Spectral dependence of light extraction efficiency of high-power III-nitride light-emitting diodes

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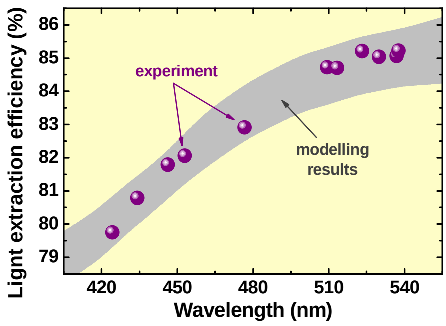
Using recently suggested method of processing the data on external quantum efficiency as a function of output optical power, we have estimated the dependence of light extraction efficiency of high-power light-emitting diodes (LEDs) on their emission wavelength varied between 425 and 540 nm. The extraction efficiency is found to increase with the wavelength from ~80% to ~85% in this spectral range and to correlate with the wavelength dependence of reflectivity of the large-area p-electrode being the essential unit of the LED chip design. The correlation found identifies the incomplete reflection of emitted light from the electrode as the major mechanism eventually controlling the spectral dependence of the efficiency of light extraction from the LEDs.



Spectral dependence of LEE of UX:3™ LED chip: comparison of experiment and modelling results.

1 Introduction One of the obstacles for more extensive penetration of solid-state lighting into human life is substantial efficiency reduction of both III-nitride and III-phosphide LEDs in the spectral range between 500 and 600 nm, which is known as the ‘green gap’ problem [1,2]. In the case of phosphide LEDs, the efficiency reduction is attributed to (i) suppression of radiative recombination caused by filling up the X-valleys of the conduction band with electrons and (ii) leakage of electrons into p-side of an LED structure over insufficiently high barriers formed in the conduction band due to low offsets. The origins of the efficiency reduction in nitride LEDs are not completely understood. Neither degradation of materials quality with the indium content in InGaN quantum wells (QWs) normally used as the active regions of LED structures nor the quantum-confined Stark effect leading to separation of electron and hole wave functions in the QWs of polar orientation are capable of explaining solely the observed efficiency reduction (see, e.g., the discussion on the spectral dependence of carrier recombination coefficients in InGaN QWs given in [3]). Therefore, it is important to gain a thorough insight into all the possible factors that may be relevant to the ‘green gap’ problem.

Generally, the measured external quantum efficiency (EQE) η_e of an LED is the product of the internal quantum efficiency (IQE) η_i and light extraction efficiency (LEE) η_{ext} . As IQE is primarily controlled by a particular design and operation conditions of the LED structure, LEE is largely dependent on properties and design of the LED chip. To distinguish between the contributions of IQE and LEE to the EQE variation in the ‘green gap’, separate evaluation of η_i and η_{ext} is highly required.

Generally, LEE can be estimated experimentally from the encapsulation gain (EG) [4,5], i.e. increase in the LED efficiency due to casting of the LED chip by a transparent material with the refractive index higher than that of air. The method is based on preliminary simulations to find correlation between EG and LEE, which is known to depend on the chip size, encapsulant shape [6], and other details of the LED design [5]. Being accurate enough, the simulations may, however, predict LEE by themselves, making the experiments unnecessary.

On the other hand, the available theoretical approaches are incapable at the moment of predicting LEE with *a priori* known accuracy. Ray tracing based on geometric optics fails to account properly for the photon scattering by textured surfaces with the features sizes comparable with the emission wavelength. Finite-difference time-domain (FDTD) computations are not so suitable to deal with the photon ensembles and exploit some artificial boundary conditions still having uncertain impact on the prediction accuracy [7]. Other approaches, considering scattering of electromagnetic waves by textured surfaces, frequently use a number of simplifications, like using Helmholtz equation instead of the Maxwell's ones; splitting the problem into those related to TE- and TM-polarization, which is correct in 2D approximation only; neglecting electro-magnetic field discontinuities at the sharp edges of the textures, etc., that do not allow one to regard them as rigorous methods. Therefore, the search of a direct experimental way for LEE evaluation seems to be important now for both comparison of various LED designs and their optimization.

