Changing of the dynamic characteristics of the spectral components of the InGaN-based LEDs spectrum during current tests

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Abstract. The results of the study of changes in the dynamic characteristics of various spectral components of the full electroluminescence spectrum of green LEDs based on InGaN during tests with a pulsed current of increased density are presented. It was found that there is a decrease in the radiation power of the LED after 200 hours, as well as a decrease in the frequency of modulation of electroluminescence by 3 dB. It was found that a frequency change of 3 dB in the short-wavelength components of the spectrum is much larger than the long-wavelength ones. The results obtained indicate that the process of defect formation during testing proceeds more intensively in areas of a heterostructure with a low In concentration.

1. Introduction
Despite the improvement of manufacturing technologies for LEDs based on group III nitrides, changing their electrophysical and optical characteristics during operation remains one of the key problems. A number of studies [1] showed that significant changes in the characteristics of LEDs occur at the run-in stage in the first 100 – 1000 hours of operation at rated direct current and are usually associated with processes in the heterostructure, which cause, inter alia, changes in the parameters of the radiative and non-radiative recombination and, as a consequence, a change in the dynamic characteristics of electroluminescence. The investigation of the possibility of reducing the duration of the run-in stage of LEDs by conducting their accelerated tests is of practical interest. The purpose of the work was to research changes in the charge carriers lifetimes in the heterostructure of InGaN-based LEDs when tested under the pulsed current of increased density.

2. Measurement of 3 dB frequencies and charge carriers lifetime
The 3dB frequency of separate spectral bands of the LED electroluminescence spectrum was measured on a hardware-software complex that included a DG4162 functional generator, an Ocean Optics USB2000+ spectrometer, and a computer with LabView software [2]. The block diagram of the hardware part of the hardware-software complex for measuring spectral quantum efficiencies and 3 dB frequencies of separate spectral emission bands of the LED is shown in figure 1. The LED is powered by current pulses from the generator AKIP 3420/3. The duration of the rise and fall of the front of the current pulse is 8 ns. The range of variation of the amplitude of current pulses is from 10 μA to 50 mA. The USB interface is used for software tuning of the pulse repetition rate from 1 kHz to 10 MHz with a uniform step on a logarithmic scale.
Figure 1. Block diagram of the measuring complex

The optical signal of the LED is fed to the input of the Ocean Optics USB2000+ spectrometer. Depending on the level of the optical signal, the integration time can be set in the range from 1 ms to 65 s. The principle of the complex’s operation is to measure the LED electroluminescence spectra when the pulse current frequency increases from 1 kHz to \(f_{3dB}\), at which the optical signal level drops 1.19 times relative to the level at the lower modulation frequency [2]. A computer program extracts from the general spectrum the separate components of the spectrum with a step of 1.5 nm, saves their amplitude-frequency characteristics to the text file and calculates the 3dB frequency.

The radiative and non-radiative charge carriers lifetime is associated with the 3 dB frequency by the expression [3]:

\[
f_{3dB} = \frac{\sqrt{3}}{2\pi \tau} = \frac{\sqrt{3}}{2\pi} \left( \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} \right),
\]

where \(\tau_r\) – radiative lifetime, \(\tau_{nr}\) – non-radiative lifetime.

On the other hand, the internal quantum efficiency is determined by the probability of radiative and nonradiative recombination of charge carriers per unit time. The probability of radiative recombination, or internal quantum efficiency, is determined by the expression [3]:

\[
\eta_{int} = \frac{\tau_r}{\tau_r + \tau_{nr}} = \frac{1}{1 + \tau_r / \tau_{nr}},
\]

By jointly solving equations (1), (2) and taking the value of the coefficient of radiation extraction from the structure equal to \(\eta_{extr} = 0.5\), we obtain expressions for calculating the radiative and non-radiative charge carriers lifetimes on different bands of the electroluminescence spectrum:

\[
\tau_r = \frac{\sqrt{3}}{2\pi} \left[ \frac{\eta}{\eta_{extr}} \right] f_{3dB}^{-1},
\]

\[
\tau_{nr} = \frac{\sqrt{3}}{2\pi} \left[ \frac{1 - \eta}{\eta_{extr}} \right] f_{3dB}^{-1},
\]

where \(\eta\) is external quantum efficiency.

