Diagnostics of inhomogeneities of parameters of light-emitting heterostructures by the photoelectric method

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Abstract. The automated measuring complex for diagnostics of spatial inhomogeneity of parameters of light emitting heterostructures by photoelectric method with local photoexcitation is described. Results of the estimation of the homogeneity of the photocurrent value distribution on the area of crystals of blue and green commercial InGaN/GaN light-emitting diodes are presented. It is shown that near the crystal boundaries the level of inhomogeneity is higher than at the center. It is revealed that inhomogeneity of photovoltaic parameters of heterostructures of green LEDs is greater than that of blue LEDs.

1. Introduction

Despite the improvement of the technologies for manufacturing light-emitting InGaN/GaN heterostructures, problems associated with the degradation of the characteristics of semiconductor devices based on them are still unresolved due to the formation of defects in the active region of the heterostructure [1]. One of the reasons leading to an increase the degree of defectiveness of the heterostructure is clusterization (the formation of local regions with a high concentration) of indium atoms in the InGaN solid solution during the growth of the structure. Due to the fluctuation of the composition of the solid solution is formed inhomogeneous current distribution over the area of the structure, as well as the formation of sites of local overheating, which leads to acceleration of the formation of defects in the heterostructure under the influence of the injection current during operation [2]. The spatial inhomogeneity of the solid solution composition is manifested in the nonuniform distribution of electro-optical and thermophysical parameters over the area of the crystal. Methods of scanning near-field electroluminescence, infrared microscopy [3], photoluminescence mapping are used for its diagnosis [4].

In this article the automated measuring complex for the diagnosis of spatial heterogeneity of the parameters of light-emitting heterostructures by photoelectric method with local photoexcitation and the results of the investigation of inhomogeneities of photovoltaic parameters of light-emitting heterostructures of commercial green and blue LEDs are presented.

2. Measuring complex

A measuring complex was developed to diagnose the lateral homogeneity of light-emitting heterostructures by photovoltaic method at local photoexcitation in static and dynamic modes [5]. The complex makes it possible to scan the working surface of a heterostructure with a step up to 10 µm when the object is irradiated with an optical spot of laser radiation in a stationary mode and in a mode of pulse or harmonic modulation of the photoexcitation intensity.
The measuring complex consists of software and hardware parts. The structural diagram of the hardware of the complex is shown in Fig. 1. The test sample is fixed to the XYZ-positioner, which allows automatically moving the investigated sample in the XY plane in the range of 10 × 10 mm with steps of 10 μm using the stepping motors controlled by the microcontroller. Sony SLD3232VF laser diode emitting at a wavelength of 405 nm is used for photoexcitation of the object. The laser diode radiation is focused on the surface of the sample by the lens and the objective. The beam diameter of the laser radiation does not exceed 10 μm. The laser diode is connected to a stabilized current source when measuring the photocurrent profile on the crystal surface in a stationary mode. To register a constant photocurrent is converted by a transimpedance amplifier to voltage use a digital multimeter Rigol DM3058. For registration DC photocurrent transformed to the voltage of the transimpedance amplifier uses the digital multi-meter Rigol DM3058.

**Figure 1.** The block diagram of the automated measuring complex

For measuring the dynamic parameters of the structure's photoresponse (the boundary modulation frequency of the photocurrent in the harmonic mode of the photoexcitation and the rise and fall of the photocurrent pulse front in the photoexcitation pulse mode) the laser radiation intensity is modulated by a software-controlled RIGOL DG1022 generator. Harmonic modulation is performed in the frequency range from 1 kHz to 20 MHz in the mode of continuous frequency tuning with a logarithmic step during the set time of swiping. In pulse modulation mode, the pulse duration is set in the range of 100 μs...1 ms with a duty cycle 2...10 depending on the frequency properties of the investigated object. For registration of a variable signal of photocurrent the transimpedance amplifier converter constructed on the OPA656 operational amplifier (OA) is used. The La-n1USB data acquisition module performs analog-to-digital conversion of the voltage coming from the output of the transimpedance amplifier and transmits the data to the memory of the computer. On retrieved data the computer program builds a three-dimensional distribution of dynamic parameters of the photoelectric response on a surface of a crystal of the investigated sample.

The software part of the complex is developed in LabVIEW graphical programming environment.

3. **Experimental results**

With the help of the developed complex the inhomogeneities of photoelectric parameters of heterostructures of commercial light-emitting diodes of two types are investigated: XREBLU-L1-0000-00K01 of blue glow and XREGRN-L1-0000-00P01 of green glow. LEDs of these types are made on the
basis of EZ1000 crystals 980x980 um, which have an InGaN / GaN heterostructure. Assessment of heterogeneity of distribution of the photocurrent on the surface of the crystal was performed based on the calculation of the relative standard deviation $\sigma/I_{\text{Ph,mean}}$ by calculating the standard deviation $\sigma$ and the average values of $I_{\text{Ph,mean}}$ the photocurrent. The crystal surface was divided into seven segments (Fig. 2).

On Fig. 2 the profile of distribution of the photocurrent value over the crystal surface of a blue LED is presented. It can be seen from the figure that the average level of the photocurrent at the center of the crystal is higher than near the crystal boundaries. In this case, near the crystal boundaries, the degree of inhomogeneity of the photocurrent distribution is higher than in the center. According to the estimates presented in Table 1, the inhomogeneity of the distribution of the photocurrent along the crystal surface of green LEDs is 1.5 ... 1.7 times higher than that of blue LEDs.

