Conference materials
UDC 621.382.088
DOI: https://doi.org/10.18721/JPM.153.344

Measurement of the internal quantum efficiency of emission in the local region of the LED chip

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Abstract. A method for measuring the internal quantum efficiency in local areas of the LED chip is presented. The method is based on measuring the emission brightness distribution profiles and 3 dB frequencies of the electroluminescence of the LED at two low values of currents with a digital CMOS camera and calculating the internal quantum efficiency for each image pixel using the formula obtained in accordance with the ABC model of charge carrier recombination in a heterostructure. The measurement method was tested on the example of commercial blue InGaN LEDs. It is shown that the degree of homogeneity of the internal quantum efficiency distribution profile is significantly higher than the degree of homogeneity of the emission brightness distribution profile, which is due to the inhomogeneity of the distribution of the light extraction efficiency coefficient in different areas of the LED chip. The presented measurement method can be used to diagnose defects in local areas of the LED heterostructure.

Keywords: LED, light-emitting heterostructure, internal quantum efficiency, measurements

Funding: The work was carried out within the framework of the state task and partially was supported by the Russian Foundation for Basic Research and Ulyanovsk region, project No. 19-47-730002.

Citation: Frolov I. V., Radaev O. A., Sergeev V. A., Measurement of the internal quantum efficiency of emission in the local region of the LED chip. St. Petersburg State Polytechnical University Journal. Physics and Mathematics, 15 (3.3) (2022) 226–229. DOI: https://doi.org/10.18721/JPM.153.344

Материалы конференции
УДК 621.382.088
DOI: https://doi.org/10.18721/JPM.153.344

Измерение внутреннего квантового выхода излучения в локальных областях кристалла светодиода

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Аннотация. Представлен способ измерений внутреннего квантового выхода излучения в локальных областях кристалла светодиода. Способ основан на измерении цифровой КМОП камерой профилей распределения яркости излучения и граничных частот электролюминесценции светодиода при двух малых значениях тока и расчете внутреннего квантового выхода для каждого пикселя изображений по формуле, полученной в соответствии с ABC моделью рекомбинации носителей заряда в гетероструктуре. Способ измерений апробирован на примере коммерческих синих InGaN гетероструктурных светодиодах. Показано, что степень однородности профиля распределения внутреннего квантового выхода существенно выше, чем степень однородности профиля распределения яркости излучения, что обусловлено неоднородностью распределения коэффициента вывода излучения по площади кристалла светодиода. Представленный способ измерений может быть использован для диагностики дефектов локальных областей гетероструктуры светодиода.

Ключевые слова: светодиод, светоизлучающая гетероструктура, внутренний квантовый выход, измерения

Финансирование: Работа выполнена в рамках государственного задания при частичной финансовой поддержке Российского фонда фундаментальных исследований и Правительства Ульяновской области, проект № 19-47-730002 р-а.

Ссылка при цитировании: Фролов И. В., Радаев О. А., Сергеев В. А. Измерение внутреннего квантового выхода излучения в локальных областях кристалла светодиода // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2022. Т. 15. № 3.3. С. 226–229. DOI: https://doi.org/10.18721/JPM.153.344

Introduction

The internal quantum efficiency (IQE) is the most important parameter of LEDs, which determines the efficiency of converting electric current into optical emission. According to the ABC model of charge carrier recombination in a heterostructure, the IQE is defined as the ratio of the radiative recombination rate to the sum of the radiative and nonradiative recombination rates [1]. Since the rate of nonradiative recombination is directly related to the defects density in the heterostructure, the IQE can be used as a parameter characterizing the quality of the structure. The investigation of factors affecting the internal quantum efficiency of InGaN/GaN LEDs and methods to increase it is an important task [2, 3].

Most of the known methods for measuring the IQE are based on measuring the photoluminescence [4] or electroluminescence [5] parameters of the LED at temperatures of 4–10 K. The application of these measurement methods in the conditions of input or output control in production is difficult.

