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# Measurement of the threshold current in the local areas of the LED chip

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**Abstract.** A method for measuring the threshold current in local areas of an LED chip is presented, which consists in recording chip images at three low currents and pixel-by-pixel calculation of threshold current values by solving a system of equations compiled for three values of the approximating function. Approbation was carried out on commercial green and blue LEDs. It is shown that the distribution of threshold current values over the chip is uneven.

**Keywords:** LED, threshold current, measurement

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# Измерение порогового тока в локальных областях кристалла светодиода

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**Аннотация.** Представлен способ измерений порогового тока в локальных областях кристалла светодиода, состоящий в регистрации изображений кристалла при трех малых токах и попиксельном расчете значений порогового тока путем решения системы уравнений, составленной для трех значений аппроксимирующей функции. Апробация выполнена на коммерческих зеленых и синих светодиодах. Показано, что распределение значений порогового тока по кристаллу неравномерное.

**Ключевые слова:** светодиод, пороговый ток, измерение

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## Introduction

Extended defects in light-emitting heterostructures with InGaN/GaN quantum wells create channels for leakage of charge carriers from the active region. The threshold current of a light-emitting heterostructure, i.e., the minimum current at which the LED emission is occurs, characterizes losses due to nonradiative recombination in a system of defects, losses of charge carriers during tunneling through a potential barrier, and their leakage from the active region into barrier layers [1]. It was shown in [2] that the values of the threshold current correlate with the values of the current at which the maximum current dependence of the external quantum efficiency of the LED is observed, and when tested in the constant current mode, LEDs with high threshold currents degrade faster than LEDs with low threshold currents.

Light-emitting InGaN/GaN heterostructures with multiple quantum wells are characterized by the inhomogeneity of the stoichiometric composition of the layers of the quantum well and a significantly inhomogeneous distribution of various kinds of defects over the volume of the active region of the heterostructure, which in turn is the reason for the inhomogeneous distribution of the current density and temperature in the device chip, the acceleration of defect formation processes in areas with increased current density [3–5]. Electrically active defects affect the mechanisms of current passage through the heterostructure. Thus, the degree of defectness of the structure can be qualitatively and quantitatively assessed by the electrophysical and electro-optical parameters and characteristics of LEDs.

The paper presents a method for measuring the threshold current in local areas of the LED chip, which can be used to assess the structural perfection of light-emitting heterostructures.

## Materials and Methods

According to the ABC model of charge carrier recombination in a heterostructure, the total LED current $I$ can be determined by the expression [6–8]:

$$I = \frac{eV}{\eta_{inj}}\left(An + Bn^2 + Cn^3\right) + f(n), \quad (1)$$

where $e$ is elementary charge; $V$ is heterostructure active region volume; $\eta_{inj}$ is coefficient of charge carrier injection into the active region; $A$, $B$ and $C$ are coefficients of nonradiative Shockley-Reed-Hall recombination, radiative recombination and nonradiative Auger recombination, respectively; $n$ is charge carrier concentration; $f(n)$ is a function that determines the leakage of charge carriers from the active region into the barrier layers of the heterostructure.

The function $f(n)$ depends on the leakage mechanism and becomes significant at high charge carrier concentrations. At low carrier concentrations, much lower than the concentration at which the maximum quantum efficiency is reached, the charge carrier leakage current is a fraction of a percent of the total LED current [8]. As the concentration of charge carriers tends to zero $n \to 0$, the term $f(n)$ acquires the meaning of the threshold current $I_{th}$, i.e., the minimum current at which emission from the structure occurs: $f(n) \to I_{th}$. At low currents, the effect of Auger recombination can be neglected [9]. In this case, the expression for small currents can be represented as

$$I \approx \frac{eV}{\eta_{inj}}\left(An + Bn^2\right) + I_{th}. \quad (2)$$

The power of emission that goes beyond the LED is determined by the expression

$$P = \eta_{extr} V \frac{hc}{\lambda} Bn^2, \quad (3)$$

where $\eta_{extr}$ is light extraction efficiency; $h$ is Planck's constant; $c$ is speed of light; $\lambda$ is emission wavelength [10].

Expressing the charge carriers concentration from (2) and substituting into (3), we obtain the function of approximating the *P-I* characteristic of the LED in the vicinity of the threshold current [11]:

$$P(I) = \frac{m}{2}\left(\sqrt{1+2q(I-I_{th})}-1\right)^2, \tag{4}$$

where $m = \eta_{extr} V \frac{hc}{\lambda} \frac{A^2}{2B}$ is "scale factor"; $q = \frac{\eta_{inj}}{eV} \frac{2B}{A^2}$ is "form factor", that determines the curvature of the characteristic.

With this representation of the *P-I* characteristic of the LED, the threshold current $I_{th}$ is an objective parameter that characterizes the quality of the light-emitting heterostructure and does not depend on the sensitivity and noise of the photodetector.

To determine the threshold current $I_{th}$ it is necessary to solve a system of equations of the form

$$P(I_i) = \frac{m}{2}\left(\sqrt{1+2q(I_i-I_{th})}-1\right)^2, i = 1,2,3, \tag{5}$$

compiled on the basis of the results of three measurements of the emission power of the LED $P(I_1)$, $P(I_2)$ and $P(I_3)$ at currents $I_1$, $I_2$ and $I_3$ respectively.

