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Model of degradation of InGaN/GaN LED during current tests taking into account the inhomogeneous distribution of temperature and current density in the heterostructure

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Abstract: **A diffusion kinetic model of the optical emission power degradation of an LED based on a double InGaN/GaN heterostructure during testing under the direct current is presented. Ac-cording to the model, the diffusion of Mg impurity atoms from the p-barrier layer of the heterostructure into the active region is main process causing the LED optical power decrease. The model takes into account the effect of inhomogeneous current distribution due to non-uniform heating of the chip by a high-density current and it can be used to predict the lifetime of an LED when operating in continuous and pulsed modes.**

Keywords: **LED, tests, decrease of emission power, model**

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Contents

1. INTRODUCTION

Improving reliability and extending lifetime is one of the key challenges in LED design. The stability of the electro-optical characteristics of LEDs largely depends on the operating mode and operating conditions. At present, mathematical models based on extrapolation of the experimental studies results of the emission power decrease during accelerated tests under the elevated temperature and current [1-3] and models designed on the basis of a theoretical analysis of physical processes in light emitting heterostructure with prolonged current flow [4,5] are used to predict the LEDs lifetime.

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. Therefore, in the finished structure, part of the magnesium acts as an acceptor impurity, and part is in a bound state [5]. Under the action of high temperature and electric current, Mg–H com-plexes can be destroyed, which leads to an increase in the effective concentration of acceptors and the formation of free hydrogen. In the scientifical literature it is noted that during the operation of the LED, the following diffusion mechanisms in the heterostructure are possible: hydrogen diffusion and magnesium diffusion [4-8]. 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 a decrease of the LED emission power [9,10].

The main factor accelerating the impurities diffusion and the LEDs optical power decrease is the increased temperature of the active region of the chip. It is known that an inhomogeneous current distribution causes overheating of the structure in the chip regions with an increased current density [11]. Due to the action of positive thermal feedback, the current density in some regions of the chip can significantly exceed the average value, which will lead to an acceleration of the rate of optical power degradation. In the known models of InGaN-based LEDs degradation, the effect of positive thermal feedback is not taken into account, and the coefficients of the influence of current and temperature on the dependence of the LED emission power on the operating time are applied independently of each other [2].

The aim of this work is to develop a diffusion model of optical degradation of LEDs based on a double InGaN/GaN heterostructure operating in a direct current mode [12] for a pulsed mode of operation at an increased current density, taking into account the inhomogeneous temperature distribution over the active region.

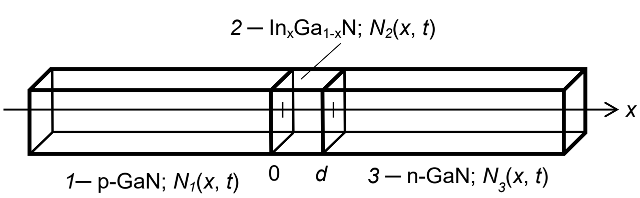

Fig. 1. *Geometry of the kinetic model of LED degradation.*

2. LED DEGRADATION MODEL

The one-dimensional geometry of the kinetic model of LED degradation (**Fig. 1**) is a part of the semiconductor chip structure, which consists of the following elements: 1 – *p*-GaN:Mg layer; 2 – $In_xGa_{1-x}N$ active layer, thickness d (the relative indium concentration x varies within 0.2 − 0.43); 3 – *n*-GaN:Si layer.

The mathematical model consists of the following equations:

1)balance equation for determining of the nonequilibrium carriers concentration $n(t)$ in the active region of the LED heterostructure

$$\frac{J(t)}{ed} - \left(An(t)N_{2av}(t) + Bn(t)^2 + Cn(t)^3 \right) = 0, \quad n(0) = n_0, \tag{1}$$

where J is injection current density; A, B, C are nonradiactive, radiative and Auger recombination coefficients, respectively [13]; $N_{2av}(t)$ is average concentration of impurity atoms in the active region of the structure; n_0 is initial carrier concentration; e is electron charge;

2)impurity atoms diffusion equation

$$\frac{\partial N_i(x,t)}{\partial t} = D_i \frac{\partial^2 N_i(x,t)}{\partial x^2} - D_i^{el} \frac{\partial N_i(x,t)}{\partial x}, \tag{2}$$

where $i = 1, 2, 3$; $N_i(x,t)$ is the concentration of impurity atoms in the i-th region of the LED structure; D_i, $D_i^{el} = \frac{D_i E q_{eff}}{k_B T}$ – are diffusion and electrodiffusion coefficients in the i-th region; E is the external electric field strength; k_B is Boltzmann's constant; T is chip temperature; $q_{\text{eff}} = q_i - |e| n_e l_e \sigma_{in}$ is effective charge [14]; n_e, l_e are the concentration and mean electrons free length; σ_{in} is the mean cross section for scattering of electrons by ions.

