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Investigation of the relationship between the defects density in light-emitting InGaN/GaN heterostructures and the parameters of the P-I characteristic

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The article shows that the parameter of the function that approximates the P-I characteristic of an InGaN/GaN LED in the low current range, which determines the degree of nonlinearity of the P-I characteristic, is inversely proportional to the square root of the defects density. This dependence is confirmed by experimentally established strong correlations between this parameter and the level of low-frequency noise of LEDs and the parameters of heterostructure luminescence inhomogeneity in the microplasma breakdown mode. This parameter can be used to assess the defectness of light-emitting heterostructures.

Keywords: light-emitting heterostructure, defect density, P-I characteristic, low-frequency noise, microplasma breakdown.

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InGaN/GaN light-emitting heterostructures with multiple quantum wells are characterised by the presence of various microdefects (indium clusters, dislocations, vacancies etc.) in the active region, which is the cause of accelerated degradation of LEDs based on them during operation [1,2]. Existing methods of LED diagnostics by current-voltage characteristic, light flux, colour temperature, thermal resistance, etc. [3,4] do not allow effectively identifying LEDs with increased concentration of microdefects, which do not affect these characteristics under control, but during operation lead to faster degradation processes.

Thus, searching for informative parameters allowing to estimate the degree of defectiveness of light-emitting heterostructures is a topical problem. The purpose of this investigation was to determine the possibility of assessing the degree of defectiveness of light-emitting heterostructure InGaN/GaN based on the parameter of the function that approximates the watt-ampere characteristic of LEDs in the range of small currents.

To approximate the watt-ampere characteristic of the LED in the range of small currents, at which the effect of Auger recombination can be neglected, in [5] a function was obtained based on the ABC model of charge carrier recombination in the heterostructure:

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

where the coefficients m and q are related to the recombination parameters of the light-emitting structure.

It is also shown in [5] that the coefficient q, which determines the degree of nonlinearity of the watt-ampere characteristic, is directly proportional to the radiative recombination coefficient B and inversely proportional to the square of the coefficient A of non-radiative recombination:

$$q=\frac{\eta_{\text{inj}}}{eV}\frac{2B}{A^2}, \tag{2}$$

where η_{inj} — the coefficient of charge carriers injection into the active region, e — elementary charge, V — the volume of the active region of the heterostructure.

The parameter m is calculated using the following formula

$$m=\eta_{\text{extr}}V\frac{hc}{\lambda}\frac{A^2}{2B}, \tag{3}$$

where η_{extr} — the light extraction efficiency, h — the Planck constant, c — the speed of light, λ — the emission wavelength.

As q decreases, the degree of nonlinearity of the function (1) increases, and at $2qI \ll 1$

$$P(I)\approx\frac{m}{2}q^2I^2.$$

As q increases, the function (1) approaches linear, and at $2qI \gg 1$

$$P(I)\approx mqI.$$

In turn, as shown in [6], the nonradiative recombination coefficient A is proportional to the concentration of the charge carrier capture centres (defects): $A\sim N_T$. Thus, the concentration of defects N_T and the parameter q are related by the dependence of the form

$$N_T\sim 1/\sqrt{q}. \tag{4}$$

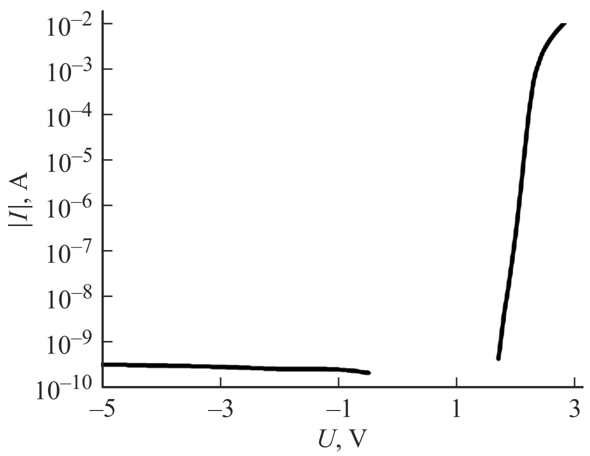

Figure 1. Current-voltage characteristic of one of the LEDs of the investigated sampling.

To confirm the obtained model dependence (3), we carried out an indirect assessment of the degree of light-emitting heterostructures defectiveness using the parameters of low-frequency (LF) noise of the LED and the parameters of heterostructure luminescence inhomogeneity in the microplasma (MP) breakdown mode. Low-frequency noise parameters due to their high sensitivity to inhomogeneities and structure defects can be used to diagnose the quality of semiconductor devices, including those based on light-emitting heterostructures [7–10]. In [9,10] it is shown that at low currents (of the order of tens μA) the mean square of the LED noise current is directly proportional to the defect concentration of the heterostructure: $S_I \sim N_T$. In [11] it is shown that in the MP breakdown mode the structure luminescence occurs in regions with increased defect concentration.