Defects and indium concentration fluctuations in InGaN-based light-emitting heterostructures are responsible for the inhomogeneous distribution of electroluminescence parameters over the chip area. The presence in the structure of local regions with an increased defects density can cause accelerated degradation of the LED characteristics. In this regard, the development of new methods and means for measuring the electro-optical parameters of local regions of LED chips at room temperatures is an actual task from the point of view of increasing the efficiency of detecting and rejecting defective and potentially unreliable LEDs.

The purpose of the work was to develop and experimentally test a method for measuring the IQE of emission from local regions of the InGaN LED chip.

Materials and Methods

The method for measuring the IQE of emission presented in [6] was used as a basis. The measurement method is based on the ABC model of charge carrier recombination in the InGaN heterostructure of the LED, which establishes the relationship between the IQE of the LED emission and the concentration of charge carriers in the active region through recombination coefficients: defect-related SRH recombination coefficient A, radiative recombination coefficient B, and Auger non-radiative recombination coefficient C. At low currents the effect of Auger recombination can be neglected. The ABC model also establishes a relationship between the recombination coefficients and the 3 dB frequency of the electroluminescence of the LED. Based on the ABC model in [6] an expression was obtained for calculating the IQE η at the LED current I1 from the results of measurements of the emission power and 3dB frequencies of the electroluminescence of the LED at two low values of currents:

$$\eta(I_1)=\left[\frac{f_{3dB}(I_2)/f_{3dB}(I_1)-1}{\sqrt{P(I_2)/P(I_1)}-1}\right]\Bigg/\left[2-\frac{f_{3dB}(I_2)/f_{3dB}(I_1)-1}{\sqrt{P(I_2)/P(I_1)}-1}\right]. \qquad (1)$$

where $f_{3dB}(I_1)$ and $f_{3dB}(I_2)$ are 3_{dB} frequencies of LED electroluminescence measured at current I_1 and I_2, respectively; $P(I_1)$ и $P(I_2)$ are LED emission power at current I_1 and I_2, respectively.

To measure the IQE of emission in local region of the LED chip, a hardware-software complex [7] was used. The hardware-software complex includes a Levenhuk D320L microscope, which includes an FL-20BW digital camera with a maximum resolution of 5472×3648, a DG4162 pulse generator, and a LED supply mode setting unit. The LED is fixed on the microscope stage. A direct pulsed current with amplitude I_1, duty cycle 50% and pulse repetition rates of 1 kHz and 500 kHz is alternately passed through the LED, and then a direct pulsed current with amplitude I_1 and a frequency of 500 kHz is passed through the LED with the reverse polarity voltage applied to the LED at the end of the current pulse. The images of the LED chip obtained by a digital camera are stored in the computer memory in the form of a matrix, the elements of which have a 16-bit capacity. That is, the brightness of a pixel can take values in the range from 0 to 65535 arbitrary units (a. u). Then the measurements are repeated at a pulsed current with amplitude I_2. For each pixel of the LED chip image, a 3 dB frequency is calculated and the IQE is calculated by formula (1).

Results and Discussion

Approbation of the method was performed on a commercial blue InGaN LED TO-3216BC-BF. The profiles of $f_{3dB}(I)$ and $P(I)$ were measured at currents I_1 = 50 μA and I_2 = 100 μA. Fig. 1 shows the profile of the distribution of the brightness over the chip area of one of the investigated LEDs, measured at a current of 50 μA with a digital camera exposure time of 5 ms. The brightness range was divided into eight subranges. Areas of the chip, the brightness of which is within one of the subranges are highlighted in color in accordance with the color scale. It can be seen from the Fig. 1 that the profile contains local areas with increased brightness.

Fig. 2 shows the distribution profile of the IQE over the LED chip area, measured at a current of 50 μA. The average of IQE is 0.56 a. u. This profile is more uniform than the brightness profile shown in Fig. 1.