The initial concentrations of impurity atoms in the considered regions of the structure N_{i0} and the continuity of the substance flux density at the internal boundaries of the structure are set as the initial and boundary conditions.

The model was designed under the following assumptions: nonequilibrium *n* and *p* concentrations in the active region are approximately equal; *A, B* and *C* recombination coefficients do not depend on the *n* and *p* concentrations; the active region of the heterostructure is assumed to be a homogeneous medium. Equation (1) is considered in the quasi-stationary approximation, since the carrier density reaches its equilibrium value very quickly compared to the rate of the LEDs degradation.

Equations (1)-(2) were solved by the numerical finite element method using the COMSOL Multiphysics modeling program complex. The injection current density was modeled by the functione

$$J(t) = J_0 \sum_{m=0}^{M} \left(H\left(t - m\frac{t_p}{K}\right) - H\left(t - t_p\left(\frac{m}{K} + 1\right)\right)\right), \quad (3)$$

where $H(t)$ is the Heaviside function; M is the total number of pulses in the considered time interval; m is the number of pulses; t_p is the pulse duration; K is duty cycle.

Calculated studies of the LEDs optical power decrease during tests under the pulsed current of increased density were carried out for green LEDs manufactured by Arlight. The geometric dimensions of the chip are 340×270×100 μm, a sapphire substrate, the maximum direct current density is 35 A/cm^2, the wavelength at the maximum of the emission spectrum is 525 nm (x = 0.37 is relative content of indium in the active region). The values of current density J, pulse duration t_p and duty cycle K were chosen in the following intervals: J = (100÷500) A/cm$_2$, t_p = (100÷500) μs, K = (0.01÷0.1).

To take into account the effect of positive thermal feedback at high current densities, the dif-fusion coefficient D_i and electrodiffusion coefficient D_i^{el} were calculated proceeding from the condition of the inhomogeneous distribution of the current density over the active region of the LED semiconductor structure and the corresponding temperature distribution. For this purpose, thermal 3*D* modeling of the LED structure was performed and the calculation of the temperature field with inhomogeneous current density over the LED active region was made according to the method presented in [11]. **Fig. 2** shows the results of calculating of changes in the maximum values of the current density (*a*) and the temperature of the active region of the chip (*b*) during the action of one current pulse for one of the design options: J = 500 A/cm^2, K = 0.1; t_p = 500 μs. It can be seen that the maximum value of the overheating temperature of the active region relative to the ambient temperature (300 *K*) is 78 *K*, and the maximum current density increases nonlinearly and by the end of the pulse is 35% higher than the average value of the current density J = 500 A/cm^2.

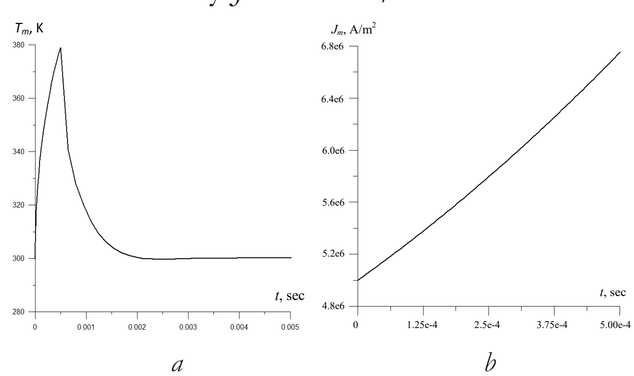

Fig. 2. *Maximum temperature (a) and current density (b) of the LED active area: J = 500 A/cm², t_p = 500 μs, K = 0.1*

The diffusion coefficient value was determined by solving the inverse one-dimensional diffusion problem. To solve, we used the charge carriers concentration distribution profiles, measured by the method of capacitance-voltage characteristics at different time intervals of LED degradation for 12.000 *h* at a direct current with a density of 30 A/cm^2, which were taken as a solution to Eq. (2) at the considered time [12].

