the mode density is given by

$$\rho_{\text{max}} = \frac{(R_1 R_2)^{3/4}}{1 - \sqrt{R_1 R_2}} \frac{4n}{c} \quad (1.20)$$

Because the emission rate at a given wavelength is directly proportional to the optical mode density, the emission rate *enhancement spectrum* is given by the ratio of the 1D cavity mode density to the 1D free-space mode density. The enhancement factor at the resonance wavelength is thus given by the ratio of the optical mode densities with and without a cavity, i.e.

$$G_e = \frac{\rho_{\max}}{\rho^{1D}} \approx \frac{2}{\pi} F \approx \frac{2}{\pi} \frac{\pi(R_1 R_2)^{1/4}}{1 - \sqrt{R_1 R_2}} \quad (1.21)$$

This equation shows that a strong enhancement of the spontaneous emission rate along the cavity axis can be achieved with microcavities.

Equation (1.21) represents the *average* emission rate enhancement out of *both* reflectors of the cavity. To find the enhancement out a *single* direction, we multiply the enhancement given by Eq. (1.21) by the fraction of the light exiting the mirror with reflectivity R_1 (i. e. $1 - R_1$) divided by the average loss of the two mirrors for one round trip in the cavity {i. e. $(1/2) [(1 - R_1) + (1 - R_2)]$ }. For large R_1 and R_2 , this consideration gives for the enhancement of the emission exiting R_1

$$G_e \approx \frac{2(1 - R_1)}{2 - R_1 - R_2} \frac{2F}{\pi} \approx \frac{1 - R_1}{1 - \sqrt{R_1 R_2}} \frac{2F}{\pi} \approx \frac{2}{\pi} \frac{\pi(R_1 R_2)^{1/4} (1 - R_1)}{(1 - \sqrt{R_1 R_2})^2} \quad (1.22)$$

where we used the approximation $1 - (R_1 R_2)^{1/2} \approx (1/2) (1 - R_1 R_2) \approx (1/2) (2 - R_1 - R_2)$. Equation (1.22) represents the emission rate enhancement from a *single* reflector with reflectivity R_1 .

The total enhancement *integrated over wavelength*, rather than the enhancement at the resonance wavelength, is relevant for many practical devices. *On resonance*, the emission is enhanced along the axis of the cavity. However, sufficiently far *off resonance*, the emission is suppressed. Because the natural emission spectrum of the active medium (without a cavity) can be much broader than the cavity resonance, it is, *a priori*, not clear whether the integrated emission is enhanced. To calculate the wavelength-integrated enhancement, the spectral width of the cavity resonance and the spectral width of the natural emission spectrum must be determined. The resonance spectral width can be calculated from the finesse of the cavity or the cavity quality factor.

The theoretical width of the emission spectrum of bulk semiconductors is $1.8kT$ (see, for example, ref. [22]), where k is Boltzmann's constant and T is the absolute temperature. At room temperature, $1.8kT$ corresponds to an emission linewidth of $\Delta\lambda_n = 31$ nm for an emission wavelength of 900 nm. For a cavity resonance width of 5–10 nm, one part of the spectrum is strongly enhanced, whereas the rest of the spectrum is suppressed. The integrated enhancement ratio (or suppression ratio) can be calculated analytically by assuming a Gaussian natural emission spectrum. For semiconductors at 300 K, the linewidth of the natural emission is, in the case of high-finesse cavities, *larger* than the width of the cavity resonance. The Gaussian emission spectrum has a width of $\Delta\lambda_n = 2\sigma (2 \ln 2)^{1/2}$ and a peak value of $(\sigma (2\pi)^{1/2})^{-1}$, where σ is the standard deviation of the Gaussian function. The integrated enhancement ratio (or suppression ratio) is then given by [23]

$$G_{\text{int}} = \frac{\pi}{2} G_e \Delta\lambda \frac{1}{\sigma\sqrt{2\pi}} = G_e \sqrt{\pi \ln 2} \frac{\Delta\lambda}{\Delta\lambda_n} \quad (1.23)$$

where the factor of $\pi/2$ is due to the Lorentzian lineshape of the enhancement spectrum. Hence, the integrated emission enhancement depends on the natural

Fig. 1.8 Optical mode density for (a) a short and (b) a long cavity with the same finesse F . (c) Spontaneous free-space emission spectrum of an LED active region. The spontaneous emission spectrum has a better overlap with the short-cavity mode spectrum compared with the long-cavity mode spectrum.

emission linewidth of the active material. The value of G_{int} can be quite different for different types of optically active materials. Narrow atomic emission spectra can be enhanced by several orders of magnitude [12]. On the other hand, materials having broad emission spectra such as dyes or polymers may not exhibit any integrated enhancement at all. Equation 1.23 also shows that the width of the resonance has a profound influence on the integrated enhancement. [8, 9] Narrow resonance spectral widths, i. e. high finesse values or long cavities, reduce the integrated enhancement [18].

