Modeling of Light-Emitting Diode with Nonuniform Current Injection

Yohei Nishidate1, Julia Kholopova2, Anatoly Kovalchuk2, Bogdan Shevchenko3, Irina Khmyryova1, and Sergei Shapoval2
1University of Aizu, Aizu-Wakamatsu, Fukushima, 965-8580, Japan
2IMT RAS, Chernogolovka, 142432, Russia
3LETI, St.Petersburg, 197376 Russia

Abstract—Light-emitting diode (LED) with nonuniform current injection caused by the mesh-like design of top metal electrode is studied numerically. Three-dimensional Laplace equation for electric potential is solved by finite element method. The numerical model incorporates mapped infinite element to account for potential decay far away from the LED structure and finite element model developed for boundary condition at semiconductor-air interface in the mesh opening. Simulation results demonstrate the effect of the mesh geometrical parameters on the total output power.

I. INTRODUCTION

Light-emitting diodes (LEDs) grown on sapphire substrate usually have planar configuration with both n- and p-electrodes on the same side of the device and light extraction via top surface. The most light generated beneath the electrode of such LED is prevented from being extracted. Several approaches were proposed to overcome this shielding effect, in particular, different designs and configurations of the p-electrodes [1]-[3]. Significant enhancement of optical output reported for the LED with top metal p-electrode designed as a mesh [1] has been related to a spatially nonuniform electric potential created by such electrode which could result in current injection and light generation even in the portions of active region beneath the mesh openings [4]. Validity of the mechanism proposed in Ref. [4] was confirmed by numerical simulation based on analytical model approximating the strips of the meshed electrode by thick wires [5]. However, there is a limit to what can be done with thick-wire approximation. For example, it is not possible to vary only the width or thickness of the strips. To analyze realistic LED structure one needs to consider the mesh strips of square or rectangular crosssection. In this paper we study numerically an LED with top metal electrode designed as a mesh with the strips of rectangular crosssection. Previously developed numerical model and procedure [6] are used as a basis.

II. NUMERICAL MODEL AND SIMULATION RESULTS

To focus on the effect of the mesh-like electrode we simplify an LED structure assuming that it contains narrow-gap active region sandwiched between top and bottom wide-gap p- and n-semiconductor layers. Metal solid n- and patterned as a mesh with the strips of rectangular cross-section p-electrodes are located on the bottom and top LED surfaces, respectively. Periodicity of the meshed electrode makes it possible to consider a unit cell (UC) of the LED structure beneath a single cell of the mesh with pitch a as shown schematically in Fig. 1a. To find electric potential along the active region in the UC we solve three-dimensional Laplace equation

$$\left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) \varphi(x, y, z) = 0, \quad (1)$$

by finite element method. Boundary conditions were set \( \varphi = 2 \) V and \( \varphi = 0 \) at the top meshed and bottom solid electrodes, respectively. Due to symmetry of the structure electric field at the side faces of the UC were set \( \partial \varphi / \partial x |_{x=a} = \partial \varphi / \partial y |_{y=0,a} = 0 \). Air volume above the UC is included into computation domain (Fig. 1a) and the mapped infinite element is introduced into numerical model to account for potential decay far away from the structure. Numerical model also includes finite element model developed for boundary condition at semiconductor-air interface in the mesh opening. Potential distributions \( \varphi(x = a/2, y, z_{act}) \) in the plane of the active region obtained by solution of Eq. (1) using the developed FEM model are shown in Fig. 2 for different mesh pitches and width and height of the strips \( w = h = 100 \) nm (opaque symbols). Potential distributions for the mesh strips approximated by wires of finite radius \( R = 50 \) nm were also calculated using analytical expression for electric potential (filled symbols in Fig. 2). One can see from Fig. 2 that strip approximation by thick wires results in underestimation of electric potential along the active region.

Spatially nonuniform electric potential promotes spatial
Fig. 3. Normalized total output optical power versus mesh strip height $h$ for mesh strips with square cross-section and versus wire diameter for finite-radius wire approximation for the mesh strips. The height and width of the strips were set to be equal to each other $h = w$. Calculations were made at applied voltage $V = 2$ V and mesh pitches $a = 400$, 800 and 1200 nm.

**III. Conclusions**

Numerical model and procedure are used to study the output performance of the light-emitting diode with top metal electrode designed as a mesh with the strips of square cross-section. Three-dimensional Laplace equation for electric potential is solved by finite element method. The mapped infinite element is introduced into numerical model to account for potential decay far away from the LED structure and finite element model developed for boundary condition at semiconductor-air interface in the mesh opening. Simulation results demonstrate the effect of the mesh pitch, height and width of the strips on the total output optical power. It is also demonstrated that analytical model based on finite-radius wire approximation for the mesh strips results in underestimation of electric potential and output optical power.

**References**


