Modeling of Light-Emitting Diode with Nonuniform Current Injection

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***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 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 crossection. In this paper we study numerically an LED with top metal electrode designed as a mesh with the strips of rectangular crossection. 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

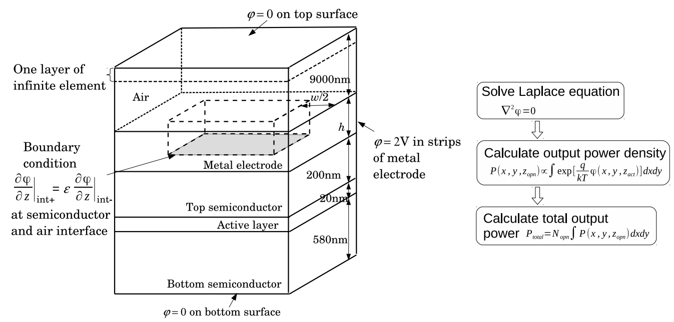

Fig. 1. (a) Computation domain of the LED's unit cell. Dimensions of the LED structure and boundary conditions for Laplace equation are indicated. (b) Simulation flow chart.

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

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 $\partial\varphi/\partial x|_{x=0,a} = \partial\varphi/\partial y|_{y=0,a} = 0$. 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

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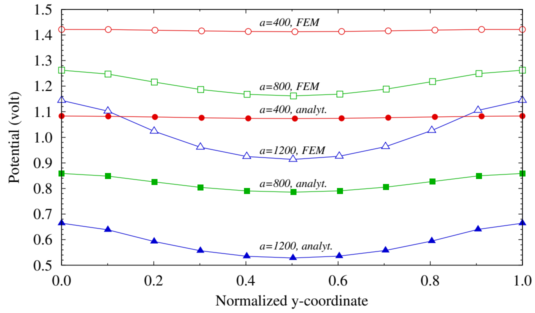

Fig. 2. Potential distributions in the plane of the active region along y-axis at $x = 0.5a$ for the mesh strips of square crossection (FEM method, opaque symbols) and strips approximated by finite radius wires (filled symbols). Mesh pitches $a = 400$, 800 and 1200 nm, applied voltage $V = 2$ V, width and height of the strips $w = h = 100$ nm, wire radius $R = 50$ nm.

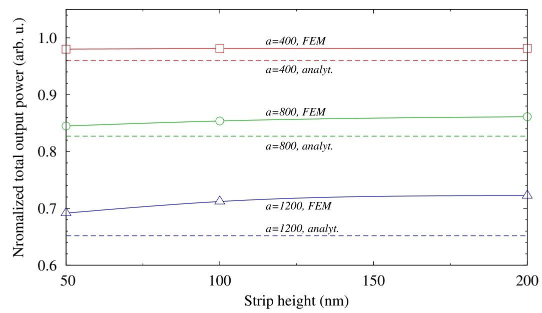

Fig. 3. Normalized total output optical power versus mesh strip height h for mesh strips with square crossection and versus wire diameter for finite-radius wire approximation for the mesh strips. The height and width of the strips were set to be equal to each other $h = w$. Calculations were made at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

nonuniformity of injected current

$$J(x, y, z_{act}) = J_0 \exp\left[\frac{q}{kT}\varphi(x, y, z_{act})\right] \quad (2)$$

and power of light extracted via output semiconductor-air interface at any point $\{x, y, z_{opn}\}$ of the mesh opening

$$P(x, y, z_{opn}) \propto \int_{circ} \frac{\cos(\theta_i)}{4\pi r^2} T(\theta_i) J(x, y, z_{act}) dxdy \quad (3)$$

where q and k are electron charge and the Boltzmann constant, T is the temperature in Kelvin, J_0 is the saturation current. In Eq. (3) integration is performed over the active region within the circle subtended by the escape cone determined by the angle of total internal reflection θ_c, $T(\theta_i)$ is polarization dependent transmission coefficient for semiconductor-air interface. Total optical power P_{total} extracted from the LED was evaluated by integration of $P(x, y, z_{opn})$ obtained with Eq. (3) over the mesh opening and multiplication by the number of mesh cells N_{opn}. Scattered data interpolation of the finite element solution (electric potential) was performed to sample electric potential value at arbitrary position and for its re-sampling moving least squares (MLS) approximation was adopted. The Gauss quadrature rule [7] with rapid approach to the true integral value was applied to integrate the value $P(x, y, z_{opn})$ given by Eq. (3) over rectangular mesh opening.

The developed numerical model and strategy were used to evaluate total output optical power for the LED with mesh strips of square cross-section and strips approximated by wires of finite radius (analytical model for potential distribution). Fig. 3 shows normalized total output power versus height of the strips at fixed mesh pitch. The width and height of the strips were equal to each other and to diameter of the wire. An increase in the strip's width at a fixed mesh pitch results in the reduced area of the mesh opening which should reduce the extracted optical power. However, an increase in height and width of the strips contribute to the potential distribution in such a way that the total output power even slightly increases as it is shown in Fig. 3 (in particular, pitch $a = 1200$ nm). Fig. 3 demonstrates also that the total power for the square-crossection strips exceeds that obtained with finite-radius wire approximation (analytical model) at the same mesh pitch.

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.

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