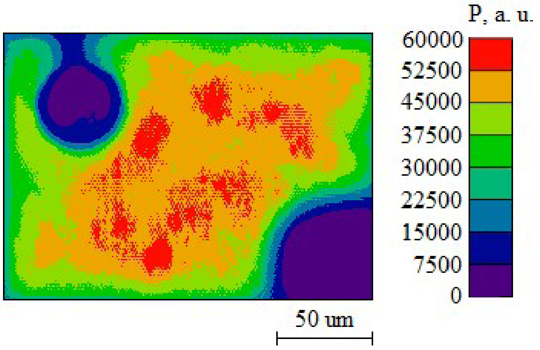

Fig. 1. The profile of the distribution of the brightness over the area of the LED chip at 50 μA

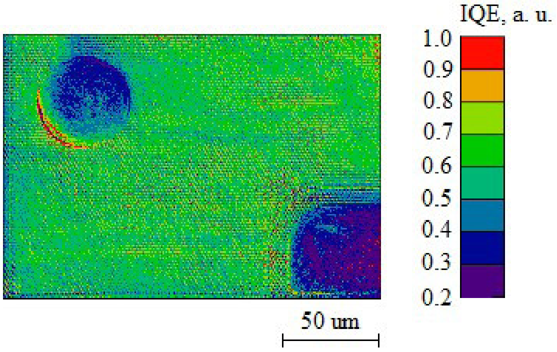

Fig. 2. IQE distribution profile over LED chip area at 50 μA

The degree of homogeneity of the distribution profiles was assessed as follows. We calculated the average value of the brightness $\bar{P}$ and internal quantum efficiency $\overline{\mathrm{IQE}}$ over the area of the active region of the chip (the area occupied by the electrodes was subtracted from the total area of the chip), the standard deviations of values σ_P and σ_{IQE}, and the coefficients $k_P = S_P/S$ and $k_{\mathrm{IQE}} = S_{\mathrm{IQE}}/S$ were calculated, where S_P is the LED chip area within which the brightness is in the range $(\bar{P}-\sigma_P;\ \bar{P}+\sigma_P)$; S_{IQE} is the chip area within which IQE is in the range $\left(\overline{\mathrm{IQE}}-\sigma_{\mathrm{IOE}};\overline{\mathrm{IQE}}+\sigma_{\mathrm{IOE}}\right)$; S is the areas of the active region of the LED chip. According to the obtained estimates, for the investigated LED k_P = 0.44, k_{IQE} = 0.69. This means that the distribution of IQE is more homogeneous and close to the normal distribution law, that is, in the predominant part of the LED chip area, IQE takes values close to the average value. The brightness distribution is less uniform and differs from the normal distribution law; a significant part of the LED chip area is occupied by areas with a brightness significantly exceeding the average value.

Differences in the distribution profiles of brightness and IQE are explained by the uneven distribution of the light emission extraction coefficient over the LED chip area. This may be due to the inhomogeneity of the optically transparent layers above the heterostructure. Thus, the obtained results show that to assess the uniformity of the parameters of a light-emitting heterostructure, it is necessary to use the IQE values, since they characterize the heterostructure and do not depend on the light emission extraction coefficient.

Conclusion

The results of experimental testing of the method for measuring the internal quantum efficiency in local regions of the LED chip are presented. The method is based on measuring the distribution profiles of brightness and 3 dB frequencies at two low values of currents and calculating the IQE value from the functional dependence obtained on the basis of the ABC model of charge carriers recombination in a heterostructure. The measurement method can be implemented on standard radio measuring equipment under normal conditions and does not require cryogenic temperature. It is shown that the distribution profiles of brightness and IQE are different. This difference is due to the inhomogeneity of the distribution of the light emission extraction coefficient. The measurement method can be used to control the parameters of the light-emitting heterostructure, including in its local areas.

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Received 12.07.2022. Approved after reviewing 14.07.2022. Accepted 14.07.2022.