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# Change of the defects density distribution profile over the area of the InGaN/GaN light-emitting heterostructures during current tests

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**Abstract**. A method for measuring of the defects density distribution profile over the area of the LED chip is presented. Using the blue commercial LEDs as an example, it is shown that the emission power decreases when LEDs testing under the increased density pulsed current for 190 h. The decrease of the LEDs emission power is accompanied by a change in the defects density distribution profile. It was determined that during the degradation process a non-uniform increase in the defects density occurs in various regions of the heterostructure: in regions with a higher defect density, the increment in the density of defects is larger.

#### 1. Introduction

When considering the problems of improving of the InGaN-based LEDs reliability and ensuring the long-term stability of their characteristics, one of the key problems remains the degradation of electrooptical characteristics under the direct current. The most significant reason for the decrease in the LED emission power during testing and operation is the formation of additional non-radiative recombination centers in the active region. It is known that InGaN-based heterostructures are characterized by spatial heterogeneity of optical properties due to fluctuations in the composition of the InGaN solid solution and the presence of a system of extended defects penetrating the material [1, 2]. The inhomogeneous distribution of defects may cause an accelerated defect formation process in local regions of the light-emitting heterostructure.

The purpose of the work was to investigate the change in the defects density distribution profile over the area of the InGaN-based LED chips during accelerated tests under the high-density pulse current.

# 2. A method for measuring of the defects density distribution profile over the area of the lightemitting heterostructure

The method for measuring of the defects density distribution profile over the area of the light-emitting heterostructure is based on the generally accepted ABC model of the charge carriers recombination in the LED heterostructure, which establishes the relationship between the internal quantum efficiency of the LED emission and the charge carriers concentration in the active region through recombination coefficients: Shockley-Reed-Hall nonradiative recombination coefficient A, radiative recombination coefficient B and non-radiative Auger recombination coefficient C [3]. At low currents, the effect of

Auger recombination can be neglected ( $Cn^3 \approx 0$ ). In this case, in the absence of carrier leakage from the active region, the internal quantum efficiency is determined by the expression:

$$\eta_{\rm int} \approx \frac{Bn^2}{An + Bn^2}.$$
 (1)

The nonradiative recombination coefficient A is directly proportional to the defect density  $N_T$  in the structure [4]:

$$A = \frac{1}{2}\sigma v N_T, \qquad (2)$$

where  $\sigma$  is the capture cross section, and v is the thermal velocity of charge carriers.

The radiative recombination coefficient *B* determines the power of light emission generated in the LED structure. The power of light emission which go beyond the light emitting diode depends on the light extraction coefficient  $\eta_{extr}$  and defined by the expression:

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

where V is the volume of the active region; h is Planck's constant; c is light speed;  $\lambda$  is light emission wavelength.

At the same time differential charge carriers lifetime determined by A and B recombination coefficients and carrier concentration n by the following equation [1]:

$$\tau^{-1} = A + 2Bn. \tag{4}$$

Combine expressions (3) and (4), we write a set of equations for two charge carrier concentrations  $n_1$  and  $n_2$ :

$$\begin{cases}
P_{1} = \eta_{extr} V \frac{hc}{\lambda} Bn_{1}^{2}; \\
P_{2} = \eta_{extr} V \frac{hc}{\lambda} Bn_{2}^{2}; \\
\tau_{1}^{-1} = A + 2Bn_{1}; \\
\tau_{2}^{-1} = A + 2Bn_{2}.
\end{cases}$$
(5)

where  $P_1$  and  $P_2$  is power of LED light emission measured at the current  $I_1$  and  $I_2$  respectively ( $I_2 > I_1$ )

Given that differential lifetime is inversely proportional to  $f_{3dB}$  3 dB frequency  $\tau = \sqrt{3} / (2\pi f_{3dB})$  [1], from (5) taking into account (2) we get the formula for calculation of defect density:

$$N_{T} = \frac{A}{\sigma v} = \frac{4\pi f_{3dB_{-1}}}{\sqrt{3}\sigma v} \left( 1 - \frac{f_{3dB_{-2}} / f_{3dB_{-1}} - 1}{\sqrt{P_{2} / P_{1}} - 1} \right), \tag{6}$$

where  $f_{3dB_1}$  and  $f_{3dB_2}$  3 dB frequency measured at LED current  $I_1$  and  $I_2$  respectively.

To determine the defects density  $N_T$  distribution profile over the area of the LED chip, an automated installation was developed that allows one to measure the distribution profiles of the emission power and the 3 dB frequencies [5, 6]. The measurement installation includes a Levenhuk D320L microscope with magnification up to 1600x, which incorporates a digital camera FL-20BW with a maximum resolution of 5472×3648, and a pulse generator DG4162 that sets the LED current. The spatial distribution profile of the electroluminescence intensity was measured at currents  $I_1 = 1 \mu A$  and  $I_2 = 10 \mu A$  by storing images of the LED chip. The exposure time of the digital camera was set in the range from 30 ms to 2 s so that the maximum value of the image brightness was on a linear portion

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of the brightness characteristic of the CMOS camera. For each image pixel, the value of the  $P_2/P_1$  parameter and the3 dB frequency were calculated. The technique for measuring the 3 dB frequencies when the LED is powered by a pulsed current with a duty cycle of 50% is presented in [7, 8]. The defects density  $N_T$  was calculated according to formula (6) with the capture cross section  $\sigma = 10^{-15}$  cm<sup>2</sup> and the thermal velocity of charge carriers  $v = 10^7$  cm/s [4].