The choice of currents $I_1$, $I_2$ and $I_3$ is determined from the condition of minimizing systematic and random errors in measuring of the emission power. The current $I_1$ is set to the smallest one that provides an acceptable level of error. The current $I_3$ should be about 5 times less than the current $I_{max}$, at which the maximum quantum efficiency is achieved. In this case, as shown in [12], the component of the error due to the approximation of the ABC model does not exceed 1%. The current $I_2$ is selected from the condition $I_2 \approx 0.5\, I_3$. In this case, the random error caused by the influence of the photodetector noise on the results of measurements of the LED emission powers is minimized [13].

Approbation of the method of measuring the threshold current was carried out on commercial blue LEDs XRCBLU-L1-0000-00G01 and green LEDs XRCGRN-L1-0000-00M01. The maximum quantum efficiency of LEDs of these types is achieved at currents of 1...5 mA. The dimensions of the LED chip are 980×980 µm.

## Results and Discussion

The threshold current $I_{th}$ in local regions of the LED chip was measured using a hardware-software complex [14] consisting of a Levenhuk D320L microscope, an FL-20BW monochrome digital CMOS camera, a computer, a laboratory power supply, and a Tektronix DMM4040 precision multimeter used as an ammeter. The threshold current distribution profiles over the LED chip area were measured at room temperature in the following order. The LED was placed on the microscope stage. Constant currents $I_1$ = 100 nA, $I_2$ = 10 µA, and $I_3$ = 20 µA were alternately passed through the LED and chip images were recorded. The spectral sensitivity range of the FL-20BW camera is 300–1100 nm, the maximum sensitivity is achieved at a emission wavelength of 495 nm. During measurements, the exposure time was set equal to 3600 s at current $I_1$, 700 ms at current $I_2$, and 300 ms at current $I_3$. Monochrome images with a resolution of 5472×3648 pixels and a bit depth of 16 bits, obtained by the camera, were stored in the computer's memory. Then, per-pixel calculation of the threshold current value was carried out by solving the system of equations (5).

On (Fig. 1) shows the distribution profile of the current $I_{th}$ over the chip area of the investigated LEDs.

The distribution of the $I_{th}$ current over the chip area of the investigated LEDs is uneven. The average value of threshold current of green LED is 58 nA. In local areas, the current $I_{th}$ reaches values of 80 nA. The average value of threshold current of blue LED is 11 nA. In local areas, the current $I_{th}$ reaches values of 30 nA.

The degree of homogeneity of the distribution profiles was assessed as follows. We calculated the average values of the threshold current over the chip area $\overline{I_{th}}$, the standard deviation $\sigma_{Ith}$, and the coefficient $k = S_1/S$, where $S_1$ is the chip area within which the threshold current values

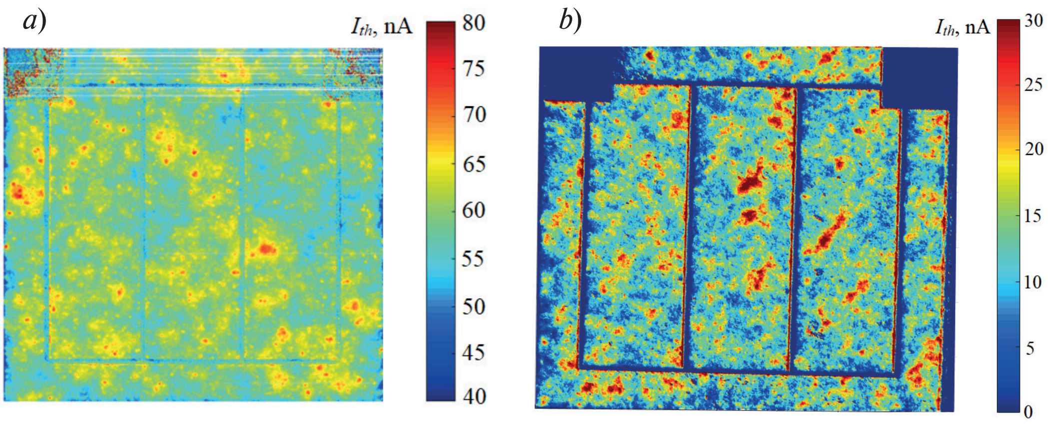


Fig. 1. Threshold current $I_{th}$ distribution profiles across the chip of green LED XRCGRN-L1-0000-00M01 (*a*) and blue LED XRCBLU-L1-0000-00G01 (*b*)

exceed $\left(\overline{I_{th}} \pm \sigma_{Ith}\right)$; $S$ is the area of the chip. According to the estimates obtained, $k$ = 0.33 for the blue LED, and $k$ = 0.21 for the green LED. This means that the distribution of the threshold current over the area of the green LED chip is more uniform than the distribution over the area of the blue LED chip, in which a significant part of the area consists of regions with threshold current values that are significantly higher than the average value.

## Conclusion

A method for measuring the threshold current in local areas of the LED chip is presented. The method is based on the approximation of the *P-I* characteristic of the LED in the vicinity of the threshold current by a function obtained on the basis of the ABC model of charge carrier recombination in a heterostructure. The method consists in recording LED chip images with a digital camera at three low currents and pixel-by-pixel calculation of threshold current values by solving a system of equations relating measured emission power values at specified currents with an approximating function. Testing on commercial green and blue LEDs showed that the distribution of the threshold current values over the chip area of the investigated LEDs is significantly uneven, with blue LEDs having a greater inhomogeneity than green LEDs. The method can be used to evaluate the structural perfection of light-emitting heterostructures.

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