Degradation of green InGaN-based LEDs during the tests at the constant current

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Abstract. The article presents the results of investigation of the degradation of electrical and optical characteristics of green InGaN-based LEDs under tests at constant direct current for 5000 hours. It is determined that LEDs which were subjected to a 4-hours exposure of high-density pulsed current degrade slowly than LEDs not exposed to this exposure. The external quantum efficiency (EQE) of the short-wave components of the radiation spectrum of the LEDs when testing reduced by a greater amount than the EQE of the long-wave components of the spectrum. For LEDs that have a current-voltage characteristic with a non-ideality factor of \( m \approx 2 \), the rate of decrease of optical power during testing is lower than for LEDs with \( m > 2 \).

1. Introduction
The effects of decreasing of the EQE of InGaN-based LEDs with multiple quantum wells in the process of exploitation have been actively investigated over the last two decades [1,2], however, the physical mechanisms of these effects have not been fully studied and the problem of degradation remains relevant at the present time. One of the tasks aimed to improving the stability of the characteristics of LED-based devices in the process of their operation is the development of methods for forecasting of the service life of LEDs according to their initial characteristics [3]. The article presents the results of investigation of degradation of commercial green InGaN-based LEDs of type ARL-5213 PGC during tests at the constant direct current and results of estimates of the relationship between the rate of decrease of optical power and LEDs initial characteristics.

2. Experimental conditions
We investigated the commercial green InGaN-based LEDs in an amount of \( N = 30 \) pieces with following parameters: central wavelength of the radiation spectrum \( \lambda_{\text{max}} = 525 \) nm, maximum forward current is 30 mA, chip sizes is 270x320 \( \mu \text{m} \), maximum pulse forward current is 100 mA at the duty cycle \( \leq 1/10 \) and the pulse width \( \leq 10 \) ms, the maximum dissipated power is 120 mW.

Before the tests, the LEDs were separated into three groups of 10 pieces each. The first group of LEDs was tested for 4 hours under the pulses of direct current with an amplitude of 0.5 A, a duration of 100 \( \mu \text{s} \) and a duty cycle of 1/100 at an ambient temperature of 25 °C. The average value of the power dissipation in this mode was 42 mW. According to the estimates obtained by measuring of the thermal resistance and the thermal time constant of the LED crystal, the average temperature of the LEDs active region during the tests did not exceed 30 °C. The first group of LEDs, which passed 4-hour pulse tests, and the second group of LEDs which not subjected to pulse tests, were put on long-term tests under the direct current of 20 mA \( (j = 23 \) A/cm²). The third group of LEDs was put on testing under the direct current of 25 mA \( (j = 29 \) A/cm²). The LEDs were tested for 5000 hours. Measurement of the radiation power of the LEDs was performed on the measuring sphere TKA-KK1.
3. Decrease of optical power of LEDs during testing

Figure 1 presents the time dependencies of the optical power during the testing of LEDs subjected to and not subjected to 4-hour tests under a pulsed current. The radiation power was measured at a current of 10 mA. The graphs are plotted from the average values of the radiation power of the LEDs within each group. There are three regions on the graphs: a region of a slight change of optical power during the first 1000 hours of testing, a region of rapid decrease from 1000 to 2000 hours, and a region of slow decrease after 2000 hours. It can be seen from the graphs that the LEDs subjected to 4-hour pulse tests degrade slowly than the LEDs that did not pass the pulse tests: the average value of the radiation power of the LEDs of this group after 5000 hours of testing is 6% higher.

Figure 2 shows a optical power reduction of the third group of LEDs when tested at a direct current of 25 mA. There are three regions on the graphs also. The region of a slight change of optical power is much smaller and amounts to 150 hours. The region of fast decrease of optical power lies in the interval from 150 to 2000 hours, and the slow decrease also occurs after 2000 hours. Under the influence of a direct current of 25 mA, the radiation power of the LEDs decreases faster than at a current of 20 mA: in the time interval from 1000 to 2000 hours – by 1.2 times, in the interval from 2000 to 5000 hours – by 2.7 times.

During the tests, the EQE of the LEDs was measured at several current values in the range from 1 μA to 50 mA. Figure 3 shows the graphs of the current dependences of the EQE of one of the investigated LEDs before the tests and after 5000 hours of testing, measured in the full electroluminescence (EL) spectrum.

![Figure 1](image1.png)  
**Figure 1.** Optical power degradation measured during test at the constant current 20 mA (measuring current 10 mA).

![Figure 2](image2.png)  
**Figure 2.** Optical power degradation measured during test at the constant current 25 mA (measuring current 10 mA).

![Figure 3](image3.png)  
**Figure 3.** External quantum efficiency vs injected current curve measured on full electroluminescence spectrum.
It was found that the largest decrease of EQE occurs in the range of low currents corresponding to the growth area of the EQE (I) dependence. During the test, the maximum of the EQE shifts towards higher currents: after 5000 hours of testing, the current value has changed from 500 μA to 1 mA.

