The model of degradation of an InGaN/GaN LED during current tests taking into account the inhomogeneous distribution of the defects density in the heterostructure

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Abstract. A model of the optical power degradation of an InGaN/GaN LED during testing under direct current, which takes into account the inhomogeneous distribution of the defects density in the heterostructure, is presented. According to the simulation results, the rate of degradation of the LED optical power significantly depends on the degree of inhomogeneity of the defects density distribution profile. Experimental testing of the model has been carried out. The proposed model makes it possible to predict the rate of degradation of InGaN-based LEDs with varying degrees of inhomogeneity of the defects density distribution profile and can be used to develop a technique for rejecting defective and potentially unreliable LEDs.

1. Introduction

Due to the high efficiency of converting electrical energy into optical energy the InGaN-based LEDs are widely used in various fields of technology: display devices, lighting devices. The main reason for the gradual decrease (degradation) of the optical emission power of light-emitting devices based on semiconductor heterostructures during long-term operation is the formation of additional nonradiative recombination centers in the active region under the action of an electric current [1].

To improve the reliability and ensure long-term stability of the characteristics of LED devices, methods and means of non-destructive quality control of LEDs are currently being actively developed. This methods make it possible to identify devices with a high degree of presence of defects at the stage of sorting. As well as methods for predicting the rate of the LEDs emission power degradation according to their initial electrophysical and electro-optical parameters are developed [2-4]. The difficulty of identifying of InGaN/GaN LEDs with a high degree of structural defects by standard nondestructive testing methods is associated with the inherent spatial heterogeneity of properties of such materials, inhomogeneities in the composition of the solid solution and the system of defects in the material [5-7].

The aim of this work was to create a model of the degradation of an InGaN/GaN LED during tests under the direct electric current, taking into account the degree of inhomogeneity of the defects density distribution profile over the area of the heterostructure active region.
2. The model of LED degradation

During the growth of the light-emitting InGaN/GaN heterostructure in the magnesium-doped p-GaN barrier layer, electrically neutral magnesium-hydrogen complexes Mg–H are formed. In the finished structure, part of the magnesium acts as an acceptor impurity, and part is in a localized state [8]. Under the action of elevated temperature and electric current, Mg–H complexes can be decomposed, which leads to an increase in the effective concentration of acceptors and the formation of free hydrogen. Diffusion of magnesium from the p-GaN barrier layer into the active region of the heterostructure leads to the formation of additional centers of nonradiative recombination and to decrease in the LED emission power [9, 10].

According to the developed model of the degradation of a LED based on an InGaN/GaN heterostructure, the main process causing a decrease in the optical power is the diffusion of Mg impurity atoms from the barrier p-layer into the active region. The model makes it possible to calculate the change in the LED optical power during testing under the direct electric current, taking into account the initial degree of inhomogeneity of the defects density distribution profile in the active region. When developing the model, it was assumed that during the operation of the LED, as a result of the diffusion of magnesium from the p-GaN barrier layer into the active region of the heterostructure, the concentration of defects in its local regions increases, which leads to an increase in the nonradiative recombination coefficient and a decrease of the LED emission power.

In the simulation, the LED with an active region of area $S$ was divided into a set of $M$ parallel-connected diodes. The area of the LED active region with the defects density $N_l$ will be equal to 

$$S_l = \frac{m_l}{M} S, \quad (l = 1...L)$$

where $m_l$ is number of diodes with $N_l$ defect density.

The following relative values were introduced: $K_{Sl} = \frac{S_l}{S} = \frac{m_l}{M}$ and $K_{Nl} = \frac{N_l}{\bar{N}}$, where $\bar{N}$ is the average value of the defects density over the LED active region.