Recently, a novel procedure for LEE estimation based on ABC-model has been proposed and applied to analysis of temperature-dependent efficiency of commercial blue LEDs [8]. Here, we extend the procedure to a wider spectral range and use it for analysis of wavelength-dependent LEE of advanced UX:3^{TM} chips normally utilized in production of high-brightness LEDs. The results of the analysis are compared with predictions of a simple theoretical model, which enables identification of the main factors controlling the LEE spectral dependence.

2 Experimental

2.1 Samples and efficiency measurements

Single-quantum well (SQW) LED structures emitting at the wavelengths between 425 and 540 nm were grown by metal-organic vapour phase epitaxy on (0001) sapphire substrates. The detailed structure design was described elsewhere [9]. The grown structures were processed into 1×1 mm^2 thin-film UX:3^{TM} dice where silver-based electrodes were formed to the p-contact layer, after removing the sapphire substrate the back surface of the n-contact layer was textured to increase LEE, and the current access to the n-contact layer was provided by the metallic column electrodes passing through blind vias made in the structure [10]. Finally, the processed dice were packaged into standard TO-18 cases.

Room-temperature EQE was measured as a function of current in integrating sphere. The use of pulsed measurements at high currents enabled minimizing of self-heating effects on the LED efficiency (see discussion on the measurements and heating control given in [9]).

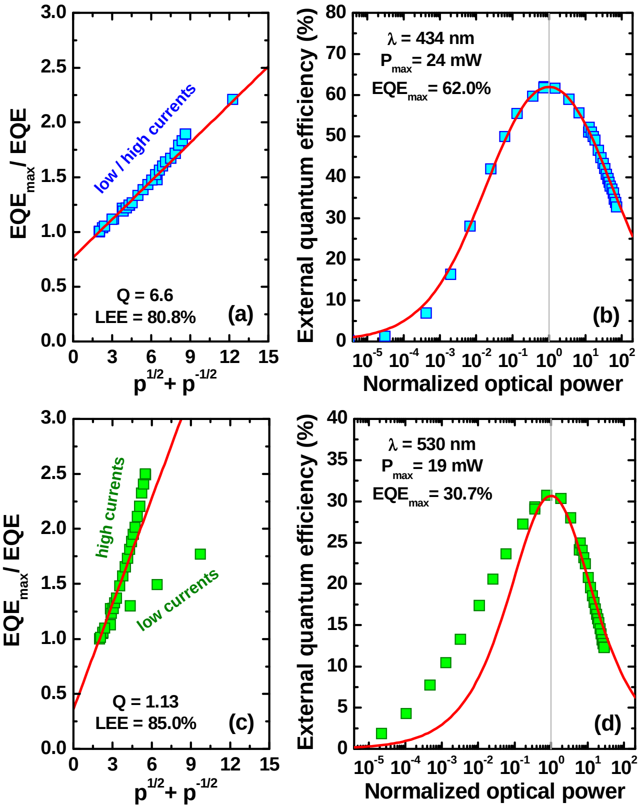


Figure 1 The η_{max}/η_e ratio as a function of $p^{1/2}+p^{-1/2}$ (a,c) and experimental and theoretical EQE *vs.* normalized optical power p (b,d) obtained for the emission wavelengths of 434 nm (a,b) and 530 nm (c,d). Squares are experimental point, lines are fittings with ABC-model.

2.2 Data processing

To estimate LEE, the measured EQE was plotted *versus* output optical power P_{out}, then the power P_{max} corresponding to the EQE maximum η_{max} was found, and the ratio η_{max}/η_e was replotted as a function of $p^{1/2}+p^{-1/2}$, where $p = P_{out}/P_{max}$ is the normalized optical power (NOP) – see Fig.1a,c. In the case of blue LEDs, low- and high-current values of the η_{max}/η_e ratio merge, forming a function nearly linear in $p^{1/2}+p^{-1/2}$ with the slope equal to $(Q+2)^{-1}$ (Fig.1a). Here, the dimensionless quality factor $Q=(B/AC)^{1/2}$ and A , B, and C are the recombination coefficients of the ABC-model (see [3,8] for more detail). As the maximum IQE value is equal to $Q/(Q+2)$ within the model, LEE can be estimated as the ratio of the maximum EQE to maximum IQE value, i.e. $\eta_{ext}=\eta_{max}(Q+2)/Q$. LEE obtained in such a way accounts for both the efficiency of light extraction from LED chip by itself and the package efficiency related to the light extraction from the LED case. As soon as the quality factor Q is found from approximation of experimental data, EQE as a function of p can be then calculated as $\eta_e = \eta_{ext}\, Q/(Q + p^{1/2} + p^{-1/2})$ in the whole range of the NOP variation (see Fig.1b).