The relation between the overlap of the spontaneous emission spectrum and the cavity length is illustrated in Fig. 1.8, which shows the optical mode density of a short and a long cavity. Both cavities have the same mirror reflectivities and finesse. The natural emission spectrum of the active region is shown in Fig. 1.8(c). The best overlap between the resonant optical mode and the active region emission spectrum is obtained for the *shortest* cavity. Thus a cavity length of $\lambda/2$ provides the largest enhancement.

The largest enhancements are achieved with the shortest cavities, which in turn are obtained if the *fundamental* cavity mode is in resonance with the emission from the active medium. The cavity length is shortest for metallic reflectors. DBRs with a short penetration depth, i. e. DBRs consisting of two materials with a large difference in refractive index, also reduce the cavity length.

The reflection and emission properties of the RCLED are shown in Fig. 1.9(a) and (b). The reflection spectrum of the RCLED exhibits a highly reflective band for wavelengths > 900 nm and a dip in the reflectivity at the cavity resonance. The spectral width of the cavity resonance is 6.3 nm. The emission spectrum of an electrically pumped device, shown in Fig. 1.9(b), has nearly the same shape and width as the cavity resonance.

In conventional LEDs, the spectral characteristics of the devices reflect the thermal distribution of electrons and holes in the conduction and valence band. The spectral characteristics of light emission from microcavities are as intriguing as they are complex. However, restricting our considerations to the optical axis of the cavity simplifies the cavity physics considerably. If we assume that the cavity resonance is much narrower than the natural emission spectrum of the semiconductor, then the on-resonance luminescence is enhanced whereas the off-resonance luminescence is suppressed. The on-axis emission spectrum should therefore reflect the enhancement, that is, the resonance spectrum of the cavity. The experimental results shown in Fig. 1.9 confirm this conjecture.

Particularly high spontaneous emission enhancements can be attained with emitters that have very narrow emission lines. Atomic transitions, e.g. in rare-earth elements have such narrow emission lines. For this reason, rare-earth doped cavities are a prime example of the emission enhancement provided by resonant cavities. The emission spectrum of an erbium-doped Si/SiO₂ resonant cav-

Fig. 1.9

(a) Reflectance of a resonant cavity consisting of a 10-pair AlAs/GaAs distributed Bragg reflector and an Ag reflector. (b) Emission spectrum of a RCLED consisting of a 10-pair AlAs/GaAs distributed Bragg reflector and an Ag reflector (after ref. [20]).

Fig. 1.10 Photoluminescence spectra of Er-doped SiO_2 . One of the spectra is for the Er-doped SiO_2 located in a cavity resonant at 1540 nm. The other spectrum is without a cavity. The emission enhancement factor is 50 (after ref. [12]).

ity is shown in Fig. 1.10 [12]. A distinct narrowing of the Er emission spectrum is found for emission along the optical axis. A huge emission enhancement with cavity is found, a factor greater than 50, when compared to a noncavity structure.

The peak emission wavelength depends on the emission angle with respect to the surface normal (polar angle). Denoting the polar emission angle in air as Θ_0 , the emission wavelength is given by

$$\lambda_e = \lambda_{\text{res}} \cos \left[\arcsin \left(\frac{1}{n} \sin \Theta_0 \right) \right] \quad (1.24)$$

where λ_{res} is the resonance wavelength of the cavity. For small angles, the equation can be approximated by

$$\lambda_e = \lambda_{\text{res}} \left(1 - \frac{\Theta_0^2}{2n^2} \right) \quad (1.25)$$

where the refractive index n is the effective refractive index of the medium. The angular dependence of the peak emission wavelength is shown in Fig. 1.11. The dashed line is the approximate solution of Eq. (1.25). A refractive index of 1.5 has been used in this calculation.

RCLEDs are now commercial products that are manufactured by the millions per year. Primary applications are in signage and communication. The devices are particularly well suited for plastic optical fiber systems. The directed emission pattern improves LED-fiber coupling efficiency. The narrow emission line reduces material and chromatic dispersion effects. As a result, RCLEDs enable longer transmission distances and simultaneously higher data rates.

The enhanced coupling and narrow emission line of the fiber-coupled intensity is shown in Fig. 1.12. Inspection of the figure reveals the much higher power coupled to a fiber and the narrower emission spectrum of the RCLED.

Fig. 1.11 Emission wavelength as a function of angle for a planar resonant cavity (after ref. [12]).

Fig. 1.12 Spectra of light coupled into a plastic optical fiber from an GaInP/AlGaInP MQW RCLED and a conventional GaInP/AlGaInP LED at different drive currents. Note the narrower spectrum and higher coupled power of the RCLED (after ref. [24]).

1.4

Current Transport in LED Structures

LEDs can be grown on conductive as well as insulating substrates. Whereas the current flow is mostly vertical (normal to the substrate plane) in structures grown on conductive substrates, it is mostly lateral (horizontal) in devices grown on insulating substrates. The location and size of ohmic contacts are relevant to light extraction, as metal contacts generally are opaque. This section discusses the current flow patterns of different device structures aimed at high extraction efficiency.

Fig. 1.13 (a) Current-spreading structure used in AlGaInP LEDs. (b) Current crowding in a mesa-structured GaN-based LED grown on an insulating substrate. (c) Lateral injection geometry. The corresponding equivalent circuits are shown as well.