3. EXPERIMENTAL VALIDATION OF THE MODEL

In **Fig. 3***a*, solid lines show the dependences of the optical power of the LED during its operation in the pulsed mode at three values of the current density, the pulse duration t_p = 500 μs, and the duty cycle K = 0.1, obtained using the developed model. The points on the graph indicate the test results of three groups of LEDs, 5 examples in each group. The dotted line marks the boundaries of the standard deviation. It can be seen from the graph that the experimental dependence $P(t)/P_0$ is in good agreement with the dependence calculated using the diffusion kinetic model.

The curves in the Fig. 3 are approximated by a function

$$P_{opt}(t)/P_{opt0} = -0{,}08\ln\left(f(J)t + 3.73\text{e-}6\right), \quad (4)$$

where $f(J)$ = 1.084e-7×exp (7.66e-3×J).

An estimate of the operating time $t_{0.7}$, at which the optical power decreases to 70% of the initial value was made at different values of the current density J (**Fig. 3***b*). The dependence $t_{0.7}(J)$ is described by an exponential function

$$t_{0,7}(J) = \tau e^{-J/J_0}, \quad (5)$$

where τ = 14600 *h* and J_0 = 130 A/cm^2 for the specified operating mode of the investigated LEDs.

4. CONCLUSION

The developed diffusion model of degradation of the LED based on a double InGaN/GaN heterostructure makes it possible to obtain the dependence of the optical emission power on the operating time at a constant and/or pulsed current, including at high current densities, which cause overheating of the active region.

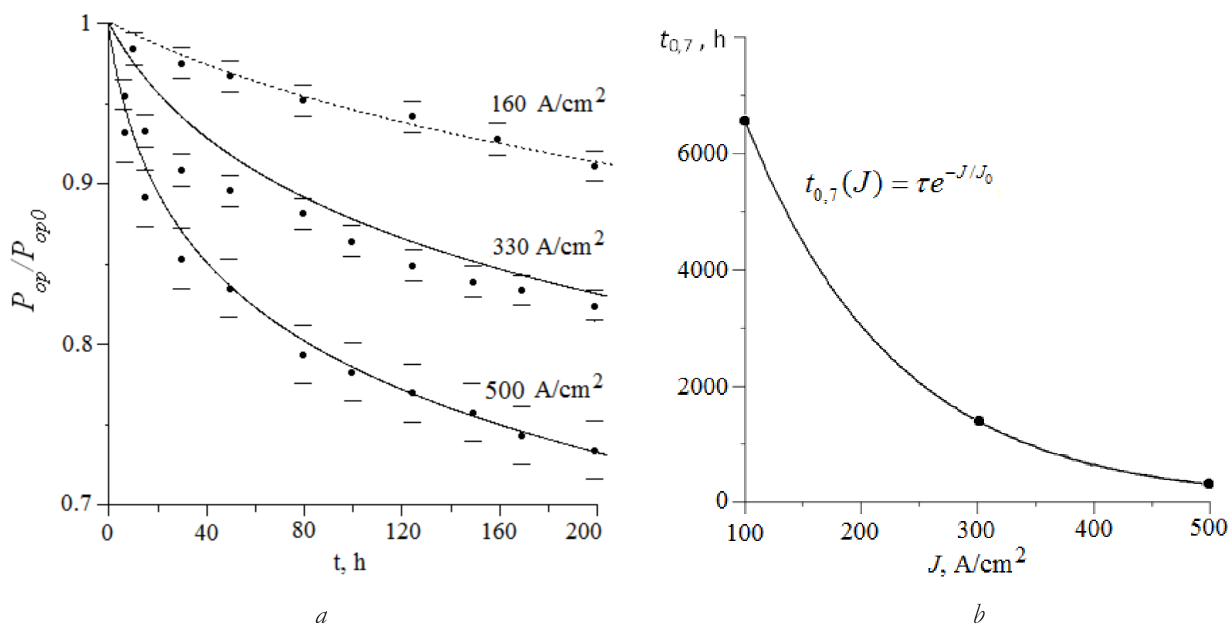

Fig. 3. *Dependence of the LEDs optical power on time (a) and the dependence of the time $t_{0.7}$ of the optical power decrease to 70% on the current density (b) when LED operates in a pulsed mode (t_p = 500 μs, K = 0.1).*

The model takes into account the effect of inhomogeneous current distribution due to non-uniform heating of the chip by a high-density current. The model can be used to predict the LED lifetime when operating in the nominal mode at a known value of the diffusion coefficient of Mg impurity from the barrier layer to the active region of the heterostructure, which can be obtained from the results of accelerated tests in the pulsed mode at an increased current density.

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