Application of the same procedure to green LEDs provides the low- and high-current branches of the η_{max}/η_e ratio as a function of $p^{1/2} + p^{-1/2}$ that do not merge with each other (Fig.1c). In this case, the low-current branch is less reliable for the fit by ABC-model, as it can be affected by either carrier localization due to composition fluctuations in InGaN or by violation of the InGaN QW electric neutrality (see [3] for more detail). Therefore, fitting of the high-current branch only was used in our study to determine LEE of the LED chip in the green spectral range, as shown in Fig.1c. Such an approach is similar to that previously employed for determination of recombination coefficients in the SQW LED structures [9].

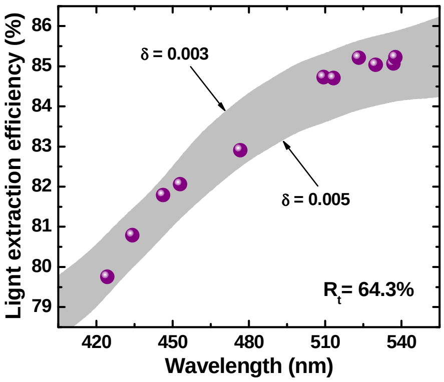


Figure 2 Spectral dependence of LEE of UX:3^{TM} LED chips. Balls are data obtained by the fitting procedure based on ABC-model. Grey shadow represents the modelling results obtained with the integral absorption parameter δ ranged from 0.003 (upper boundary) to 0.005 (lower boundary) – see text for more detail.

Figure 2 shows the spectral dependence of LEE of the UX:3^{TM} chips obtained by the processing procedure described above. The extraction efficiency is found to grow with the emission wavelength taken at the EQE maximum from ~80% to ~85% in the spectral range of 425-540 nm.

3 Modelling In order to interpret the observed LEE spectral dependence, three mechanisms of optical losses in the LED die have to be considered. The first one is the interband absorption of the emitted light in the SQW active region. As the Stokes shift between the absorption edge and luminescence peak increases with the Indium content in InGaN SQW [11], one can expect such kind of absorption to be reduced at longer wavelengths. Another loss mechanism is the free-carrier absorption in the p- and n-contact layers, enhancing with the LED emission wavelength. And, the third mechanism is the incomplete light reflection from the large-area metallic electrode formed to the p-contact layer. We do not discuss here the optical losses in the LED case, as they unlikely exhibit strong wavelength dependence which could control the observed spectral dependence of the overall LEE.

To assess to role of the above mechanisms for LEE, we apply a simple model considering the LED chip as a slab with infinite lateral dimensions, highly reflective electrode at the bottom surface, and textured top surface. Let $i_+(\theta)$ and $i_-(\theta)$ be the photon fluxes, averaged over the light polarization and azimuthal angle, that come to and go out of the top surface at an angle θ counted from the normal to the surface. These fluxes are interrelated with each other:

$$\begin{aligned} i_-(\theta) &= \int_0^{\pi/2} \rho(\theta,\theta')\cdot i_+(\theta')\sin\theta' d\theta' \\ i_+(\theta) &= g_+(\theta)\, e^{-\delta_n/\cos\theta} + R_m(\theta) g_-(\theta)\, e^{-(\delta_n+2\delta_p)/\cos\theta} \\ &\quad + R_m(\theta)\, i_-(\theta)\, e^{-2(\delta_p+\delta_n)/\cos\theta} \end{aligned} \qquad (1)$$

Here $\rho(\theta,\theta')$ is the kernel accounting for changing the photon direction due to its scattering at the textured surface, $g_+(\theta)$ and $g_-(\theta)$ are the photon fluxes emitted by the active region towards the top and bottom surfaces, respectively, $R_m(\theta)$ is the averaged over polarization reflectivity of the metallic electrode, and δ_n and δ_p are the products of the n- and p-contact layer thicknesses and corresponding absorption coefficients. Equations (1) do not include the interband absorption in the active layer by the reasons discussed below.