#### 3. Experimental results

Changes of the defects density distribution profile over the area of the LED chip were envestigated in tests under the pulsed current. Oasistek-produced commercial blue InGaN-based LEDs with a chip size of  $200 \times 130 \ \mu$ m, a maximum permissible direct current density of 95 A/cm<sup>2</sup>, and a central wavelength of the emission spectrum of 468 nm were studied. The LEDs were tested for 190 h at the following current pulse values: amplitude of current density is 500 A/cm<sup>2</sup>, pulse duration is 500  $\mu$ s, pulse period is 5 ms. During the tests, measurements of the *P-I* characteristics in the current range of 50 nA – 5  $\mu$ A, corresponding to the range of currents at which the chip luminescence occur, and measurements of the defects density distribution profile with a spatial resolution of 0.65  $\mu$ m were performed.

Figure 1 shows a graph of the decrease in emission power P during testing of one of the LEDs from the investigated sample, normalized to the value of the radiation power before testing  $P_0$ . The emission power decreases most intensively in the first 14 hours of testing (by 5%), then the rate of power decline decreases.



Figure 1. LED power drop during testing

The most noticeable changes in the defects density distribution profile over the LED chip area were recorded after 8 hours of testing.

In figure 2 (a) shows the initial profile, in figure 2 (b) shows the profile after 8 hours of testing. It can be seen from the figures that along the perimeter of the active region of the LED chip present local regions in which the defects density is higher than the average defects density in the chip.



Figure 2. Defects density distribution profiles over the area of the LED chip before tests (a) and after 8 hours of tests (b)

Figure 3 shows the distribution histograms of the local areas  $S_i$  of the LED chip, normalized to the chip area S, in terms of the defects density value before and after 8 hours of testing. It can be seen that after the tests the proportion of local regions with a high defects density increases. The average value of the defects density before testing was  $6.2 \times 10^{13}$  cm<sup>-3</sup>, and after 8 hours of testing was  $6.4 \times 10^{13}$  cm<sup>-3</sup>, that is, it increased by 3%. In this case, the decrease in the emission power, according to the graph in figure 1 was 2.5%. The root-mean-square deviation  $\sigma$  of the defects density was equal to  $0.4 \times 10^{13}$  cm<sup>-3</sup> before testing and  $0.5 \times 10^{13}$  cm<sup>-3</sup> after 8 hours of testing, respectively, the coefficient of variation  $\gamma = \sigma/2$ 

 $\overline{N_{\tau}}$  before testing was 0.065, and after testing was 0.078. Since the coefficient of variation is much less than 0.33, the distribution of the defects density over the chip area can be considered uniform, and the use of the ABC recombination model for the analysis of such heterostructures is justified.



Figure 3. Distribution histograms of the local areas of the LED chip by the value of the defects density before and after 8 hours of testing

A joint analysis of the defects density distribution profiles over the area of the LED chip (figure 2) and the distribution histogram of the local areas of the LED chip by the value of the defect density (figure 3) showed that the defects density in local point regions located along the perimeter of the chip

(see an example of such a point region in the inset in figure 3), exceeds the value of  $\overline{N_T} + 3\sigma$  and is in the range of  $8 \times 10^{13} \dots 10 \times 10^{13}$  cm<sup>-3</sup>. In this case, the area of the chip regions in which the defects density exceeds the value of  $\overline{N_T} + 3\sigma$  is 0.55% and 0.69% of the total area of the chip before testing and after 8 hours of testing respectively.

In accordance with the model presented in [9], the investigated LED was presented in the form of two parallel-connected diodes that differ from each other in the areas of the active region  $S_1$  and  $S_2$ . The area  $S_1$  of the first diode is comprised of the chip regions of the LED under study, in which the

defects density  $N_1$  is lower than the average value of the defects density throughout the chip  $N_T$ , and the area  $S_2$  of the second diode is the region of the chip with the defects density  $N_2$  greater than the average value of the defects density throughout the chip. The model parameter  $K_S = S_2/S_1$  shows how many times the area of the active region of the LED with a high defects density differs from the area of the active region of the LED with a low defects density. In figure 4 shows a graph of the change in the  $K_S$  parameter during the LED test.



Figure 4. K<sub>s</sub> parameter change during LED test

The graph shows that the area of the more defective area is less than the area of the less defective area ( $K_s < 1$ ). During the tests, the  $K_s$  parameter increases, which indicates that the LED degradation process is accompanied by an non-uniform increase in the defects density in various areas of the chip: in more defective areas, the increment in the defects density is larger.

# 4. Conclusions

A method for measuring of the defects density distribution profile over the area of the LED chip, based on the measuring of the distribution profiles of the electroluminescence brightness and the 3 dB frequencies over the area of the LED chip at two low currents is presented. The commercial blue InGaN-based LEDs were tested under the high-density pulse current. It was determined that the emission power decreases most intensively in the first 14 hours of testing, then the rate of power decline decreases. During the tests, the defects density distribution profile changes. In particular, the formation of local regions around the perimeter of the active region of the chip is detected, in which the defect density higher than the average value of the defect density in the chip. It was determined that the process of LED degradation is accompanied by an non-uniform increase in the defects density in various areas of the chip: in more defective areas, the increment in the defects density is larger.

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