Differential Charge Carrier Lifetime Investigated in a Blue InGaN LED at Operational Conditions

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ABSTRACT

Investigation to reveal the discrepancy appeared between the current-dependent differential charge carrier lifetime in the InGaN/GaN light emitting diodes (LEDs) active region at low current working conditions and that predicted by the ABC-model was conducted. Photoluminescence frequency-domain lifetime measurement technique using resonant small-signal optical excitation and detection from the LED active region – the quantum wells, was applied to investigate InGaN/GaN LED emitting light in the blue spectra region. When analyzing the dependencies of the differential lifetime τ_{DLT} vs. normalized optical output power p and obtaining the best fit, charge carrier escape time from the quantum well in the range of 100 – 150 ns was encountered. Finally, it turned out that the escape rate is rather influential and exceeding even the Shockley-Read-Hall recombination rate at low current condition. The consequences for the ABC-model and for the evaluation of the related recombination coefficients are discussed.

Keywords: differential lifetime, light emitting diode, laser diode, InGaN, frequency-domain, escape.

1. INTRODUCTION

Investigation of non-equilibrium charge carrier dynamic properties in a light-emitting diode (LED) under working conditions is of essential importance, since none of the extrapolation methods either from the relative low or high charge carrier supply will give better insight into the processes within the LED structure. Knowledge about the charge carrier transport across the structure, mechanisms and competition of various electron-hole recombination channels inside the structure is still a challenge for an operating LED. The ABC-model considering three recombination mechanisms – the Shockley-Read-Hall recombination via defects (coefficient *A*), the bimolecular recombination (coefficient *B*) and the Auger recombination (coefficient *C*) – is a commonly used tool to interpret the processes related to internal quantum efficiency (IQE) of an LED. Evaluation of these coefficients paves the way towards understanding of fundamental mechanisms limiting the LED efficiency and practical optimization of the LED structures. Most unambiguous estimation of the coefficients is possible when the current-dependent differential lifetime (DLT) of electrons and holes in the LED active region is considered. The DLT measurements for biased InGaN LEDs were already performed with either electrical or optical small signal techniques. The electrical modulation technique is challenged by recharging of the space-charge region inside the LED structure, which has to be encountered for accurate lifetime estimation [1]. The optical modulation techniques both time resolved photoluminescence (TRPL) and photoluminescence frequency-domain lifetime measurement (FDLM) using resonant excitation and detection from the LED active region – the InGaN quantum wells – have confirmed also their capability of extracting the ABC-model recombination coefficients [2,3]. However, when carried out in a wide range of LED operating current a discrepancy between the DLT measured at lower current (less charge carrier density injected) and that predicted by the ABC-model has been revealed. To overcome the problem and to define correctly the recombination coefficients of the ABC-model a charge carrier escape from the quantum well as one of the important factors was suggested [4]. In this work, we have extended the investigation of differential charge carrier lifetime and the determination of recombination coefficients for the ABC-model, while encountering the charge carrier escape process in a blue light emitting InGaN/GaN LED.

2. SAMPLES AND EXPERIMENTAL

We have investigated a commercial LED emitting light in blue spectral region. The emission peak wavelength and the full width at half maximum were 448 nm and 20 nm, respectively. The normalized room-temperature electroluminescence intensity spectra of the LED measured at the operating current of 20 mA is shown in Fig. 1a.

Small-signal optical excitation of the LED was performed by commercially available laser diodes (LDs), oscillation spectra of which were peaked at 398 and 424 nm. These LDs are referred to hereafter by their peak wavelengths, e.g. LD398, LD424. The use of various LDs was aimed at better understanding the influence of the quantum energy of the optical excitation on DLT measurements in the LEDs. When the LD emission line was spectrally close to the LED emission band, we failed to measure reliably the lifetime, thus not all of the LDs planned to apply were used for the optical excitation.

