Measurement and analysis of the recombination coefficients distribution on the area of light-emitting InGaN/GaN heterostructures

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Abstract. A method and an installation for evaluation the profile of distribution of recombination coefficients and current density over the area of light-emitting heterostructures at low injection levels based on local values of the 3 dB frequency are described. Using the example of measuring the parameters of commercial blue InGaN/GaN-based LEDs, it is shown that the current density is higher in those areas of the chip where the 3 dB frequency is lower.

1. Introduction
A fundamental characteristic of light-emitting InGaN/GaN heterostructures is the spatial inhomogeneity of the electrical and optical properties due to fluctuations in the composition of the InGaN solid solution and the presence of a system of extended defects penetrating the material. The compositional fluctuations of the band gap in the active region of the InGaN/GaN light-emitting heterostructure lead to the localization of charge carriers in regions with a high content of indium (with a minimum potential energy) [1]. As shown in [2], indium clusters can reach sizes of the order of 5 ... 10 μm, and the spatial dispersion of the central luminescence wavelength for green light-emitting heterostructures is several times greater than for blue light-emitting heterostructures. The non-uniform distribution of the centers of radiative and nonradiative recombination in the heterostructure causes a non-uniform distribution of the current density, temperature, and electroluminescence intensity. A local increase in the current density during operation leads to a local heating of the structure, which in turn causes an increase in the rate of the heterostructure degradation [3]. To measure the inhomogeneity parameters of the composition of light-emitting heterostructures, the methods of near-field mapping of photoluminescence [4], near-field scanning optical microscopy [5], and dynamic photoelectric spectroscopy [6, 7] are used. The aim of the work is to develop and experimentally test an automated complex for measuring spatial inhomogeneity of the distribution of the Shockley-Read-Hall (SRH) and radiative recombination coefficients and current density over the area of the LED chip using dynamic electroluminescence parameters.

2. Measuring installation
To measure the distribution profile of the dynamic electroluminescence parameters over the area of light-emitting heterostructures, an automated installation has been developed, consisting of an AG 1022F functional generator, a Levenhuk D320L microscope with magnification up to 1600x, incorporating a digital camera C310T NG with a maximum resolution of 2048x1536, and a personal computer with LabView software.
The principle of operation of the measuring setup is as follows. From the output of the generator to the LED under investigation, a sequence of current pulses is supplied with a duty cycle of 2. The frequency of the current pulses is tuned in the range of 1 kHz to 5 MHz with a logarithmic step. For each frequency set, the digital camera registers a photo of the chip, and the brightness of the image of the chip is directly proportional to half the amplitude of the variable optical signal. The exposure time of the camera is set in such a way as to minimize the effect of non-linearity of the brightness characteristic of a digital camera. The resulting array of images is stored in the computer's memory, after which the program calculates the amplitude-frequency characteristic of each image pixel and calculates the 3dB modulation frequency, at which the brightness of the pixel drops 50% relative to the value measured at 1 kHz.

3. Experimental results
The operation of the automated measuring installation was tested on the example of measuring the distribution of the $f_{3dB}$ frequency over the chip area of commercial blue InGaN LEDs with a chip size of $240 \times 240 \, \mu m$. Measurements are performed at currents of 10 $\mu$A and 20 $\mu$A. Fig. 1 shows the distribution profile of the 3dB frequency values over the chip area at a current of 10 $\mu$A.

![Figure 1. The distribution profile of the $f_{3dB}$ frequency over the area of the LED chip at the 10 $\mu$A current](image)

If the capacitance of the LED is small, the 3dB frequency $f_{3dB}$ is determined by the charge carriers lifetime in heterostructure $\tau$ [8, 9]:

$$f_{3dB} = \frac{\sqrt{3}}{2\pi\tau}.$$  \hspace{1cm} (1)

Using the values of the lifetime of charge carriers, one can estimate the non-radiative recombination coefficients of SRH (A), radiative (B) and Auger recombination (C) [10]:

$$\tau = \left( A + 2Bn + 3Cn^2 \right)^{-1},$$ \hspace{1cm} (2)

where $n$ is the concentration of charge carriers in the active region.

