Organic Light Emitting Devices

Synthesis, Properties and Applications

Edited by Klaus Müllen and Ullrich Scherf



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Preface

Organic electroluminescent devices have been one of the most attractive research topics in Material Sciences during the last two decades. The attraction and fascination of this field stem mainly from the interdisciplinary nature of the approach which includes synthetic and physical chemistry, device physics and electrical engineering. Particularly appealing and inspiring is the palpable link between both basic and applied science and an immense industrial and commercial interest in its applications.

When surveying the progress of research and development in electroluminescent devices, it becomes obvious that such emerging technologies always develop by way of competition with existing technologies which are themselves undergoing continual optimization. One is thus "shooting at moving targets". The strong competition between the as yet progressing "conventional" semiconductor technology and the "new" field of organic electronics applications forms the backdrop for the development of organic electroluminescent devices. Moreover, the competition is not only focused on scientific problems such as materials design and optimization, device structure and performance (including power consumption and lifetime/stability), but close to market also issues such as large scale production, manufacturing costs and market prices become important. Despite all these problems the commercialization of organic electroluminescent devices is forging ahead with impressive speed and capacity. The process is driven globally by numerous large multinational companies as well as small start-up companies.

Research into organic electronic materials was dominated until the 1980s by the search for "synthetic metals" with a high electrical conductivity. In this endeavor, oxidatively or reductively doped organic materials were most favored. Thereafter the electronic and emissive properties of neutral, undoped organic semiconductors also became focal points of major scientific activities. The spearhead of the organic electroluminescence research was achieved by Ching Tang's group at Kodak in the late 1980s. Their impressive contributions to organic electroluminescent and photovoltaic devices paved the way for all the subsequent progress. Some years later Richard Friend's group in Cambridge performed pioneering work which introduced light-emitting semiconducting polymers as an additional class of promising emissive organic materials for electroluminescent devices. New technology requires new or improved materials. For example, the pioneering OLED work of the Friend group published in 1990 used low quality, so-called "precursor poly(phenylene vinylene)" (PPV) as the emissive material. Their initial, very promising findings then stimulated a wealth of synthetic work. After 15 years of materials improvement soluble PPV-type materials with high purity, structural regularity and excellent OLED performance are now commercially available. No doubt, the synthetic protocols employed to generate these polymers are crucial for achieving reasonably high molecular weights and structural perfection, as the presence of defects has major and usually deleterious effects upon the performance of OLED devices.

However, the competition between different concepts is not limited to the chemical structure and molecular weight of the organic materials. Also the techniques for their processing are a key factor. While low molecular weight organic materials are commonly processed by well-established ultra-high vacuum techniques (MBD, PVD, and CVD) as widely used in the production of inorganic semiconductor devices, wet processing is an alternate procedure for the deposition of semiconducting oligomers and polymers, e. g. by spin casting, doctor blading, and screen or inkjet printing. Solution based processing techniques seem pivotal to the search for low cost fabrication alternatives. The wet processing of semiconducting materials for OLED devices, however, is by no ways a trivial task, so that the solubility behavior of the solution-processed components assumes particular attention. Since multilayer devices are the mostly favored OLED design, either a strict orthogonality in the solubility of different materials or a subsequent cross-linking of previously solution-deposited layers is required.

The complexity of the competition, however, does not end with this example. Much of the industrial interest in organic electroluminescent materials sprang from the hope that a future display technology would be mainly based on organic light emitting diodes (OLED) and was derived from envisaged advantages as high brightness, wide viewing angles and low cost. But meanwhile also liquid crystalbased displays (LCD) were tremendously improved. It is by no means clear which technology will finally win the contest and whether electroluminescence of organic materials will be used primarily in OLED displays or for solid-state lighting applications.

