Impact of Mesh-Like Top p-Electrode on Output Performance of Light-Emitting Diode: Numerical Study

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***Abstract*—Numerical model and procedure for the light-emitting diode (LED) with realistic mesh strips having square cross-section are developed and used for simulation of electrical and output optical characteristics at different dimensions of the mesh and bias voltages. Performances simulated for realistic square cross-section strips and analytical model based on the finite-radius wire approximation were compared. Comparison demonstrates the advantages of realistic model, in particular, for extraction of the mesh-like electrode parameters resulting in maximum optical output.**

I. Introduction

Although the commercialization of semiconductor light-emitting diodes (LEDs) is quite successful, some challenges still remain to be tackled. Enhancement of the output optical power of the LED with light extraction via top surface is one of such challenges. One of the proposed approaches to cope with the problem is based on the mesh-like patterning of the top metal electrode of the LED [1]. Mechanism of the output optical power enhancement is related to a specific profile of electric potential created by such electrode which can promote current injection and light generation even in the uncovered portions of active region [2]. This was confirmed by numerical simulation performed using analytical model based on the thick-wire approximation for the strips of the meshed electrode [3], [4]. However, thick-wire approximation has some limitations, in particular, it does not allow to vary separately the height and width of the mesh strips which can be required in the solution of optimization problem.

In this paper we present modeling of the optical output of the LED using numerical model and procedure developed for the case of the mesh-like electrode with realistic square cross-section strips.

II. Equations. Numerical Model and Procedure. Simulation Results

We consider a simple model of an LED with narrow-gap active region sandwiched between top and bottom wide-gap p- and n-semiconductor layers shown schematically in Fig. 1a. Top metal p-electrode is patterned as a mesh with the strips of square cross-section and pitch a. Due to periodical configuration of the mesh the consideration is limited by a unit cell (UC) of the LED structure beneath a single mesh cell. A bi-plane computation domain representing a UC is shown in Fig. 1b.

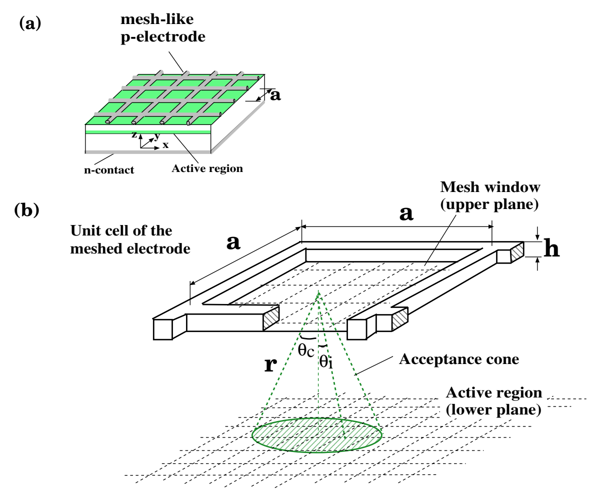

Fig. 1. (a) Schematics of the LED with top p-electrode designed as a mesh. (b) Bi-plane computation domain for the LED's unit cell. Strips of the meshed electrode have square cross-section. Lower and upper planes correspond to a light-generating layer and output semiconductor-air interface, respectively.

Power of light generated in the unit volume of the active region depends on the current injected into it which, in turn, is determined by an electric potential $\varphi(x, y, z_{act})$. Optical power which can be extracted via output semiconductor-air interface at any point $\{x, y, z_{opn}\}$ of the mesh opening comes from the encircled portion of the active region within the escape cone determined by the angle of total internal reflection θ_c (Fig. 1b). It can be expressed in the following form:

$$P(x, y, z_{opn}) \propto J_0 \int_{circ} \frac{\cos(\theta_i)}{4\pi r^2} T(\theta_i) \exp\left[\frac{q}{kT}\varphi(x_{circ}, y_{circ}, z_{act})\right] dxdy, \quad (1)$$

where q and k are electron charge and the Boltzmann constant, T is the temperature in Kelvin, J_0 is the saturation current, r is the distance indicated in Fig. 1b, θ_i is the angle of incidence, $T(\theta_i)$ is polarization dependent transmission coefficient for semiconductor-air interface. Integrating $P(x, y, z_{opn})$ from Eq.