In LEDs with thin top confinement layers, the current is injected into the active region mostly under the top electrode. Thus, light is generated under an opaque metal electrode, which results in a low extraction efficiency. The problem can be avoided with a *current-spreading layer* or *window layer* that spreads the current under the top electrode to regions not covered by the opaque top electrode.

The usefulness of current-spreading layers was shown by Nuese et al. [25] who demonstrated a substantial improvement of the optical output power in GaAsP LEDs. The effect of the current-spreading layer is illustrated schematically in Fig. 1.13(a). Current-spreading layers are employed in top-emitting LEDs. A GaP current-spreading layer in an AlGaInP LED was reported by Kuo et al. [26] and Fletcher et al. [27, 28]. AlGaAs current-spreading layers in AlGaInP LEDs were reported by Sugawara et al. [29–31].

For circular contact geometry, the thickness of the current spreading layer, t , results a current-spreading length L_s given by [32]

$$t = \rho L_s \left(r_c + \frac{L_s}{2} \right) \ln \left(1 + \frac{L_s}{r_c} \right) \left(J_0 \frac{e}{n_{\text{ideal}} kT} \right) \quad (1.26)$$

where J_0 is the current density at the edge of the contact, r_c is the contact radius. The equation allows one to calculate the required current-spreading layer thickness t for a given resistivity of this layer and the desired current-spreading length L_s .

Current crowding also occurs in mesa-structured LEDs grown on *insulating* substrates, e. g. GaInN/GaN LEDs grown on sapphire substrates. In common GaInN devices, the p-type contact is located on the top of the mesa, and the n-type contact is located on an n-type buffer layer at the bottom of the mesa. As a result, the current crowds at the edge of the mesa contact adjoining the n-type contact.

A lateral p-side-up mesa LED grown on an insulating substrate is shown in Fig. 1.13(b). It is intuitively clear that the p-n junction current crowds near the edge of the mesa as indicated in the figure. An equivalent circuit model is shown in Fig. 1.13(b) and includes the p-type contact resistance and the resistances of the n-type and p-type cladding layers. The p-n junction is approximated by an ideal diode. The circuit model also shows several nodes separated by a distance dx . The current distribution decreases exponentially with distance from the contact edge. The current-spreading length is given by [33]

$$L_s = \sqrt{(\rho_c + \rho_p t_p) t_n / \rho_n} \quad (1.27)$$

where $\rho_{n,p}$ and $t_{n,p}$ are the resistivities and thickness of the n-type and p-type layers, respectively, and ρ_c is the specific contact resistance. This equation shows that the current distribution depends on epitaxial layer thicknesses and material resistivities. A thick low-resistivity n-type buffer layer is needed to ensure that current crowding is minimized. For *low* p-type contact and confinement resistances, strong current crowding results, unless the n-type buffer layer is very conductive so that t_n / ρ_n is very large. In GaN/GaInN devices, the sum of p-type contact and p-type layer resistances can be larger than the n-type cladding resistance, especially if t_n is small.

A device structure with a lateral current-injection scheme is shown in Fig. 1.13(c). The current is transported laterally in both the n-type and p-type cladding layers. Light is generated in the region between the contacts where the extraction is not hindered by contacts. If the n-type sheet resistance ρ_n / t_n is much lower than the p-type sheet resistance ρ_p / t_p , the current prefers to flow laterally in the low-resistance n-layer rather than the p-layer. As a result, the junction current crowds near the p-type contact.

A schematic equivalent circuit suitable for the quantitative analysis is shown in Fig. 1.13(c) where a pn-junction current density of $J(0)$ is assumed at the edge of the p-type contact. The analytic solution of the equivalent circuit shown in Fig. 1.13(c) is an exponential function [34, 35].

Fig. 1.14 (a) Interdigitated stripe-contact structure for uniform current injection. (b) Top view. (c) Photograph of flip-chip GaInN LED (after LED Museum, see ref. [38]).

For uniform light generation across the gap between the contacts, it is desirable to have a long exponential decay length L_s . This can be achieved by high doping or thick confinement layers. To attain high powers, one may be tempted to scale the device structure in size. However, for large contact separations L , the device becomes generally more resistive unless very thick confinement layers are being used (which may be impractical). Scaling such device structures can be accomplished by employing arrays of many small devices rather than scaling up a single device.

Note that current crowding becomes increasingly severe with larger device sizes, unless novel contact geometries are introduced to alleviate the problem. Such novel contact geometries include interdigitated structures with p-type finger widths of less than L_s [36, 37]. For device dimensions much smaller than L_s , the current crowding effect can be neglected.

The schematic structure and a photograph of an interdigitated stripe-contact geometry are shown in Fig. 1.14. Uniform current injection into the active region is achieved by the p-type contact width ($W_{p\text{-contact}}$) being smaller than the current-spreading length. The width of the n-type contact ($W_{n\text{-contact}}$) must be at least equal to the contact transfer length to ensure low contact resistance. The contact transfer length follows from the transmission line model (TLM) used for characterization of ohmic contacts (see, for example, ref. [39]).

