ABC-Model for Interpretation of Internal Quantum Efficiency and Its Droop in III-Nitride LEDs

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Abstract **— The paper reviews applications of ABC-model to interpret internal quantum efficiency and its droop in III-nitride light-emitting diodes (LEDs). Advantages of the model, its intrinsic limitations, and tentative mechanisms responsible for deviation of the model predictions from available observations are discussed. New experimental information on recombination processes in the LED active regions coming from the ABC-model is considered along with still open questions and tasks for further experimental and theoretical research.**

Keywords — III-nitride semiconductors; light-emitting diodes; ABC-model; Auger recombination; efficiency droop; modeling

ABC-model has recently become very popular for analysis of internal quantum efficiency (IQE) and its droop observed in III-nitride LEDs. This is due to the fact that (i) the model provides excellent fitting of external quantum efficiency (EQE) of blue LEDs measured in a wide range of operating current variation (see, e. g. Fig.1b) and (ii) experimental information on the recombination processes in LED structures comes now only in terms of the ABC-model. Being the basis for the guess on the influential role of Auger recombination for LED efficiency [1], the ABC-model turned out to be helpful for finding effective ways to improve the device performance [2]. On the other hand, the model is criticized severely for oversimplified treatment of the considered physical processes and for some disagreement with a number of observations. This paper is aimed at reviewing strong and weak points of the ABC-model and discussing the questions for which the model may provide valuable answers and problems still waiting for more detailed experimental and theoretical investigation.

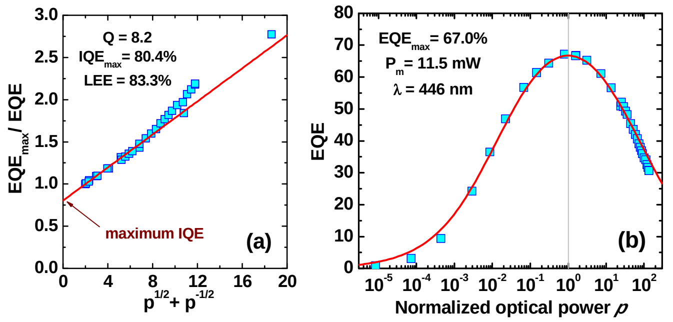

Fig. 1. η_{max}/η_e *vs.* $p^{1/2}+p^{-1/2}$ (a) and measured room-temperature EQE of a blue LED as a function of normalized optical power p (b). Symbols indicate the data obtained at Osram OS [3], lines are fittings of the data by ABC-model.

The advantages of the ABC-model become clear, if EQE η_e of an LED conventionally measured as a function of current is plotted *vs.* output optical power P_{out} , then the power P_m corresponding to the EQE maximum η_{max} is found from the above plot, and, finally, η_e is plotted as a function of the normalized optical power (NOP) $p = P_{out}/P_m$. In this case, the ABC-model provides the analytical expressions for EQE and IQE (η_i) [4]:

$$\eta_e(p) = \eta_{ext}\eta_i \quad , \quad \eta_i = \frac{Q}{Q + p^{1/2} + p^{-1/2}} \tag{1}$$

Here η_{ext} is the light extraction efficiency (LEE) of the LED chip and $Q = B/(AC)^{1/2}$ is a dimensionless combination of the Shockley-Read (A), radiative (B), and Auger (C) recombination coefficients. Plotting the η_{max}/η_e ratio *vs.* $p^{1/2}+p^{-1/2}$, enables finding the IQE maximum, Q-factor, and η_{ext} , as the ratio of η_{max} to the maximum IQE value equal to $Q/(Q+2)$ (Fig.1a). Then η_e as a function of p can be calculated with Eq.(1), providing adequate fitting of the EQE behavior in a wide range of NOP or, the same, operating current variation (Fig.1b).

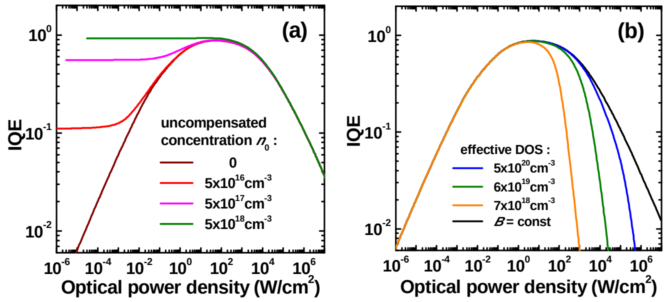

Fig. 2. IQE *vs.* optical power density calculated for case of (a) deviation from the electric neutrality in the QW and (b) hole degeneration. Calculations were made for 3 nm SQW at $A = 10^6$ s^{-1}, $B = 5\times10^{-12}$ cm^3/s, and $C = 1\times10^{-31}$ cm^6/s.

