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Threshold current of separate spectral components of the emission spectrum of InGaN LEDs

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Abstract. The results of measurements of the threshold current of ultraviolet, blue and green InGaN LEDs on different spectral components of the full emission spectrum are presented. It is shown that the threshold current of long-wave components of the spectrum is greater than the threshold current of short-wave components. The relative difference in the values of the threshold current of the spectral components of the short-wave and long-wave wings of the emission spectrum at the level of half the radiation power is associated with the inhomogeneous distribution of indium concentration in the quantum well of the InGaN/GaN heterostructure and for the studied ultraviolet LEDs is 2.8%, 4.4% for blue, 25.7% for green.

Keywords: LED, InGaN/GaN heterostructure, emission spectrum, threshold current, measurement

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Пороговый ток отдельных спектральных составляющих спектра излучения светодиодов на основе InGaN

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Аннотация. Представлены результаты измерений порогового тока ультрафиолетовых, голубых и зеленых InGaN светодиодов на разных спектральных составляющих полного спектра излучения. Показано, что пороговый ток длинноволновых составляющих спектра больше, чем пороговый ток коротковолновых составляющих. Относительная разница в значениях порогового тока спектральных компонентов коротковолнового и длинноволнового крыльев спектра излучения на уровне половины мощности излучения связана с неоднородным распределением концентрации индия в квантовой яме гетероструктуры InGaN/GaN и для исследованных ультрафиолетовых светодиодов составляет 2,8%, для синего – 4,4%, для зеленого – 25,7%.

Ключевые слова: светодиод, спектр излучения, пороговый ток, измерение

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Introduction

Light-emitting InGaN/GaN heterostructures with multiple quantum wells are characterized by a nonuniform distribution of indium in the InGaN quantum well [1] and a significantly nonuniform distribution of defects over the volume of the active region of the heterostructure [2]. The development of methods and means for assessing the inhomogeneity of indium distribution for the purpose of diagnostic quality control of InGaN/GaN heterostructures is an urgent task. In [3] it is shown that the P–I characteristics measured in the range of extreme currents are sensitive to defects in the heterostructure. The threshold current of a light-emitting heterostructure, i.e., the minimum current at which radiation occurs, is an informative parameter characterizing its quality [4]. The paper presents the results of measurements of the threshold current on different spectral components of the emission spectrum.

Objects of research and methods

Commercial LEDs based on $In_xGa_{1-x}N/GaN$ heterostructure ultraviolet (UV) (λ_{max} = 363 nm, x = 0.02), blue (λ_{max} = 465 nm, x = 0.19) and green (λ_{max} = 525 nm, x = 0.38) luminescence have been investigated.

Emission spectra of LEDs at several values of low currents (100–1000 nA for blue and green LEDs and 25–70 μA for UV LEDs) were measured with an Ocean Optics USB 2000 spectrometer having a resolution of 1.5 nm and saved into text files. The exposure time of the optical signal during measurements was set in the range of 100 ms–5 s. From the complete emission spectra, components in different parts of the spectrum were programmatically separated with a step of 5 nm and the *P–I* characteristic was constructed. To determine the threshold current I_{th}, the measured *P–I* characteristic was approximated by a function obtained in work [5] based on the ABC model of charge carrier recombination in a heterostructure in the range of low currents, at which the effect of Auger recombination can be neglected, and the parameters m and q of which are related to the recombination parameters of the light-emitting structure.

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

where $m = \eta_{extr} V \frac{hc}{\lambda}\frac{A^2}{2B}$ is the scale factor; $q = \frac{\eta_{inj}}{eV}\frac{2B}{A^2}$ is the form factor, that determines the curvature of the characteristic; I_{th} is the threshold current; η_{extr} is light extraction efficiency; h is Planck's constant; c is speed of light; λ is emission wavelength; e is elementary charge; V is heterostructure active region volume; η_{inj} is coefficient of charge carrier injection into the active region; A and B are coefficients of nonradiative Shockley-Reed-Hall recombination and radiative recombination, respectively.

Results and Discussion

The results of measuring of the threshold currents of separate spectral components of the investigated LEDs are shown in Fig. 1. For all LEDs, the threshold current of long-wavelength components of the spectrum is greater than the threshold current of short-wavelength components. The relative difference in the threshold current values of the spectral components of the short-wave and long-wave wings of the emission spectrum at the level of half the emission power is 2.8% for ultraviolet, 4.4% for blue, and 25.7% for green.