1.5

Extraction Efficiency

The active region of an idealized LED emits *one photon for every electron* injected. Each charge quantum-particle (electron) produces one light quantum-particle (photon). Thus the active region of an idealized LED has a *quantum efficiency* of one. The *internal quantum efficiency* is defined as

$$\eta_{\text{int}} = \frac{\text{\# of photons emitted from active region per second}}{\text{\# of electrons injected into LED per second}} = \frac{P_{\text{int}} / (h \nu)}{I / e} \quad (1.28)$$

where P_{int} is the optical power emitted from the active region and I is the injection current.

Photons emitted by the active region should escape from the LED chip. In an idealized LED, all photons emitted by the active region are also emitted into free space. Such an LED would have 100 % *extraction efficiency*. However, in a real LED, not all the power emitted from the active region is emitted into free space. Some photons may never leave the semiconductor chip. This is due to a number of possible loss mechanisms. For example, light emitted by the active region can be re-absorbed in the substrate of the LED, assuming that the substrate is absorbing at the emission wavelength. Light may be incident on a metallic contact surface and be absorbed by the metal. In addition, the phenomenon of *total internal reflection*, also referred to as the *trapped light phenomenon*, reduces the ability of the light to escape from the semiconductor. The *light extraction efficiency* is defined as

$$\eta_{\text{extraction}} = \frac{\text{\# of photons emitted into free space per second}}{\text{\# of photons emitted from active region per second}} = \frac{P / (h \nu)}{P_{\text{int}} / (h \nu)} \quad (1.29)$$

where P is the optical power emitted into free space.

The extraction efficiency can be a severe limitation for high-performance LEDs. It is quite difficult to increase the extraction efficiency beyond 50 % without resorting to highly sophisticated and costly device processes.

The *external quantum efficiency* is defined as

$$\eta_{\text{ext}} = \frac{\text{\# of photons emitted into free space per second}}{\text{\# of electrons injected into LED per second}} = \frac{P / (h \nu)}{I / e} = \eta_{\text{int}} \eta_{\text{extraction}} \quad (1.30)$$

The external quantum efficiency gives the ratio of the number of usable light particles to the number of injected charge particles.

One of the most important problems facing high-efficiency LEDs is the occurrence of trapped light within the semiconductor. Owing to the high refractive index of semiconductors, light incident on a planar semiconductor/air interface is totally internally reflected, if the angle of incidence is sufficiently large. Snell's law gives the critical angle of total internal reflection. This angle defines the escape cone. Light rays with a propagation direction that lies within the escape

cone are able to leave the LED chip. Light trapped in the semiconductor will eventually be reabsorbed by a defect, the substrate, active region, or another absorbing layer.

If the light is absorbed by the substrate, the electron–hole pair will most likely recombine nonradiatively due to the inherently low efficiency of substrates. If the light is absorbed by the active region, the electron–hole pair may re-emit a photon (“recycling” of a photon) or recombine nonradiatively. If re-emitted as a photon, the photon propagation direction may fall into the escape cone. Thus the exact magnitude of the active region internal quantum efficiency and the probability of a photon to be emitted into the escape cone will determine the overall quantum efficiency of a device and the strategy (direct light extraction or light extraction by photon recycling) to attain higher efficiency. In the limit of low and high internal efficiency, photon recycling is an ineffective and effective strategy to maximize power efficiency, respectively.

The occurrence of trapped light is illustrated in Fig. 1.15. A light ray emitted by the active region will be subject to total internal reflection, as predicted by Snell’s law. In the high-index approximation, the angle of total internal reflection is given by

$$\alpha_c = \bar{n}_s^{-1} \quad (1.31)$$

where $\bar{n}_s$ is the semiconductor refractive index and the critical angle α_c is given in radians. For high-index semiconductors, the critical angle is quite small. For example, for the GaAs refractive index of 3.3, the critical angle for total internal

Fig. 1.15 (a) Light rays emanating from a point-like emitter are trapped inside the semiconductor due to total internal reflection. Only light rays with propagation directions falling within the escape cone can leave the semiconductor. Strategies increasing the extraction efficiency include (b) resonant-cavity (c) textured (d) chip-shaped LEDs.

reflection is only 17° . Thus, most of the light emitted by the active region is trapped inside the semiconductor.

The light-escape problem has been known since the 1960s. It has also been known that the geometrical shape of the LED die plays a critical role. The optimum LED would be spherical in shape with a point-like light-emitting region in the center of the LED. Light emanating from the point-like active region is incident at a normal angle at the semiconductor/air interface. As a result, total internal reflection would not occur. Note, however, that the light is still subject to Fresnel reflection at the interface unless the sphere is coated with an antireflection coating.

The most common LED structure has the shape of a rectangular parallelepiped. Such LED dies are fabricated by cleaving the wafer along its natural cleaving planes. The LEDs have a total of six escape cones, two of them perpendicular to the wafer surface, and four of them parallel to the wafer surface [40]. The bottom escape cone will be absorbed by the substrate if the substrate has a lower bandgap than the active region. The four in-plane escape cones will be at least partially absorbed by the substrate. Light in the top escape cone will be obstructed by the top contact, unless a thick current-spreading layer is employed. Thus the simple rectangular parallelepiped LED has low extraction efficiency. However, low manufacturing cost is an advantage.