Let us assume now the light emission from the active region and light scattering by the top textured surface to be isotropic, i.e. $g_+(\theta) = g_-(\theta) = ½G_a$ and $\rho(\theta,\theta') = R_t$ where G_a is the total photon flux emitted by the active region in all directions and R_t is the integral back-scattering coefficient of the textured surface. In addition, we assume the photon gas in the slab to equilibrate well due to random scattering at the textured surface, leading to $i_+(\theta) \approx \langle i_+\rangle$ and $i_-(\theta) \approx \langle i_-\rangle$ [12], where $\langle f \rangle = \int_0^{\pi/2} f(\theta)\cdot\sin\theta d\theta$ for any angle-dependent function f. The efficiency of light extraction from the LED chip $\eta_{ext} = I_{out}/G_a$ where $I_{out} = \langle i_+\rangle - \langle i_-\rangle$ is the photon flux outgoing from the slab. Thus, integrating Eqs.(1) over the polar angle, one can obtain under the above assumptions the following expression for LEE:

$$\eta_{ext} = \frac{\frac{1}{2}(1-R_t)(I+R_1)}{1-R_t R_2} \qquad (2)$$

Here $R_1 = \left\langle R_m\, e^{-(\delta_n+2\delta_p)/\cos\theta}\right\rangle$, $R_2 = \left\langle R_m\, e^{-2(\delta_p+\delta_n)/\cos\theta}\right\rangle$, and $I = \left\langle e^{-\delta_n/\cos\theta}\right\rangle$ are integrals that can be calculated numerically. Equation (2) may be further simplified, accounting for the fact that δ_n and δ_p are both much less than unity (see estimates made below) and that $R_m(\theta) \approx 1$ in the case of the highly reflective p-electrode. Therefore, $I + R_1 \approx 1 + R_2$, and the expression (2) may be finally reduced to

$$\eta_{ext} \cong \frac{\frac{1}{2}(1-R_t)(1+R_2)}{1-R_t R_2} \quad , \quad R_2 = \left\langle R_m \, e^{-\delta/\cos\theta} \right\rangle \qquad (3)$$

where R_2 is dependent only on the integral absorption losses accounted for by the integral absorption parameter $\delta = 2(\delta_n + \delta_p)$ (see Fig.3a). By a similar manner and within the same approximation accuracy, the interband absorption in the active layer can be also included in the parameter δ, if necessary. Such a way enables avoiding of consideration in Eqs.(1) various positions of the photon emission points inside the active region.

The impact of interband absorption on operation of violet LEDs with a bulk InGaN active region is found to be substantial [5]. In our case of blue and green LEDs, we expect it to be weaker primarily due to a remarkably larger Stokes shift between the emission and absorption spectra [11]. The expectation is, however, primarily relevant to the SQW LED structures considered in our study. In the case of commercial MQW LEDs, the interband absorption may be more important and, therefore, it should also be accounted for in the integral absorption parameter δ.

Using the available data on free-carrier absorption cross-sections for electrons and holes in GaN [13-14], making simulations of the interband absorption in the active region by a commercial package [15], and accounting for typical thicknesses of the n- and p-contact layers, we have estimated the total-loss parameter δ to vary between 0.003 and 0.005 in the spectral range of 405-555 nm.