The study is carried out using a sampling of 75 units of commercial green InGaN/GaN LEDs of type TO-3216BC-PG. The crystal dimensions of the LEDs are $200 \times 130\,\mu$m, the wavelength corresponding to the maximum of the emission spectrum is 525 nm at a current of 20 mA, the external quantum efficiency of the emission at a current of 20 mA (current density 77 A/cm^2) is 0.1, and the maximum value is reached at a current $50\,\mu$A (current density 0.19 A/cm^2) and equals 0.2. The current-voltage characteristic of one of the LEDs of the investigated sampling is shown in Fig. 1. In the range of reverse voltages up to −5 V the reverse current does not exceed 0.5 nA.

Measurements of the watt-ampere characteristics in the current range from $1\,\mu$A to 1 mA were carried out by an LED threshold current meter [12]. The signal at the output of the photodetector included in the meter, which is proportional to the LED optical emission power, was measured by a 16-bit analogue-to-digital converter (ADC). The LED emission power values were expressed in relative units reduced to the maximum signal value at the output of the ADC.

The parameter q was determined by approximating the measurement results with a function (1) using the least-squares method. For the LEDs of the investigated sample, the parameter q varied from 30746 to 62026 A^{-1} with an average value of 45937 A^{-1}.

Fig. 2 shows the watt-ampere characteristics of LEDs №1 and №2 with significantly different value of the approximating function parameter q. At low currents, the watt-ampere characteristic of LED №1 is steeper than the watt-ampere characteristic of LED №2.

The power spectral density (PSD) of the low-frequency noise current S_I was measured by the hardware and software system described in [13], which implements the power doubling method: a constant current $20\,\mu$A was passed through the LED connected through a matching transformer to a Unipan-233 selective nanovoltmeter, and the steady-state readings of the selective nanovoltmeter tuned to a frequency of 1 kHz with a bandwidth of 40 Hz were increased 2 times with a G2-37 white noise generator connected in parallel to the LED during the integration time (of the order of 10 s). The PSD of the noise of LED №1 with the maximum value of parameter q was $1.3 \cdot 10^{-21}$ A^2/Hz, and the PSD of LED №2 with the minimum value of parameter q — $2.6 \cdot 10^{-21}$ A^2/Hz. The

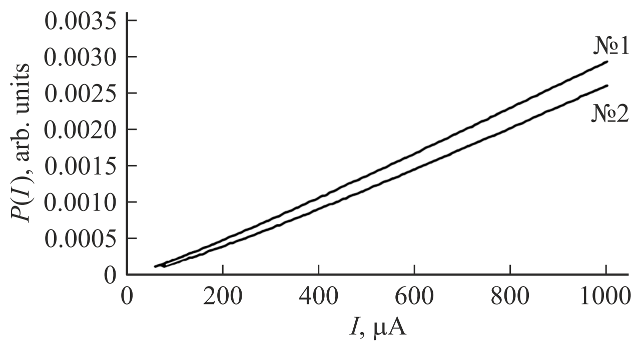

Figure 2. The watt-ampere characteristics of the two LEDs: №1 — $q = 62026$ A^{-1}, №2 — $q = 30746$ A^{-1}.

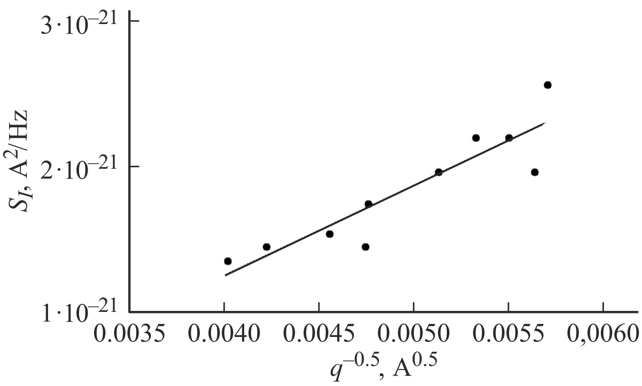

Figure 3. The correlation field between the LF noise power spectral density (PSD) and the parameter q in coordinates S_I–$1/\sqrt{q}$.