There are different strategies to increase light extraction from LEDs including the resonant-cavity, surface-roughened, and chip-shaped LED shown in Fig. 1.15(b), (c), and (d), respectively. The resonant-cavity light-emitting diode (RCLED) has a light-emitting region inside an optical cavity [41, 42]. The optical cavity has a thickness of typically one-half or one times the wavelength of light, i. e. a fraction of a micrometer for devices emitting in the visible or in the infrared. The resonance wavelength of the cavity coincides with the emission wavelength of the active region. The spontaneous emission properties from a light-emitting region located inside the resonant cavity are enhanced by the change in optical mode density that has a maximum at or near the emission wavelength. The RCLED was the first practical device making use of spontaneous emission enhancement occurring in resonant cavities.

Other efficient ways to increase the light extraction efficiency include the use of *textured semiconductor surfaces* (see, for example, refs. [43–47]) and the use of tapered output couplers [48–50]. A cone-shaped surface roughening is shown in Fig. 1.15(b). Light rays emanating from the active region below the base of the cone undergo multiple reflections until they eventually have near-normal incidence at the semiconductor/air interface and escape from the chip. For infrared GaAs-based devices, external quantum efficiencies of 40% have been demonstrated with surface-textured LEDs and devices having tapered output couplers. A detailed discussion of properties and fabrication of microstructured surfaces was given by Sinzinger and Jahns [51].

Several chip-shaped LEDs have been commercialized including the *pedestal-shaped chip* shown in Figs. 1.16(a) and (b) and the *truncated inverted pyramid (TIP) chip* shown in Figs. 1.16(c) and (d) [52]. The ray traces indicated in the fig-

Fig. 1.16 Die-shaped devices: (a) Blue GaInN emitter on SiC substrate with trade name “Aton”. (b) Schematic ray traces illustrating enhanced light extraction. (c) Micrograph of truncated inverted pyramid (TIP) AlGaInP/GaP LED. (d) Schematic diagram illustrating enhanced extraction (after Osram, 2001; ref. [52]).

ures show that light rays at the base of the pyramid can escape from the semiconductor after undergoing one or multiple internal reflections. The TIP geometry reduces the mean photon pathlength within the crystal, and thus reduces internal losses. Ray-tracing computer models are employed to optimize the sidewall angle θ to maximize light extraction.

The TIP LED is a high-power LED with a large p-n junction area of $500\ \mu\text{m} \times 500\ \mu\text{m}$. The luminous efficiency of TIP LEDs exceeds $100\ \text{lm/W}$ and is one of the highest ever achieved with LEDs [52]. A peak luminous efficiency of $102\ \text{lm/W}$ was measured for orange-spectrum ($\lambda \approx 610\ \text{nm}$) devices at an injection current of $100\ \text{mA}$. This luminous efficiency exceeds that of most fluorescent ($50\text{--}104\ \text{lm/W}$) and all metal-halide ($68\text{--}95\ \text{lm/W}$) lamps. In the amber color regime, the TIP LED provides a photometric efficiency of $68\ \text{lm/W}$ ($\lambda \approx 598\ \text{nm}$). This efficiency is comparable to the efficiency of high-pressure sodium discharge lamps. A peak external quantum efficiency of 55% was measured for red-emitting ($\lambda \approx 650\ \text{nm}$) TIP LEDs. Under pulsed operation (1% duty cycle), an efficiency of 60.9% was achieved, which sets a lower bound on the extraction efficiency of these devices [52].

1.6

Omnidirectional Reflectors

There are several different ways to obtain highly reflective coatings in the visible wavelength region. Metallic layers provide robust reflectors capable of reflecting visible light over a wide range of wavelengths and incident angles. Metals reflect visible light since this frequency range is well below typical plasma frequencies of the free-electron gas. However, electron oscillations induced by incident light waves not only result in reflection but also in substantial absorption caused by electron–phonon scattering.

Distributed-Bragg reflectors (DBRs) are periodic structures with a unit cell of two dielectric layers having different refractive indices n_i and thicknesses d_i ($i = 1, 2$). DBRs can be regarded as one-dimensional photonic-crystals with a high-reflectivity stop band (“photonic-crystal gap”) comprising the nonpropagating light states in the crystal. DBRs are usually designed to have a certain center wavelength λ_{center} at *perpendicular* incidence. However, the DBR reflectivity depends on the incidence angle θ such that the stop band shifts towards shorter wavelengths for increasing θ without changing its spectral width [53]. As a result, DBRs become transparent for oblique angles of incidence.

The reflection properties of metals and DBRs depend on the polarization of the incident lightwave. According to Brewster’s law, the reflection of light polarized parallel to the plane of incidence (TM-mode) has a minimum at the incidence angle

$$\tan \theta_B = \frac{n_1}{n_2} \quad (1.32)$$

where n_1 and n_2 are the refractive indices of the adjacent materials. This is particularly important for DBRs that exhibit a drastic reflectivity decrease at θ_B . DBRs with improved wide-angle reflectivity can be achieved, e. g., by using *aperiodically* stacked layers with thickness gradients or random thickness distributions [54, 55].