In logarithmic scale, the $\eta_e(p)$ dependence predicted by conventional ABC-model is symmetric with respect to the point $p = 1$. The symmetry is frequently broken, especially in the case of green LEDs, where the measured EQE is normally higher than the theoretical one in the low-current region. The paper considers tentative mechanisms responsible for the discrepancy between the theory and experiment. For the low-current region, carrier localization by composition fluctuations and deviation from the electric neutrality in InGaN quantum wells (QWs) are thus regarded (see Fig.2a; similar results were recently reported in [5]). For high currents, the active region self-heating, electron leakage into p-layers of the LED hetero-structure, current crowding in the LED chip, and dependence of the radiative recombination constant B on non-equilibrium carrier density (degeneration of the hole gas – see Fig.2b) are discussed. In particular, the idea of including in the model higher-order recombination terms is criticized.

It is impossible to find separately all the recombination coefficients from conventional LED characterization. Indeed, the

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ABC-model enables experimental evaluation of only two parameters: the Q-factor and the power $P_m = E_{ph}\,\eta_{ext}\,R_{ph}$ with the photon emission rate $R_{ph} = B(A/C)^{1/2}V_r$ and E_{ph} and V_r being the mean energy of emitted photons and the recombination volume, respectively. Other experiments, e. g. measurements of differential carrier life time τ_d *vs.* operating current [3,6], makes finding the recombination coefficients feasible. In particular, the life time $\tau_d = A^{-1}/(1+2Qp^{1/2}+3p)$ is directly related to the Shockley-Read recombination coefficient A. Other coefficients can be thus found from the value of A and experimentally measured Q and P_m.

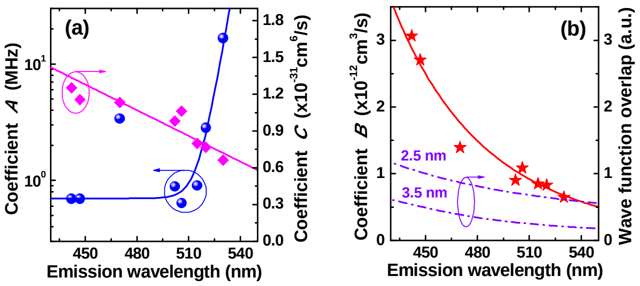

Fig. 3. Non-radiative (a) and raduative (b) recombination coefficients as a fucntion of emission wavelength [3]. Symbols are experimental points, solid lines are drawn for eyes. Dot-dashed lines show the theoretical wavelength dependence of the square of electron and hole wave functions multiplied by photon energy.

Detailed data reported in [3] for LEDs emitting light in a wide spectral range show that (i) the Auger coefficient C is weakly dependent on the emission wavelength (Fig.3a), whereas its value agrees with recent theoretical estimates, (ii) spectral dependence of the radiative recombination coefficient B does not agree with theoretical predictions made by a conventional approach (Fig.3b), and (iii) the recombination coefficient A exhibits dramatic rise at the wavelengths longer than ~510-515 nm, in contrast to the B and C coefficients (Fig.3). While the increase in the coefficient A in the green spectral range may be attributed to intensive defect generation in the high-indium content QWs, variation of the coefficient B with the emission wavelength is unclear and requires further both experimental and theoretical investigations.

One more unexpected behavior of recombination coefficients has been revealed in [7]. Calculating theoretically the constant B and using the EQE data of [8] to evaluate other recombination coefficients, authors of [7] concluded that the Auger coefficient C should decay with temperature. A similar finding was obtained for InGaN quantum-dot (QD) laser diodes emitting at 630 nm [12]. Being in conflict with existing theories [9-11], the above phenomenon cannot be, nevertheless, considered as unphysical. Indeed, the Auger coefficient decaying with temperature was observed in heavy-doped p-SiC [13] and predicted theoretically for specific non-threshold Auger processes in low-dimensional structures, QWs and QDs, where the momentum conservation rule is not so rigorous [14,15].

Despite the recent progress in the theory of Auger recombination in III-nitride heterostructures [9-11], there still remains a number of other open questions. One of them is identification of the dominant microscopic Auger process. Recent experiments have pointed out that both *nnp* and *npp* processes are involved in Auger recombination [16], whereas the *nnp* process dominates, at least, in blue LED structures [5]. This conclusion requires its quantitative theoretical justification.

In conclusion, the ABC-model bridges now the experimental and theoretical studies of recombination processes in III-nitride LED structures, providing new valuable information and putting forward new tasks for further research. Among these tasks the most important seem to be: (i) measuring and modeling the basic temperature and wavelength dependences of the recombination coefficients, (ii) understanding the crystal orientation effect on the recombination coefficients, and (iii) revealing the nature of 'green gap' in the LED efficiency in terms of the interplay between the recombination channels.

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