Research into OLEDs has generated important scientific problems, such as how to control not only the emission wavelength so as to obtain full color red/green/ blue (RGB) OLED devices, but also the migration of excitations within or between individual molecules, the balancing of the concentrations of charge carriers, the design of optimized interfaces between organic layers and electrodes, etc. Important criteria, hereby, are a maximum power efficiency and lifetime/stability of the resulting OLED devices. The introduction of transition metal-based electrophosphorescent emitters defined a further milestone towards technologically relevant device efficiencies. The enormous progress made in the application of triplet emitters has initiated a new round of OLED research. Again, the device optimization (performance-lifetime-stability) is the key challenge, e. g., a combination of a maximum device performance with sufficient lifetimes. As a next step, technological problems resulting from large scale fabrication of devices are at the focus of efforts towards a commercialization of OLED devices. It is important to note that LCD and OLED display panels are designed upon similar principles since behind the active organic layers, both require driving electronics based on thin-film transistors. This similarity suggests that the commercialization of OLED devices is not only guided by the device performance, but to a great extent by fabrication technology and production costs.

The concept of "Organic Electroluminescent Devices" follows the above outlined landscape. The logical place to begin is by first covering the background against which all research into OLEDs occurs – the existing but still evolving technology of inorganic LEDs, which is the immediate competitor against which OLEDs must seek to establish themselves. We therefore start with an introductory chapter by Fred Schubert on inorganic semiconductors for LEDs.

Obviously before one can hope to optimize OLEDs one needs to understand the scientific fundamentals behind their operation. So we then proceed with contributions from two of the world's leading experts on the photophysics of organic semiconductors into the fundamental issues involved in emission from organic materials. Heinz Bässler provides an overview of the photophysics of emissive organic materials, while Richard Friend presents a discussion of his recent work into one of the key topics in the physics of OLEDs: the electronic processes at polymer heterojunctions. This leads logically on to considering how one goes about optimizing OLEDs, which is covered by two contributions which between them illustrate many of the methods being used to achieve this vital goal. Alan Heeger describes the various research approaches being investigated at Santa Barbara, while Shuit-Tong Lee presents some of the recent work from his group at Hong Kong.

Having established the fundamentals of OLEDs and their development, we next turn to consider the materials that are to go into them and their processing. One needs to know not only what types of materials have been or could be used in OLEDs, but also how their properties can be controlled by synthetic design. Here we have overviews of the synthesis of two of the main components in OLEDs. Andrew Grimsdale describes the main classes of electroluminescent polymers, with an emphasis on how their properties and device performance can be optimised by synthetic design, while Yasuhiko Shirota reviews materials for use as charge-transporting and hole-blocking layers in multilayer devices. Dendrimers are a class of material which are generating increasing interest in all areas of materials science and John Lupton provides us with a review of their use in OLEDs. Finally Klaus Meerholz describes some of his exciting work which beautifully demonstrates how the intended processing of materials must be an integral feature of their design.

Finally, novel directions are continually opening up in OLED research and development, and so we end with accounts of three of the most exciting of those that have appeared in recent years. An optimal material for an LED would combine the advantages of inorganic and organic materials, and so Andrey Rogach provides an account of work into inorganic/organic hybrid materials, which seek to achieve this. A major limit on the performance of OLEDs has always been that the energy of the majority of excited states, the triplets, was wasted. Dieter Neher describes how electrophosphorescent devices based on triplet emitters are being developed which utilize this resource and so offer the prospect of much higher device efficiencies. Finally, the ultimate development of OLED technology would be to make an electrically pumped organic laser diode and so we conclude with a contribution from Uli Lemmer on the work being done on organic semiconductor lasers which aims to cross that final frontier.

We would like to express our gratitude to Martin Ottmar at Wiley-VCH for inviting us to bring this exciting field of research to a wider audience, to all our distinguished contributors for their efforts, and especially to Andrew Grimsdale for his assistance in coordinating the project.