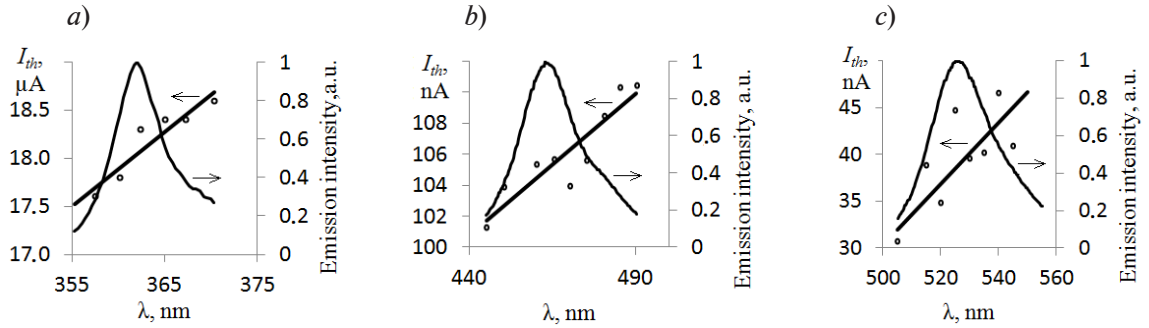

Fig. 1. Results of measurements of threshold current of violet (*a*), blue (*b*) and green (*c*) LEDs in different parts of emission spectrum

To explain the obtained results, let us consider the model of the formation of the emission spectrum of an InGaN/GaN heterostructure with a nonuniform distribution of indium, presented in [6]. According to the model, an LED can be represented by a set of parallel-connected microdiodes that have the same parameters of wide-gap *n*-GaN and *p*-GaN emitters, but differ from each other in the indium concentration *x* in quantum wells (Fig. 2).

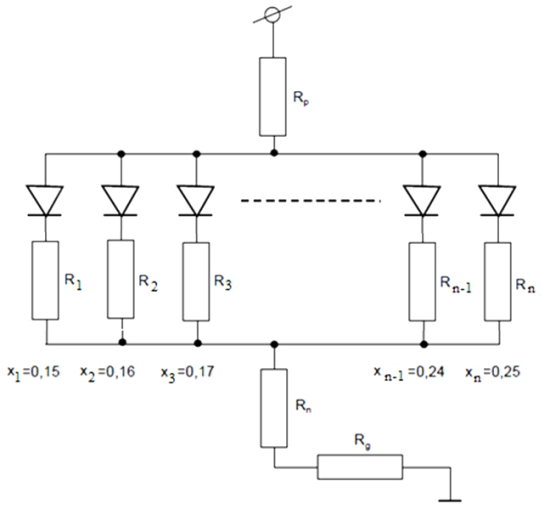

Fig. 2. Electrical model of LED with inhomogeneous distribution of indium in InGaN/GaN heterostructure quantum well [6]

The total contact resistance is connected in series with this set of microdiodes. The areas of microdiodes (sectors, areas) $S(x)$ with different indium content x in quantum wells can, to a first approximation, be described by a Gaussian distribution relative to the average values $x = 0.4$ for green LEDs and $x = 0.2$ for blue ones. At values $x = 0.15–0.17$, the current density is significantly higher than at values $x = 0.18–0.25$. Each microdiode has a threshold voltage U_{th_i} ($I = 1,...,n$), which is directly proportional to the band gap width and inversely proportional to the indium concentration x in the quantum wells. Since the difference between U_{th_1} and U_{th_n} is a few percent, the difference in the threshold current values I_{th_1} and I_{th_n} is due to the difference in the series (differential) resistances of the microdiodes R_i: $R_1 < R_n$, which is consistent with the results of modeling the current-voltage characteristics of blue LEDs based on the principle of distributing areas with different In_x contents, presented in [6].

An increase in the indium concentration x in a quantum well leads not only to the formation of clusters, but also to an increase in the degree of inhomogeneity of its distribution [7]. The experimental results presented in [8] show that at indium concentrations exceeding $x = 0.1$, there is a significant increase in the inhomogeneity of its distribution, which is confirmed by the broadening of the optical absorption edge.

Consequently, the experimental results can be interpreted as follows: when current passes through the heterostructure, radiative recombination first occurs in regions with lower indium concentrations, forming the short-wavelength wing of the emission spectrum. As the current increases, emission occurs in areas with higher concentrations of indium. The greater the inhomogeneity of the indium concentration in the quantum well, the greater the relative difference in the I_{th} values in the long- and short-wavelength components of the spectrum. The relative difference in the values of the threshold current of the spectral components of the short-wave and long-wave wings of the emission spectrum at the level of half the emission power can be used to indirectly estimate the degree of inhomogeneity of the indium concentration distribution in the InGaN/GaN quantum well.

Conclusion

The paper presents the results of measurements of the threshold current of ultraviolet, blue and green InGaN LEDs on different spectral components of the full spectrum of emission. It is shown that the threshold current of long-wave components of the spectrum is greater than the threshold current of short-wave components. The relative difference in the values of the threshold current of the spectral components of the short-wave and long-wave wings of the emission spectrum at the level of half the emission power is associated with the inhomogeneous distribution of indium concentration in the quantum well of the InGaN/GaN heterostructure and for the investigated ultraviolet LEDs is 2.8%, 4.4% for blue, for 25.7% green. The results obtained can be used to develop a technique for indirectly assessing the degree of uniformity of indium distribution in InGaN/GaN light-emitting heterostructures.

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