4. The decrease of EQE measured at different components of the EL spectrum during the test
It is known that the inhomogeneous distribution of indium over the area of the LEDs active region leads to an inhomogeneous distribution of the current density over the chip area [4]. Through the areas with low concentration of indium currents of higher density flow. As a consequence, the generation of defects is irregular in the area of the structure, which should lead to a change in the EL spectrum during the degradation process.

The results of measuring of the EQE current dependences on different spectral components of the full EL spectrum have shown that they reach a maximum at different current values (Figure 4). In the wavelength range corresponding to the short-wave region of the EL spectrum (λ = 500 nm), the saturation of the current dependence of the EQE is not observed in the range of operating currents. As the wavelength increases the maximum of the current dependence of the EQE shifts to the region of low currents and at a wavelength of λ = 520 nm the EQE reaches a maximum at a current of 1 mA. In the long-wave range of EL spectrum (λ = 540 nm), the maximum of EQE is achieved at a current of 200 μA.

Thus, it follows from the results obtained that the intensity of the radiative recombination of charge carriers located at different energy levels is saturated at different currents of the LED, and when the current changes, the energy levels participate in the formation of the full EL spectrum.

It is determined that the EQE of the short-wave components of the electroluminescence spectrum decreases more intensively than the EQE of the long-wavelength components of the spectrum (Figure 5) during the degradation process. In Fig. 5 the EL spectra before the tests and after 5000 hours of testing shown, as well as the EQE ratio after 5000 hours to the initial EQE values shown. It follows from the graph that the component of the spectrum at a wavelength of 500 nm drops by 7% more, than the spectral component at a wavelength of 550 nm. The obtained results agree with [5].

![Figure 4](image1.png)  ![Figure 5](image2.png)

Figure 4. EQE vs injected current curve measured on the spectral components within a full LED EL spectrum.

Figure 5. EL spectrums measured on one of the analyzed LEDs and relation between EQE measured on the spectral components within a full LED EL spectrum before and after test.
5. The changes of current-voltage (I-V) and capacitance-voltage (C-V) characteristics during test

The I-V characteristics of the studied LEDs differ quite strongly in form, especially in the range of low currents. Most of the investigated samples in the range of direct voltages of the order of 2 V have a inflection of I-V characteristics (Figure 6).

![Figure 6. I-V characteristics of two LEDs measured before and after 5000 h test at the current 20 mA.](image)

The inflection point of the I-V characteristic corresponds to the current at which the optical emission of the LED is registered. It is determined that by the value of the threshold current, investigated LEDs have an exponential distribution [6, 7]. The LEDs whose I-V characteristics in the voltage range 1 ... 2 V have a large value of the non-ideality factor $m$ are characterized by larger threshold current values than the LEDs with $m = 2$. The large values of the coefficient $m$ are due to the tunneling mechanism of current flow through the levels of defects, in which radiative recombination is absent. For most of the studied LED samples, the I-V characteristic changes during the test. In the range of low currents (up to 1 μA), the non-ideality factor $m$ increases. It has been determined that the LEDs which have value of $m$ close to 2 are characterized by lower values of the threshold current and have a smaller rate of decrease of the optical power than the LEDs having the value $m = 3 \ldots 8$. The optical power of the LED A after 5000 hours of testing at a current of 25 mA decreased by 67% (the largest value within the investigated sample), and the optical power of the LED B decreased by 48% (the smallest value within the sampled sample).

During the testing of LEDs, the change of their barrier capacity was controlled. The measurement of the C-V characteristics is performed in the range of bias voltages from +2 to -20 V in the installation [8]. The apparent profiles of charge carrier concentration distribution of LED A and LED B shown in Figure 7.

![Figure 7. C-V profiles measured before and after test on two LEDs: LED A (a) and LED B (b).](image)
It is determined that when testing LEDs under the action of a direct current, the width of the space charge region decreases, the charged centers are diffused towards the metallurgical boundary of the \textit{p-n} junction, while the pronounced inhomogeneities on the CV-profile near the boundary of the space charge region are formed: for the LED A (Figure 7a) three additional maxima were formed, and for LED B (Figure 7b) an increase in the concentration of charge carriers occurred in the regions of inhomogeneities from 100 nm to 200 nm. According to the degradation model presented in [1], the movement of additional charged centers to the active region of the LED leads to nonradiative recombination probability increase and to optical power decrease.

6. Conclusions
1) LEDs that have been subjected to 4-hour tests at the high-density pulsed current have a lower rate of optical power decrease than the LEDs that did not pass these tests. Current training in the forced pulse mode of green InGaN-based LEDs can be used as a technological operation to stabilize their characteristics and to identify potentially unreliable products.

2) The LEDs that have the values of non-ideality factor \( m \) close to 2 in the voltage range from 1 to 2 V are characterized by low values of the threshold current and have a lower rate of the optical power degradation than the LEDs with \( m \), the values of which reach 10.

3) The external quantum efficiency of the short-wave components of the EL spectrum of the LEDs during the testing decrease more rapidly than the EQE of the long-wave components.

4) When testing under the forward constant current, the width of the space-charge region of LEDs decreases, the diffusion of charged centers toward the \textit{p-n} junction and the formation of inhomogeneities near the heterointerface occurs.

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