Much research was devoted to DBRs with a *complete* photonic-crystal bandgap represented by a certain frequency range where all incoming photons regardless of their momentum vector $\hbar \vec{k}$ are reflected. These omnidirectional reflectors (ODRs) have a wide range of interesting applications such as all-dielectric coaxial waveguides [56], omnidirectional mirror fibers [57], and light transport tubes [58].

Omnidirectional reflection characteristics can also be obtained with distributed Bragg reflectors that have a very high index contrast such as Si/SiO₂. Another approach used polystyrene and tellurium layers in a DBR [59]. Due to the large difference of the refractive indices, $n_{\text{SiO}_2} = 1.45$; $n_{\text{polystyrene}} = 1.8$; $n_{\text{Si}} = 3.5$; $n_{\text{tellurium}} = 5$, the Brewster angle θ_B is much larger than the critical angle θ_c for total reflection resulting in a nearly complete photonic-crystal bandgap in the wavelength range from 10 to 15 μm . Still another approach consists of the use of birefringent polymers in DBRs with two different refractive indices parallel and vertical to the DBR layer planes [58]. By adjusting the differences between the vertical and in-plane indices the value of the Brewster angle can be controlled.

Fig. 1.17 Perspective view of an omnidirectional reflector (ODR). The ODR also serves as ohmic contact.

Brewster angles up to 90° (grazing incidence) and even imaginary values are possible resulting in high reflectivity for TM-polarized light at virtually all incident angles.

Unfortunately, the applicability of the above-mentioned omnidirectional DBRs in LEDs is limited since they are electrically insulating. In addition, these omnidirectional DBR structures present a considerable thermal barrier preventing efficient heat sinking due to their large thermal resistance and thickness. DBRs have been used as a substrate coating to enhance the light extraction [60, 61]. However, the active region of a LED emits light isotropically and therefore the poor reflectivity of the regular DBRs at oblique incidence angles results in undesired losses particularly for wave-guided modes as discussed above.

A very promising electrically conductive omnidirectional reflector suitable for use in LEDs is shown in Fig. 1.17 [62, 63]. The reflector comprises the LED semiconductor material with a refractive index n_s , a low-refractive index layer (n_{li}), and a metal with a complex refractive index $N_m = n_m + i k_m$, where k_m is the extinction coefficient.

The low-index layer is perforated by many small ohmic contacts that cover only a small fraction of the entire area. The array of microcontacts allows the electrical current to pass through the dielectric layer. Assuming that the ohmic contacts have an area of 1 % of the reflector, and that the alloyed ohmic contact metal is 50 % reflective, the reflectivity of the ODR is reduced by only 0.5 %. The ODR described here can be used with low-cost Si substrates or metal substrates using conductive epoxy or a metal-to-metal bonding process. These bonding processes have much less stringent requirements than direct semiconductor-to-semiconductor wafer bonding processes.

The reflectance of the semiconductor/metal reflector as a function of the incident angle θ is given by [64]

$$R_{TE} = \left| \frac{n_s \cos\theta_1 - N_m \cos\theta_2}{n_s \cos\theta_1 + N_m \cos\theta_2} \right|^2 \quad (1.33a)$$

$$R_{TM} = \left| \frac{\frac{n_s}{\cos\theta_1} - \frac{N_m}{\cos\theta_2}}{\frac{n_s}{\cos\theta_1} + \frac{N_m}{\cos\theta_2}} \right|^2 \quad (1.33b)$$

The reflectance of the triple-layer ODR as a function of the incident angle θ (see Fig. 1.18) is given by [64]

$$R = \left| \frac{r_{01} + r_{12} \exp(2i\phi)}{1 + r_{01} \cdot r_{12} \exp(2i\phi)} \right|^2 \quad (1.34a)$$

where,

$$r_{01\text{TE}} = \frac{n_s \cos \theta_1 - n_i \cos \theta_2}{n_s \cos \theta_1 + n_i \cos \theta_2} \quad (1.34b)$$

$$r_{01\text{TM}} = \frac{n_i \cos \theta_1 - n_s \cos \theta_2}{n_i \cos \theta_1 + n_s \cos \theta_2} \quad (1.34c)$$

$$r_{12\text{TE}} = \frac{n_i \cos \theta_2 - N_m \cos \theta_3}{n_i \cos \theta_2 + N_m \cos \theta_3} \quad (1.34d)$$

$$r_{12\text{TM}} = \frac{N_m \cos \theta_2 - n_i \cos \theta_3}{N_m \cos \theta_2 + n_i \cos \theta_3} \quad (1.34e)$$