Similar to the previously developed diffusion model of the degradation of an InGaN/GaN LED [11], the change in the defects density in the $S_l$ regions with time was found from the solution of the nonstationary diffusion equation, for which the initial concentration of impurity atoms was set as the initial condition

$$N_{l0} = N_{l0}(K_{Sl}).$$

(2)

The Gaussian function was chosen as the dependence of the $m_l$ number on the defects density

$$\frac{m_l}{M} = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(K_{Nl} - 1)^2}{2\sigma^2}\right) \quad (K_{Nl} < K_{Nl} < \bar{K}_{Nl}),$$

(3)

where $\sigma$ is root-mean-square deviation of the relative defects density from the mean value; $K_{Nl}$ and $\bar{K}_{Nl}$ is lowest and highest value of the relative concentration of impurity atoms.

Then expression (2) takes the form:

$$N_{l0} = \bar{N}_0\left(1 \pm \sigma \sqrt{-2 \ln(\sqrt{2\pi}\sigma K_{Sl})}\right),$$

(4)

where $\bar{N}_0$ is initial average value of the defects density over the LED active region.

The concentrations of nonequilibrium charge carriers $n_l (l)$ in the $l$-th region were found from the solution of the balance equations for charge carriers, compiled in accordance with the ABC recombination model [12], while the nonradiative recombination coefficient was determined as
\[ A = 0.5 \Theta \Theta N_i(t), \] (5)

where \( \Theta = 10^{-15} \, \text{cm}^2 \) is capture cross section, \( \Theta = 10^7 \, \text{cm/s} \) is the thermal velocity of charge carriers [4].

The average value of the concentration of charge carriers in the LED active region was determined by the expression

\[ n(t) = \sum_{l=1}^{L} K_{S_l} I_l, \] (6)

When solving the balance equations for the charge carriers, the condition must be satisfied:

\[ I = \sum_{l=1}^{L} I_l, \] (7)

where \( I \) is the LED current; \( I_l \) is the current in the \( l \)-th local region of the heterostructure.

The optical emission power of the \( l \)-th region of the heterostructure was found as follows

\[ P_{\text{opt}} = h\nu \eta_{\text{extr}} B n_i^2(t) S_d, \] (8)

where \( B \) is radiative recombination coefficient; \( h \) is Planck's constant; \( \nu \) is emission frequency; \( \eta_{\text{extr}} \) is radiation extraction coefficient; \( d \) is active area thickness.

Then the total emission power of the LED is defined as

\[ P_{\text{opt}} = J_S \int_S P_{\text{opt}}(s) ds, \] (9)

and the dependence of the LED emission power on the test time, normalized to the initial value, is found from the ratio

\[ \frac{P_{\text{opt}}(t)}{P_{\text{opt}}(0)} = \frac{n(t)^2}{n(0)^2}, \] (10)

where \( P(0) \) determined by the initial average concentration \( \overline{N}_0 \).

The equation of diffusion of impurity atoms into the active region of heterostructure was solved by the numerical finite element method using the Comsol Multiphysics. As a basic variant for carrying out computational investigations, we chose a green light-emitting diode manufactured by Oasistek with a chip size of 200×130 μm. The area of the active region of the chip was divided into two parts with the average initial defects densities calculated in the regions of definition of function (1): (0, 1+2σ), (1+2σ, 1+4σ). The balance equations for the charge carriers in the local regions of the structure in this case are as follows:

\[ \frac{I_l}{eS_d} = 0.5 \Theta \Theta N_i(t) n_i(t) + B n_i^2(t) + C n_i^3(t), \quad l = 1, 2 \] (11)

where \( C \) is Auger recombination coefficient and the conditions are met:

\[ I = I_1 + I_2, \quad n = n_1 K_{S1} + n_2 K_{S2}. \] (12)

According to the calculation results, the rate of decrease of the LED emission power during the test depends significantly on the degree of inhomogeneity of the defects density distribution profile: the emission power of those LEDs that are characterized by a large value of the standard deviation \( \sigma \) decreases more intensively. Figure 1 shows the graphs of the dependences of the LED emission power
drop for three normalized $\sigma$ values. Thus, at $\sigma = 0.2$, the value of the emission power drop after 1000 h of testing is 17%, at $\sigma = 0.4$ is 29%, and at $\sigma = 0.6$ is 38%.