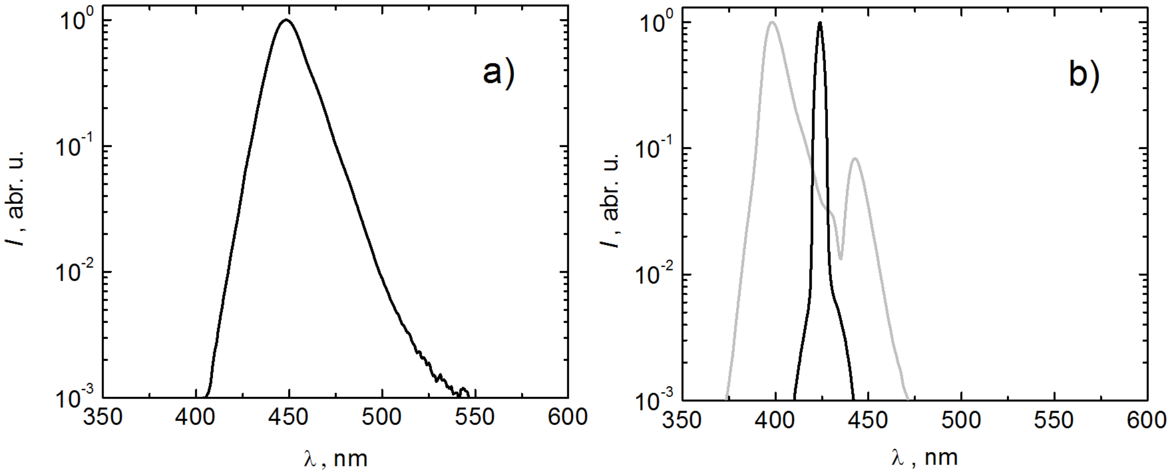

Figure 1. Normalized electroluminescence intensity spectra of the investigated LED (a) and normalized emission spectra of the laser diodes (grey line – LD398, black line – LD424) used for optical excitation (b).

Electroluminescence intensity as a function of forward current was measured using Princeton Instruments Acton SP2300 monochromator and a PIX2560E-SF CCD camera. The spectrally integrated EL signal was used to obtain EQE in arbitrary units, which enables finding the power necessary for calculating the normalized optical output power p and then the quality factor Q of the sample. The measurements were performed with the sample mounted in a thermostat pre-heated to 315 K temperature. Small-signal FDLM measurement setup used in this study has been described in detail elsewhere [3]. In addition to electrically DC driven current, the non-equilibrium charge carrier concentration was generated just in the QW region of the LED using the laser diode as a small-signal optical excitation source. The laser diode was electrically driven with a sum of DC (in order to maintain it in linear photo-response versus current regime, i.e. above oscillation threshold and below saturation) and AC power supply needed for the frequency-domain measurements. An Aeroflex IFR 2023A AC generator was used for modulation while a Stanford Research Systems SR844 lock-in amplifier with signal preamplifier was used for monitoring the phase shift of optical response – the main parameter, which dependence on the modulation frequency provided the extraction of DLT. The small-signal conditions of measurements were maintained by keeping the photo- to electrical-excitation ratio of 5%.

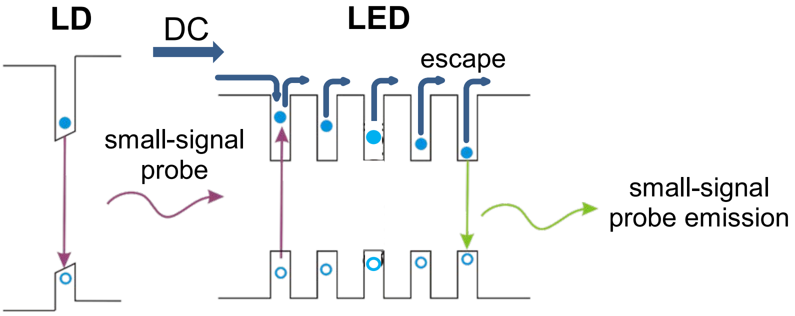

Figure 2. Schematic illustration of the band structure with small-signal resonant optical excitation of an LED under working conditions.

3. RESULTS AND ANALYSIS

First, the optical output power of the LED was measured as a function of DC forward current, which enabled to calculate the normalized external quantum efficiency $EQE / EQE_{\max}$ and to obtain the quality factor Q value 7.3±0.1 (from $EQE / EQE_{\max}$ slope versus normalized optical output power p) (for details see [3]). The quality factor as a measure of the LED IQE plays an important role for determining the ABC-model recombination coefficients ($Q = B / (AC)^{1/2}$) and for our particular case now – the Shockley-Read-Hall recombination coefficient A.

Small-signal FDLM measurements were carried out to evaluate the DLT τ_{DLT} at different LED forward current. The current values were supposed to cover a large range from the very low up to the highest possible exceeding the operational LED conditions, however, to focus on the deviation from the ABC-model [2,3] the low currents were selected, where the competition between the rates of Shockley-Read-Hall recombination and the charge carrier escape from the quantum well are not screened by the non-linear recombination mechanisms (*B* and *C*) (see Fig. 2). In this context the measured DLT comprises both rates via a simple expression: $\tau_{\mathrm{DLT}} = (\tau_{\mathrm{SRH}}^{-1} + \tau_{\mathrm{ESC}}^{-1})^{-1}$, where τ_{SRH}^{-1} is the Shockley-Read-Hall recombination rate, τ_{ESC}^{-1} is the charge carrier escape rate.