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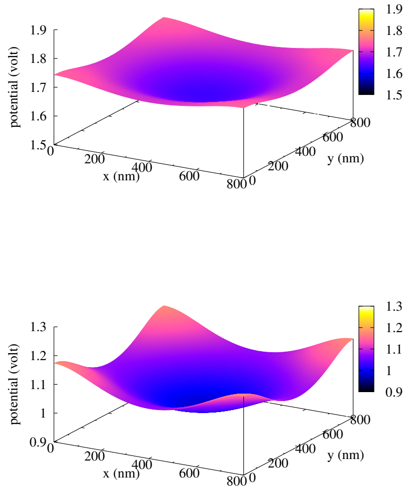

Fig. 2. (a) Spatial distributions of electric potential along the active region within the UC (a) Realistic case of the mesh strips with square cross-section 100×100 nm^2; (b) Analytical model based on thick-wire approximation for the mesh strips. Mesh pitch $a = 800$ nm, applied bias voltage $V = 2.5$ V.

(1) over the mesh opening and multiplying it by the number of mesh cells N_{opn} we can find total optical power P_{total} extracted from the LED.

Finite element method was applied to find the distribution of electric potential in the realistic case of the mesh strips with square cross-section. Three-dimensional Laplace equation

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

was solved using its weak form representation via the Galerkin's formulation. The boundary conditions at the bottom and top metal electrodes were set: $\varphi(x, y, 0) = 0$ and $\varphi(x, y, z)|_{\text{node}} = \text{const.}$, respectively; for electric field at the side faces of the computation domain we set: $d\varphi/d\{x, y\} = 0$. For sampling of electric potential value at arbitrary position scattered data interpolation of the finite element solution (electric potential) was performed. For re-sampling of electric potential value at arbitrary position, moving least squares (MLS) approximation was adopted [5]. To evaluate total output optical power the value $P(x, y, z_{opn})$ obtained by integration according to Eq.(1) over sampling points within an acceptance circle was further integrated over rectangular mesh opening. The Gauss quadrature rule[6] which provides rapid approach to the true integral value was applied.

The numerical model and strategy developed for the realistic mesh strips with square cross-section were used to simulate potential distributions in the plane of the active region shown in Fig. 2a. Potential distributions obtained with realistic model occur to be smoother along the boundaries of the UC, sag less and reveal higher values of potential at the same applied voltage than those corresponding to analytical thick-wire model shown in Fig. 2b. Distributions of output optical power along

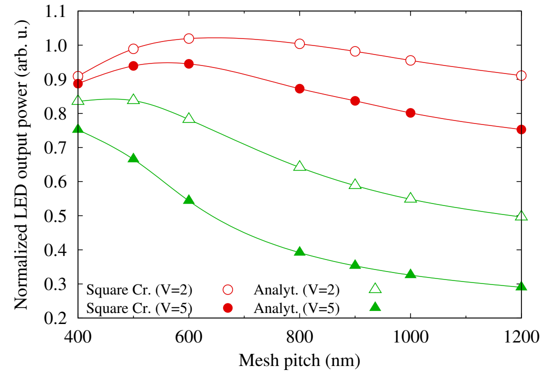

Fig. 3. Normalized total output optical power versus mesh pitch a. calculated for (a) mesh strips with square cross-section 100×100 nm^2 and (b) analytical approximation of mesh strips as wires of finite radius.

the mesh window as well as the total output power at different mesh pitches and applied voltages were also simulated. Fig. 3 demonstrates that normalized total output power in the case of realistic square cross-section strips exceeds the total power obtained with analytical model at the same mesh pitches and applied voltages. Total output power reveals maximum at mesh pitch around $a \approx 600$ nm in case of realistic model while it was not observed for analytical model.

III. Conclusions

We developed numerical model and procedure and used them to simulate optical output of the light-emitting diode with the top metal electrode designed as a mesh with the strips of square cross-section. Simulation results obtained with the realistic square cross-section strip and analytical thick-strip models were compared. The comparison revealed such advantages of the realistic square cross-section strip model as more accurate distributions of potential and output optical power. The range of mesh pitches corresponding to maximum output optical power was also evaluated with this realistic model.

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