and

$$\phi = \frac{2\pi}{\lambda} n_i h \cos \theta_2 \quad (1.34f)$$

Equations (1.34) apply to a low-index dielectric layer thickness of $\lambda_0/(4n_i)$, i. e., to a quarter wavelength layer. Fig. 1.18(b) shows the reflectivity $R(\theta)$ at $\lambda = 470$ nm of a triple-layer ODR (GaN/SiO₂/Ag), metal reflectors (GaN/Ag and GaN/Ni/Au), and 20 periods of Al_{0.25}Ga_{0.75}N/GaN DBR. The reflectivity curves were calculated using the optical transfer matrix method [53, 64] and using parameters, $n_{\text{Ag}} = 0.132$, $k_{\text{Ag}} = 2.72$, $n_{\text{SiO}_2} = 1.46$, $n_{\text{GaN}} = 2.45$ at 470 nm [65]. As opposed to the ODR and metal reflectors, $R(\theta)$ of the DBR sharply drops above 14° and recovers only at angles close to grazing incidence. Note that the reflectivity for TE-polarized light of the GaN/SiO₂/Ag ODR is higher than that of the GaN/Ag reflector for all angles of incidence.

Because the LED active region emits light isotropically, the total substrate reflectivity averaged over the solid angle would be a suitable figure-of-merit. The average reflectivity is given by

$$\bar{R}(\lambda) = \frac{1}{2\pi} \int_0^{\pi/2} R(\lambda, \theta) 2\pi \sin\theta d\theta \quad (1.35)$$

where λ denotes the emission wavelength and θ the angle of incidence in the semiconductor. As a result, the angle averaged reflectivity $\bar{R}$ is much larger for a GaN/SiO₂/Ag ODR ($\bar{R} = 0.93$ at $\lambda = 470$ nm) and Ag reflector ($\bar{R} = 0.92$ at $\lambda = 470$ nm) than for the DBR ($\bar{R} = 0.49$ for TE-polarized, $\bar{R} = 0.38$ for TM-polarized at $\lambda = 470$ nm). The averaged reflectivity of triple-layer ODRs exceeds the value of $\bar{R}$ for the transparent DBR by about a factor of two.

Note that the reflectivity increase is significant. The power of a wave-guided mode, P , attenuated by multiple reflection events (with reflectivity R) depends on the number of reflection events, N , according to

$$P = P_0 R^N \quad (1.36)$$

where P_0 is the initial power of the mode.

At perpendicular incidence, the reflectance of the triple-layer ODR is given by [62, 63]

$$R_{\text{ODR}}(\theta_1 = 0) = \frac{\{(n_S - n_{li})(n_{li} + n_m) + (n_S + n_{li})k_m\}^2 + \{(n_S - n_{li})k_m + (n_S + n_{li})(n_{li} - n_m)\}^2}{\{(n_S + n_{li})(n_{li} + n_m) + (n_S - n_{li})k_m\}^2 + \{(n_S + n_{li})k_m + (n_S - n_{li})(n_{li} - n_m)\}^2} \quad (1.37)$$

For an AlGaInP/SiO₂/Ag structure emitting at $\lambda = 630$ nm, Eq. (1.37) yields a normal-incidence reflectance $R_{\text{ODR}}(\theta = 0) > 98\%$. This value exceeds the corresponding value for a structure *without* a low-index layer by about 3 %, thereby reducing optical losses by a substantial amount. Due to the power-law dependence this improvement of R is of great importance and shows the huge potential of ODRs. The triple-layer ODR can be improved significantly by using novel low- n materials such as nanoporous SiO₂ that has a refractive index as low as 1.10 [66]. It is transparent in the visible and near UV spectrum. In contrast, SiO₂ has a refractive index of about 1.46 and very good transparency in the visible and near UV spectrum.

The schematic structure of an ODR-based LED is shown in Fig. 1.19. It consists of a top current-spreading (or window) layer, the active and confinement layers, a bottom window layer, the ODR, and a submount such as a Si or metal wafer. The active layers include the lower and upper confinement layers and the bulk or multiple-quantum-well (MQW) active region. The wafer is grown in the standard “p-side up” mode that is employed in nearly all LEDs at the present time.

The wide-angle reflectivity of the ODR allows wave guiding of light rays with much smaller attenuation than a DBR. As a result, light extraction at the edges of the LED chip is strongly increased.

Fig. 1.19 Schematic of the omnidirectional reflector (ODR) LED. An array of microcontacts perforating the ODR serves as p-type ohmic contact to the epitaxial AlGaInP layers.

1.7 Packaging

Virtually all LEDs are encapsulated with an optically transparent polymer. Encapsulants have several requirements including high transparency, high refractive index, chemical stability, high-temperature stability, and hermeticity. The refractive index contrast between the semiconductor and air is reduced by the encapsulant. A reduced index contrast at the semiconductor surface increases the angle of total internal reflection thereby enlarging the LED escape cone and extraction efficiency. Furthermore, encapsulants provide protection against unwanted mechanical shock, humidity, and chemicals. The encapsulant also stabilizes the LED chip and bonding wires. Finally the epoxy resin provides mechanical stability to the two metal leads of the LED and holds them in place.

A *low-power package* is shown in Fig. 1.20(a). The device is attached to the bottom of a cup-like depression ("reflector cup") formed in one of the lead wires

Fig. 1.20 (a) LED with hemispherical encapsulant. (b) Cross section through high-power package. The heatsink slug can be soldered to a printed circuit board for efficient heat removal (adopted from ref. [68]).