![Graph showing the time dependence of LED emission power](image)

**Figure 1.** The time dependence of LED emission power; 1 – $\sigma = 0.2$; 2 – $\sigma = 0.4$; 3 – $\sigma = 0.6$

3. **Experimental results**

Experimental testing of the model of the LED emission power degradation, taking into account the degree of inhomogeneity of the defects density distribution profile, was carried out using the example of commercial green LEDs OasisTek with the chip dimensions of $200 \times 130$ $\mu$m, the maximum forward current of 25 mA, and the central wavelength of the emission spectrum of 525 nm. The volume of the tested LEDs sample was 20 pcs. The LEDs were tested at room temperature for 500 h at a current of 25 mA. The measurements of the defects density distribution profile were carried out by the method presented in [13, 14]. The spatial resolution of the defects density distribution profile was 0.65 $\mu$m.

For each LED, the average value of the defect density $\bar{N}_T$ and the standard deviation $\sigma_{exp}$ of the distribution of the LED chip local regions by the value of the defect density were calculated. For the tested LEDs sample, the average value of the defect density over the LED active region and the standard deviation vary within the range: $\bar{N}_{exp} = (5.2 \div 9.1) \times 10^{13}$ cm$^{-3}$ and $\sigma_{exp} = (1.2 \div 1.7) \times 10^{13}$ cm$^{-3}$, respectively.

In accordance with the proposed model, the LEDs were presented in the form of two parallel connected diodes, differing from each other in the areas of the active region $S_1$ and $S_2$. The area $S_1$ of the first diode is formed by the local regions of the LED chip, in which the defects density is in the range $(0, \bar{N}_{exp}+2\sigma_{exp})$, and the area $S_2$ of the second diode is the local regions of the LED chip, in which the defects density is in the range $(\bar{N}_{exp}+2\sigma_{exp}, \bar{N}_{exp}+4\sigma_{exp})$. In this case, the area of the active region of the LED chip is $S = S_1 + S_2$. The estimation of the degree of inhomogeneity of the defects density distribution profile was carried out according to the value of the parameter $K_{SG}$, which shows the fraction of the area of the LED active region with a high defects density.
Figure 2 shows the dependences of the LEDs emission power after 500 h of testing on the initial values of the parameter $K_{S2}$: the dashed line indicates the experimental dependence of the form $P_{opt}(500)/P_{opt}(0) = 0.366 \cdot K_S^{-0.239}$, constructed by the least squares method; the solid line indicates the dependence calculated according to the presented model. The relative difference between the experimental results and the calculation results does not exceed 6%.

$$P_{opt}(500)/P_{opt}(0)$$

Figure 2. Approbation of simulation results; $\sigma = 0.2, K_N \geq 1 + 2\sigma$

4. Conclusions
A model of degradation of the optical emission power of an InGaN/GaN LED during tests under the direct current, taking into account the inhomogeneous distribution of the defects density in the heterostructure, is developed. According to the model, the main process causing a decrease of the LED emission power is the diffusion of Mg impurity atoms from the barrier p-layer of the heterostructure into the active region, which form nonradiative recombination centers. The LED is represented as a set of $M$ parallel connected diodes with the sizes of the areas of active regions $S_i$ and average defects density $N_i$ in these regions. The model parameters are the standard deviation of the defects density in local regions of the structure and the coefficient $K_S = S_2/S$, which shows the fraction of the area of the active region of the LED with a high defects density. According to the simulation results, the rate of degradation of the LED emission power significantly depends on the degree of inhomogeneity of the defects density distribution profile: at a relative value of $\sigma = 0.2$, the decrease in the emission power after 1000 h of testing is 17%, and at $\sigma = 0.6$ is 38%. The reliability of the simulation results was confirmed experimentally by the example of investigating of the emission power decrease of commercial green LEDs when tested under the direct current of 25 mA for 500 h. The proposed model makes it possible to predict the rate of degradation of InGaN/GaN LEDs with varying degrees of inhomogeneity of the defects density distribution profile and will be used in the development of a
method for rejecting defective and potentially unreliable LEDs predisposed to early degradation, taking into account the difference in the degree of heterostructure composition heterogeneity.

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