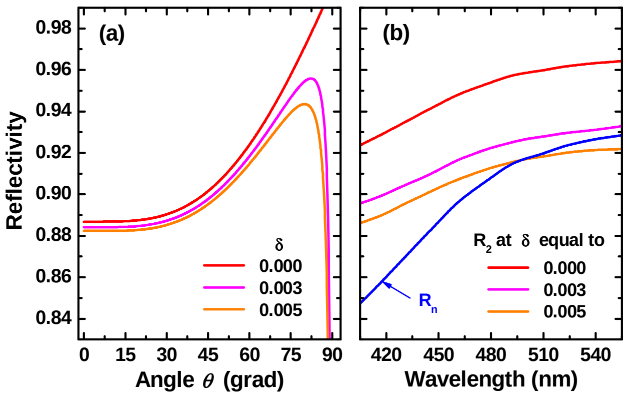


Figure 3 Angle dependence of $R_m(\theta)\,e^{-\delta/\cos\theta}$ at the emission wavelength of 450 nm (a) and normal-incidence reflectivity R_n of Ag and R_2 as a function of the wavelength (b) calculated at different values of the integral absorption parameter δ.

Figure 3b shows the spectral dependence of the Ag reflectivity at normal incidence R_n and the effective reflectivity R_2 calculated for different values of the integral absorption parameter δ. The calculations used the experimental optical constants of Ag tabulated in [16]. One can see that variation of R_2 with the wavelength are more gradual than those of R_n, which is due to considerable contribution of glancing angles to the effective reflectivity (see Fig.3a). On the other hand, R_2 is affected noticeably by the optical losses accounted for with the parameter δ. Calculation of LEE, using these values of R_2 and Eq.(3), provides the theoretical results shown in Fig.2 by grey shadow corresponding to $0.003 \le \delta \le 0.005$. Here, $R_t = 0.643$ was chosen in such a way, as to fit the mean LEE value to that obtained experimentally at 435 nm. The back-scattering coefficient R_t was assumed to be independent of the wavelength in view of the FDTD simulation results reported in [17] and demonstrating negligible spectral dependence of LEE in a thin-film LED with variable texture. Since no particular dependence of the integral absorption parameter δ is assumed in the calculations, the grey shadow in Fig.2 indicates just the range of the LEE values obtained at various δ from the above mentioned interval.

Comparison of the experimental data with the modelling results given in Fig.2 leads to two important conclusions. First, the changes in LEE caused by the variation of the absorption losses in the LED structure, ~1.0-2.0%, are smaller than the changes originated from the spectral dependence of the Ag reflectivity, ~6.5% in the range of 405-555 nm. This implies the reflectivity of the p-electrode to be the major factor determining the spectral dependence of LEE. Second, there is a rather reasonable agreement between the simple theory and experiment. Basing of the model results shown in Fig.3b and considering the effective reflectivity R_2, we can rank the absorption losses and those related to incomplete reflection of the emitted light from the metallic p-electrode. The latter kind of losses covers about 67% of the total ones at 420 nm, whereas their percentage falls down to 53% at 540 nm.

The above model does not take into account the package efficiency (PE), though it can easily be introduced in the model as a separate factor in Eq.(3). Being known, PE different from unity would produce a small correction of the fitted back-scattering coefficient R_t and, hence, of the LEE value. Such a correction was not made for the data plotted in Fig.2, so that the extracted LEE values involve integrally PE too.

4 Conclusion

In this paper, the procedure of separate LEE/IQE evaluation suggested recently for blue LEDs has been extended to the green spectral range where the ABC-model underlying the procedure fits the measured EQE less reliably. The idea of using for fitting the high-current experimental points only, i.e. those corresponding to NOP greater than unity, has provided rather reasonable results consisted with those obtained in the blue spectral range.

The above procedure has been applied to SQW LED structures processed as UX:3 ^{TM} chips. The overall light extraction efficiency of the LEDs derived from the measured EQE as a function of output optical power is found to increase gradually from ~80% to ~85% while the emission wavelength rises from 425 to 540 nm. These values agree well with that obtained earlier theoretically for such a kind of chip design [10]. The spectral dependence of LEE is primarily attributed to the optical losses caused by incomplete reflection of the emitted light from the large-area highly-reflective p-electrode and particular optical properties of the electrode material.

The above conclusion is supported by simulations using a model considering a simplified chip geometry and assuming photons to equilibrate inside the LED structure due to random scattering at the textured top surface of the chip. The model enables ranking of the optical losses in the LED chip, attributing ~67% (53%) of the total losses at 420 nm (540 nm) to those related to incomplete light reflection from the p-electrode. It may be also helpful as a framework for approximation of available data and analysis of the encapsulation gain utilized in practice.

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