(usually the cathode lead). A bond wire connects the LED top contact to the other lead wire (usually the anode lead). The LED package shown in the figure is frequently referred to as a “5 mm” or “T1-3/4” package.

In low-power LEDs, the encapsulant has the shape of a hemisphere, so that the angle of incidence at the encapsulant/air interface is always normal. As a result, total internal reflection does not occur at the encapsulant/air interface.

A *power package* is shown in Fig. 1.20 (b). Power packages have a *thermally conductive path* from the LED chip, through the package, to a heat sink, e. g. a printed circuit board. The power package shown in the figure has several advanced features. First, the package contains an Al or Cu heatsink slug with low thermal resistivity. Second, the chip is encapsulated with silicone. Because standard silicone retains mechanical softness in its cured state, the silicone encapsulant is covered with a plastic cover that also serves as a lens. Third, the chip is directly mounted on a Si submount that includes electrostatic discharge (ESD) protection [67]. Electrostatic discharge-protection circuits typically consist of a series of Si diodes or of a Si Zener diode. The current caused by an electrostatic discharge, which can be understood as a short high-voltage pulse applied to the electrodes of the device, will bypass the LED and flow mostly through the series of low-resistance Si diodes thereby protecting the LED.

The thermal resistance of LED packages together with the maximum temperature of operation determines the maximum thermal power that can be dissipated in the package. The maximum temperature of operation may be determined by reliability considerations, by the degradation of the encapsulant, and by internal quantum-efficiency considerations. Several types of LED packages and their thermal resistance are shown in Fig. 1.21 [69]. Early LED packages introduced in the late 1960s and still used for low-power packages, have a high thermal resistance of about 240 K/W. Packages using *heatsink slugs* made of Al or Cu that transfer heat from the chip directly to a printed circuit board (PCB) that in turn spreads the heat, have thermal resistances of 6–12 K/W. It is expected that thermal resistances of < 5 K/W will be achieved for advanced passively cooled power packages.

Note that the packages shown in Fig. 1.21 do not use *active cooling* (fan cooling). Heatsinks with cooling fins and fan are commonly used to cool electronic microchips including Si CMOS microprocessors. They have thermal resistances < 0.5 K/W. The use of active cooling devices would reduce the power efficiency of LED-based systems and are therefore not used.

A common encapsulant is *epoxy resin* (also called epoxy) that remains transparent and does not show degradation over many years for long-wavelength visible-spectrum and IR LEDs. However, it has been reported that epoxy resins lose transparency in LEDs emitting at shorter wavelengths, i. e. in the blue, violet, and UV [70]. Epoxy resins are chemically stable up to temperatures of about 120 °C. However, prolonged exposure to temperatures > 120 °C leads to yellowing (loss of transparency).

To overcome the limited thermal stability of epoxies, *silicone encapsulants* have been used starting in the early 2000s. Silicone is a polymer that contains Si and O thereby resembling SiO₂ more so than epoxy resins. This resemblance sug-

Fig. 1.21 Thermal resistance of LED packages: (a) 5 mm (b) low-profile (c) low-profile with extended lead frame (d) heatsink slug (e) heatsink slug mounted on printed circuit board (PCB). Trade names for these packages are “Piranha” ((b) and (c), Hewlett Packard Corp.), “Barracuda” ((d) and (e), Lumileds Corp.), and “Dragon” ((d) and (e), Osram Opto Semiconductors Corp.) (adopted from ref. [69]).

gests that silicone encapsulants are chemically and thermally stable and do not lose transparency as easily as epoxy resins. Indeed, standard silicones are stable up to temperatures of about 160 °C, i. e. significantly higher than epoxy. It is desirable to develop encapsulants that are SiO₂-like because silica has excellent thermal and chemical stability [71].

Poly (methyl methacrylate) or briefly *PMMA* is a less common encapsulant used for LEDs. PMMA is also known under the name of acrylic glass and under the product name Plexiglas. The relatively low refractive index of PMMA ($\bar{n} = 1.49$ in the wavelength range 500 – 650 nm) results in a limited extraction efficiency when used with high-index semiconductors.

1.8

Conclusion

In this chapter, properties of inorganic LEDs have been reviewed, including optical emission spectra, direct and indirect semiconductors, radiative and nonradiative recombination processes, and double-heterostructure active regions, and quantum-well active regions. We also reviewed advanced device physics including resonant-cavity designs that result in enhanced LED emission characteristics and current transport in a variety of LED structures. Advanced LED fabrication techniques for achieving high extraction efficiency, such as chip shaping, highly efficient omnidirectional reflectors, and packaging issues, were also discussed.

Inorganic semiconductor LEDs are environmentally benign and very promising candidates for high-power, high-efficiency, and low-cost lighting and illumination applications. AlGaInP-based compound semiconductors are capable of emitting in the red, orange, amber, and yellow wavelength regions with high external efficiency. AlGaInN-based semiconductors are efficient sources in the UV, violet, blue, cyan, and green wavelength regions. This enables high-brightness inorganic LEDs to be used for high-efficiency white-light sources with excellent color-rendering capabilities in solid-state lighting applications.

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