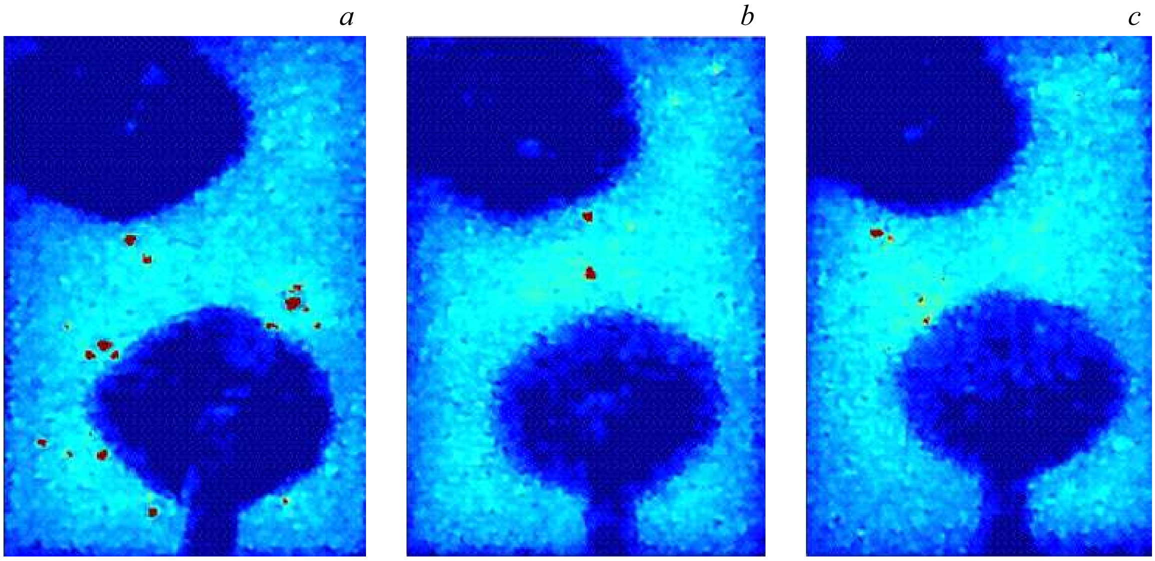

Figure 4. Crystal images of three LEDs in the MP breakdown mode: (*a*) $K = 0.67\%$, $q = 42830\,\mathrm{A}^{-1}$; (*b*) $K = 0.14\%$, $q = 48293\,\mathrm{A}^{-1}$; (*c*) $K = 0.10\%$, $q = 62026\,\mathrm{A}^{-1}$.

sample mean value of the PSD of the LED noise was as follows $1.9 \cdot 10^{-21}\,\mathrm{A}^2/\mathrm{Hz}$.

Fig. 3 shows the correlation field between the PSD of the LED noise and the parameter of the approximating function q, plotted in coordinates $S_I \sim 1/\sqrt{q}$. The experimental results of Fig. 3 are subject to linear dependence and confirm the model dependence (4).

Registration of optical emission of heterostructures in the MP breakdown mode was carried out at voltage $-60\,\mathrm{V}$ on the measurement setup described in [14]. During measurements of LED parameters in the MP breakdown mode, the power dissipation did not exceed the maximum permissible value, and as a result of these short-term (about one minute) measurements, there was no degradation of LED characteristics, including watt-ampere characteristics at low current densities.

The principle of operation of the setup is to obtain an image of the LED crystal by a CCD camera and its subsequent pixel-by-pixel processing. The image processing consisted of isolating the active region of the LED crystal, calculating the average emission intensity as the average pixel brightness E, dispersion and mean square deviation σ. According to the experimental results, in all LEDs the luminescence intensity in the MP breakdown mode is distributed unevenly over the crystal: there are local regions in which the luminescence intensity significantly exceeds the average value of the crystal luminescence intensity $\overline{E}$. To estimate the degree of inhomogeneity of the structure luminescence in the MP breakdown mode, the coefficient $K = S_{\mathrm{MP}}/S$ was used, where S — the area of the crystal, S_{MP} — the area of local regions of the structure in which the luminescence intensity exceeds the value of $\overline{E} + 3\sigma$. These regions are indicated in red in Figure 4. In LEDs with a higher degree of inhomogeneity of the structure luminescence in the MP breakdown mode K (larger area of MP breakdown), the parameter q of the function approximating the watt-ampere characteristic is lower, which also indicates a higher degree of heterostructure defectiveness.

The obtained results confirm the relation between the parameter q approximating the watt-ampere characteristic of the function and the defect concentration of the LED heterostructure as well as the possibility of using this parameter to estimate the degree of heterostructure defectiveness.

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Conflict of interest

The authors declare that they have no conflict of interest.

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