In the absence of carrier leakage from the active region of the structure, the current density in structure $J$ is associated with the recombination coefficients by the expression:

$$J = qd(An + Bn^2 + Cn^3),$$ \hspace{1cm} (3)

where $q$ is the electron charge, $d$ is the thickness of the active region.

It is known that at low currents the effect of Auger recombination ($Cn^3 \approx 0$) can be neglected. To determine the coefficients $A$ and $B$, it is sufficient to measure the boundary frequencies $f_{3dB,1,2}$ of the modulation of electroluminescence at two currents $J_1$ and $J_2$, respectively:
Based on the results of measurements of the 3dB frequency at currents of 10 μA and 20 μA, the distributions of A and B recombination coefficients over the chip area at a current of 10 μA are calculated (Fig. 2).

\[ A = \frac{2\pi}{\sqrt{3}} \left( J_1 f_{\text{rel,1}}^2 - J_2 f_{\text{rel,1}}^2 \right)^{1/2}, \]

\[ B = \frac{\pi^2 q d}{3} \left( f_{\text{rel,2}}^2 - f_{\text{rel,1}}^2 \right). \]

The current density is on average higher in those regions of the chip in which the 3dB frequency is lower.
4. Conclusions.
A method and installation have been developed for measuring the profile of the distribution of the 3dB frequencies of the electroluminescence modulation, the radiative and non-radiative recombination coefficients of Shockley-Reed-Hall and the current density over the area of light-emitting heterostructures at low injection levels. The installation was tested on the example of measuring the distribution of the 3dB frequencies of electroluminescence modulation over the chip area of commercial blue InGaN-based LEDs. The presence of local chip regions with an increased current density is revealed. It is determined that the current density is higher in those regions of the chip in which the 3 dB frequency is less. The results obtained will be used to develop methods for assessing the degree of imperfection and diagnosing the quality of light-emitting heterostructures using the parameters of the spatial inhomogeneity of the static and dynamic characteristics of electroluminescence.

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References
[1] Marutsuki G, Narukawa Y, Mitani T, Mukai T, Shinomiya G, Kaneta A, Kawakami Y, Fujita Sg 2002 Physica Status Solidi (a) 192 110–116
[2] K. Gelžinytė, R. Ivanov, S. Marcinkevičius, Zhao Y, Becerra D L, Nakamura S, DenBaars S P, and Speck J S 2015 J. Appl. Phys. 117 023111
[3] Peng Z, Lu Y, Gao Y, Chen G, Zheng J, Guo Z, Lin Y, Chen Z 2018 IEEE Photonics Journal 10 8201908
[4] Tateishi K, Wang P, Ryuzaiki S, Funato M, Kawakami Y, Okamoto K, Tamada K 2017 Applied Physics Letters 111 172105
[5] Kim M, Choi S, Lee J-H, Park C, Chung T-H, Baek J H, Cho Y-H 2017 Scientific Reports 7
[6] Sergeev V A, Vasin S V, Frolov I V, Radaev O A 2018 Measurement Techniques 61, 914
[7] Frolov I V, Radaev O A, Sergeev V A, Vasin S V 2018 Journal of Physics: Conference Series 1124 041019
[8] Schubert E F 2006 Light Emitting Diodes (Cambridge University Press)
[9] Zhao L X, Zhu S C, Wu C H, Yang C, Yu Z G, Yang H, Liu L 2016 Sci.China-Phys. Mech. Astron. 59, 107301
[10] Reklaitis I, Nippert F, Kudzma R et al. 2017 J. Appl. Phys. 121, 035701
[11] Meneghini M, Trivellin N, Meneghesso G, Zanoni E, Zehnder U, Hahn B 2009 J. Appl. Phys. 106 114508