Table 1. Photocurrent distribution parameters

| The segment number of the crystal | XREBLU-L1-0000-00K01 | XREGRN-L1-0000-00P01 |
|----------------------------------|----------------------|----------------------|
|                                  | $I_{\text{Ph,mean}}, \mu\text{A}$ | $\sigma, \mu\text{A}$ | $\sigma/I_{\text{Ph,mean}}$ | $I_{\text{Ph,mean}}, \mu\text{A}$ | $\sigma, \mu\text{A}$ | $\sigma/I_{\text{Ph,mean}}$ |
| 1                                | 89.5                 | 2.525                | 0.028                        | 34.2                     | 2.251                | 0.066                        |
| 2                                | 89.2                 | 1.884                | 0.021                        | 33.8                     | 1.683                | 0.050                        |
| 3                                | 92.3                 | 1.645                | 0.018                        | 35.6                     | 1.514                | 0.043                        |
| 4                                | 92.6                 | 1.348                | 0.015                        | 36.9                     | 1.151                | 0.031                        |
| 5                                | 93.7                 | 1.668                | 0.018                        | 37.7                     | 1.246                | 0.033                        |
| 6                                | 91.5                 | 2.380                | 0.026                        | 37.1                     | 1.141                | 0.031                        |
| 7                                | 89.9                 | 2.807                | 0.031                        | 35.2                     | 1.883                | 0.053                        |

To estimate the dynamic parameters of the photoelectric response of the heterostructure, the boundary frequency of the modulation of the photocurrent $f_{3dB}$ was measured with harmonic modulation of the photoexcitation intensity. In Fig. 3 the profile of the distribution of the values of the boundary frequency of modulation of the photocurrent along the surface of the crystal of the blue LED is shown.

![Figure 2](image2.png)

**Figure 2.** Distribution profile of the photocurrent value over the crystal surface LED XREBLU-L1-0000-00K01

![Figure 3](image3.png)

**Figure 3.** Profile of the distribution of the boundary frequency of modulation of the photocurrent along the surface of the LED XREBLU-L1-0000-00K01

It is seen from the figure that near the crystal boundaries the average value of the boundary frequency of photocurrent modulation ($f_{3dB} = 1.320$ MHz) is approximately 3% larger than at the center of the crystal ($f_{3dB} = 1.280$ MHz). This means that the average lifetime of charge carriers at the center of the crystal is smaller than near the boundaries, which indicates large nonradiative losses near the crystal boundaries [3].
Table 2 presents the results of measuring the average value of the photocurrent, the standard deviation and relative standard deviation of the distribution of the photocurrent of the two samples of green and blue LEDs of 5 pieces each. From the data of the table it follows that the average value of \( \sigma/\overline{I_{\text{Ph}}} \) parameter used to estimate the inhomogeneity of the photocurrent is 1.3 times higher for green LEDs than for blue ones. The obtained results agree with the generally accepted statement that the inhomogeneity of the composition of a solid solution of heterostructures with a high content of indium emitting in the green region of the spectrum is higher than the inhomogeneity of the composition of heterostructures emitting in the blue region of the spectrum [7].

| №   | №1   | №2   | №3   | №4   | №5   | №1   | №2   | №3   | №4   | №5   |
|-----|------|------|------|------|------|------|------|------|------|------|
| \( I_{\text{Ph},\text{mean}} \), \( \mu A \) | 69.6 | 59.2 | 69.0 | 63.2 | 69.7 | 29.9 | 32.2 | 40.8 | 31.3 | 30.7 |
| \( \sigma, \mu A \) | 1.51 | 1.77 | 1.34 | 1.73 | 1.84 | 1.3  | 0.87 | 1.1  | 0.98 | 0.583|
| \( \sigma/I_{\text{Ph,mean}} \) | 0.022 | 0.030 | 0.019 | 0.027 | 0.026 | 0.044 | 0.027 | 0.027 | 0.031 | 0.029 |

4. Conclusions
1. The automated measuring complex for registration of photoelectric response of LEDs heterostructures at their local static and dynamic photoexcitation is developed.
2. The results of the experimental testing of the complex on commercial InGaN/GaN LEDs in the static and dynamic mode of photoexcitation confirm the presence of inhomogeneities in the distribution of the photoelectric response on the surface of the LED crystal.
3. The inhomogeneity of the photovoltaic parameters of green LEDs heterostructures is greater than that of blue LEDs heterostructures.
4. The obtained results assessment of heterogeneity of distribution of the photocurrent and the boundary frequency of modulation of the photocurrent on the square of the crystal may indicate that the degree of defects in the heterostructure near the borders of the crystal is higher than in the center of the crystal.

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References
[1] Frolov I V, Radaev O A, Sergeev V A Journal of Physics: Conference Series 2017 917 052017.
[2] Leungetal K K Journal Of Applied Physics 2010 107 073103.
[3] Fischer P, Christen J, Zacharias M et al. Japanese Journal of Applied Physics, Part 1: Regular Papers and Short Notes and Review Papers 2000 39 no. 4 B 2414.
[4] Gelzinyte et al. Journal Of Applied Physics 2015 117 023111.
[5] Sergeev V A, Vasin S V, Radaev O A, Frolov I V 2018 Moscow Workshop on Electronic and Networking Technologies(MWENT) (National Research University Higher School of Economics) DOI:10.1109/MWENT.2018.8337210
[6] Schubert E F 2006 Light Emitting Diodes (Cambridge University Press).
[7] Jeong H et al. Scientific reports 2015 5:9373.