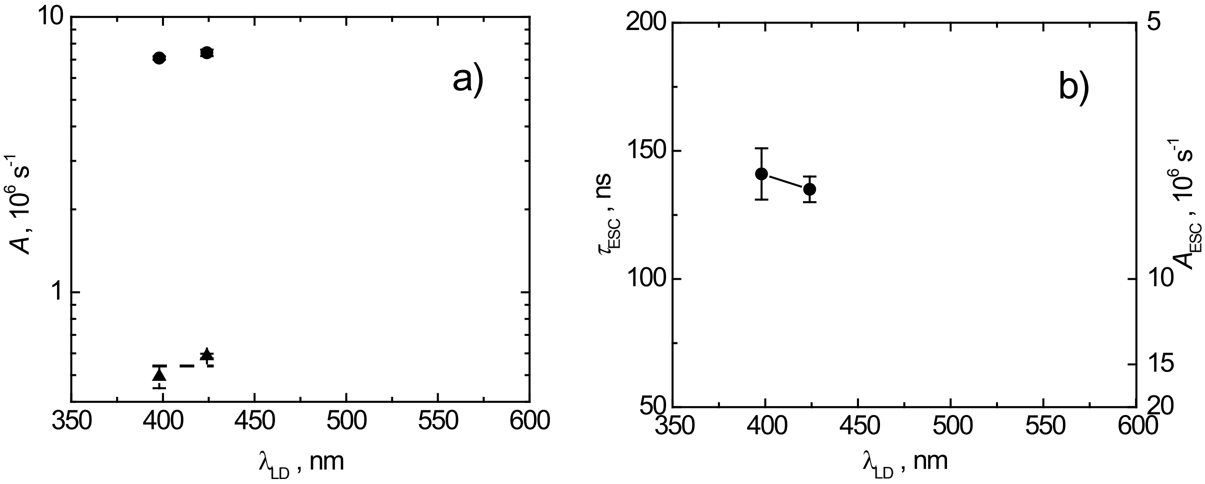

Figure 3: (a) SHR coefficient A (solid triangles) versus excitation wavelength λ_{LD} *(LD398, LD424) recovered from the best fit of the experimental data –* τ_{DLT} *vs. normalized optical output power p. Dashed line – arithmetic average of the acquired A values; (b)* τ_{ESC} *(solid points) obtained from the* τ_{DLT} *and the averaged A value. As for comparison* $A_{ESC} = \tau_{ESC}^{-1}$ *(solid points) is presented also in (a). Error bars are obtained from least square analysis.*

Coefficient *A* values extracted from the best fit of the τ_{DLT} vs. *p* are presented in Fig. 3(a). A slight deviation of the values between the two LD398 and LD424 excitation wavelengths was attributed to an error-like correction, so an arithmetic average was further used to evaluate the charge carrier escape time τ_{ESC} ~100 – 150 ns [Fig. 3(b)]. The Shockley-Read-Hall recombination via defects is a material or structure quality monitoring process, therefore, a minor shift in the excitation wavelength shouldn't influence the charge carrier lifetime (thermalization of the charge carriers in the well proceeds within femtoseconds). Differently to τ_{ESC}, which should depend on the energy levels the electron or hole is excited to. It is expected that the charge carriers are more efficient to leave the quantum well excited with higher quantum energies. This, however, appeared unaffected or even opposite in this work – higher escape rate for the excitation with lower quantum energy was observed [Fig. 3(b)]. The well-known charge carrier localization in InGaN/GaN quantum wells governed by indium concentration inhomogeneity or quantum well thickness deviation may serve as a first plausible explanation. Worthy of remark is the fact that the charge carrier escape rate in comparison to Shockley-Read-Hall recombination rate showed by more than one order of magnitude higher values saying that the chance to escape from the well is much more efficient than to recombine non-radiative (linear) in the well. All-in-all both processes hinder the LED efficiency and have to be carefully considered.

4. CONCLUSIONS

The small-signal photoluminescence frequency-domain lifetime measurement results enabled to extract the current-dependent differential lifetime of electrons and holes in the LED active region – the quantum wells, at LED operational condition. The results have demonstrated that the charge carrier escape from the quantum well has to be considered as an important process for the InGaN/GaN LED emitting light in the blue spectral region and in large surpassing the Shockley-Read-Hall recombination at low current case. These findings may have a decisive impact on the ABC-model, on a correct determination of the related recombination coefficients. To generalize the idea supporting investigations on InGaN/GaN LEDs emitting light in different spectra regions are needed.

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