Mainz and Wuppertal November 2005

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Inorganic Semiconductors for Light-emitting Diodes

1

E. Fred Schubert, Thomas Gessmann, and Jong Kyu Kim

1.1 Introduction

1

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 highpower 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

2 1 Inorganic Semiconductors for Light-emitting Diodes

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

$$R = -\frac{\mathrm{d}n}{\mathrm{d}t} = -\frac{\mathrm{d}p}{\mathrm{d}t} = B n p \tag{1.1}$$

where *B* is the *bimolecular recombination coefficient*, with a typical value of 10^{-10} cm³/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

$$E = E_{\rm C} + \frac{\hbar^2 k^2}{2 m_e^*} \qquad (\text{for electrons}) \tag{1.2}$$

and

$$E = E_{\rm V} - \frac{\hbar^2 k^2}{2 m_{\rm h}^*} \qquad (\text{for holes}) \tag{1.3}$$

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.

$$h\nu = E_{\rm e} - E_{\rm h} \approx E_{\rm g} \tag{1.4}$$

The photon energy is approximately equal to the bandgap energy, $E_{\rm g}$, if the thermal energy is small compared with the bandgap energy, that is, $kT << E_{\rm g}$. 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

$$p = m^{*} \nu = \sqrt{2 \, m^{*} \, \frac{1}{2} \, m^{*} \, \nu^{2}} = \sqrt{2 \, m^{*} \, kT} \tag{1.5}$$

The momentum of a photon with energy $E_{\rm g}$ can be obtained from the de Broglie relation

$$p = \hbar k = h \nu / c = E_g / c \tag{1.6}$$

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*-

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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*

$$h\nu = E_{\rm C} + \frac{\hbar^2 k^2}{2 m_{\rm e}^*} - E_{\rm V} + \frac{\hbar^2 k^2}{2 m_{\rm h}^*} = E_{\rm g} + \frac{\hbar^2 k^2}{2 m_{\rm r}^*}$$
(1.7)

where m_r^* is the reduced mass given by

$$\frac{1}{m_{\rm r}^*} = \frac{1}{m_{\rm e}^*} + \frac{1}{m_{\rm h}^*} \tag{1.8}$$

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

$$\rho(E) = \frac{1}{2\pi^2} \left(\frac{2m_{\rm r}^*}{\hbar^2}\right)^{3/2} \sqrt{E - E_{\rm g}}$$
(1.9)

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

$$f_{\rm R}(E) = e^{-E/(kT)}$$
(1.10)

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

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

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

$$E = E_{\rm g} + \frac{1}{2} kT \tag{1.12}$$

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

$$\Delta E = 1.8 \, kT \tag{1.13}$$

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,

$$P(\lambda) = P \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2} \left(\frac{\lambda - \lambda_{\text{peak}}}{\sigma}\right)^2\right]$$
(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. $Ga_{1-x}In_xN$. 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 $Ga_{1-x}In_xN$ LEDs

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Fig. 1.4 Emission spectrum of AlGaInP/GaAs red, GaInN/GaN green, GaInN/GaN blue, GaInN/GaN UV, and AlGaN/AlGaN 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 indirectgap 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 mechanisms 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 $\lambda / 2$.



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Fig. 1.6 (a) Schematic structure of a substrate-emitting GalnAs/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. $L_{cav} >> \lambda$. However, if the distance between the two reflectors is of the order of the wavelength, $L_{cav} \approx \lambda$, 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])

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

where $W_{\text{spont}}^{(\ell)}$ is the spontaneous transition rate into the optical mode l and $\varrho(v_{\ell})$ 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

$$\rho^{1D}(\nu) = \frac{2 n}{c}$$
(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 v_0 and $2v_0$, 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 $v_0 = c / 2nL_{cav}$ 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, $T(\nu)$,

$$\rho(\nu) = K T(\nu) \tag{1.17}$$



Fig. 1.7 (a) Optical mode density of a onedimensional planar microcavity (solid line) and of homogeneous onedimensional 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

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

The transmittance has maxima at v = 0, v_0 , $2v_0$..., and minima at $v = v_0/2$, $3v_0/2$, $5v_0/2$

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

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

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

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.