3. Experimental results

We studied commercial green InGaN-based LEDs produced by Arlight with a central wavelength of the emission spectrum of 525 nm and a rated operating current of 20 mA. The LEDs were tested in two modes: a) Long-term tests of LEDs under the direct current of 20 mA for 5000 h at an ambient temperature of 25 °C. In the process of testing the LEDs, we measured the spectral quantum efficiencies \(\eta_i\) of the separate spectral bands in the wavelength range from 500 nm to 550 nm and b) accelerated test of LED’s at ambient temperature 25 °C for 200 hours at the following parameters of the current pulses: amplitude current value 300 mA, pulse duration 500 μs, period 5 ms.

It was found that during testing under the direct current, the radiation power of the LEDs decreases. At low currents, the radiation power decreases by a larger amount than at high currents. At a measuring current of 1 mA, after 5000 h of testing, the decrease in the radiation power was 55%. In this case, the external quantum efficiency of the short-wavelength components of the spectrum decreased by a larger amount than the external quantum efficiency of the long-wavelength components of the spectrum (figure 2). For the LEDs studied, the difference between the decay of the external quantum efficiency at wavelengths of 500 nm and 550 nm was 5%.
Figure 2. The emission spectra of the green LED before and after the tests and the dependence of the magnitude of the spectral quantum decrease on the emission wavelength.

Figure 3 shows the dependence of the 3 dB frequency on the electroluminescence wavelength before and after accelerated testing by current pulses of 300 mA of one of the investigated LEDs, measured at a current of 100 μA. The graph also shows the nature of the change in the radiation spectrum after the test. The dependence $f_{3dB}(\lambda)$, characteristic of all 15 pieces of LEDs of the sample under study, has a nonmonotonic character. The most significant changes in the power $P$ of optical radiation of LEDs and frequencies of 3 dB occur in the first 100 hours of accelerated testing. With further testing, the rate of change in performance decreases.

Figure 4 shows the relative change in the 3dB frequency after 100 h of testing the afore-referenced LED. The graph shows that a decrease in the 3dB frequency of the short-wavelength components of the emission spectrum is more than a decrease in the 3 dB frequency of the long-wavelength components.

In accordance with formulas (3) and (4), the relative changes of the radiative and non-radiative charge carriers lifetime after 100 hours of testing were calculated (figure 5). It can be seen from the figures that, when the optical power of the LED is decreased, a significant increase in the radiative lifetime of charge carriers and a decrease in the nonradiative lifetime are observed. The change in the charge carriers lifetimes, the recombination of which forms the short-wavelength wing of the spectrum, is much larger than the change for the long-wavelength wing of the spectra.
Figure 5. The relative change of the radiative (a) and non-radiative (b) charge carriers lifetime after 100 hours of testing.

Similar changes in carrier lifetimes indicates to an increase in the defects density in the structure [3-5]. According to the model of the inhomogeneous distribution of the In concentration over the active area of the heterostructure [6], the short-wavelength wing of the emission spectrum is formed by local areas of the heterostructure with a low In concentration, and the long-wavelength wing is formed by local areas with a high In concentration. Thus, the results obtained indicate that the process of defect formation during testing proceeds more intensively in areas of the structure with a reduced In concentration, characterized by large values of the band gap and current density.

The results will be used to develop a methods for stabilizing changes of the LEDs characteristics in the first hundreds of hours by reducing the stage of rapid degradation due to accelerated tests under the pulsed current of increased density.

4. Conclusions
The results obtained indicate that the process of defect formation during the tests proceeds more intensively in regions of the structure with a reduced In concentration, characterized by large values of the band gap and current density. In both LED test modes, quantum efficiency decreases in the short-wavelength region of the electroluminescence spectrum. This suggests that the mechanisms of degradation are identical. In this case, long-term tests can be replaced by accelerated tests of LEDs. The results will be used to develop methods for stabilizing changes in the characteristics of LEDs in the first hundreds of hours by reducing the stage of rapid degradation due to accelerated testing under high-density pulsed current. Since the changes in the frequency of 3 dB on the short-wavelength wing of the spectrum are larger, it is assumed that the stabilization level should be controlled using this parameter.

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