Numerical Analysis of Planar Light-Emitting Diode with Designed p-Electrode

Irina Khmyrova[1], Norikazu Watanabe[1], Anatoly Kovalchuk[2],
Julia Kholopova[2], and Sergei Shapoval[2]
[1]University of Aizu, Aizu-Wakamatsu, Fukushima, 965-8580, Japan
[2]IMT RAS, Chernogolovka, 142432, Russia

***Abstract*—Light-emitting diode (LED) with designed metal electrode to the top p-semiconductor layer is studied. Original numerical model and procedure are developed for the LED with nonuniform distributions of electrical and optical characteristics caused by the mesh-like configuration of the top electrode. The proposed approach can be used to optimize the LED ouput optical performance by proper choice of the geometrical parameters of the meshed electrode.**

I. Introduction

Output optical performance of the semiconductor light-emitting diodes (LEDs) with light extraction via top surface is adversely affected by the top metal electrode which prevents the extraction of the light generated beneath it. A remarkable enhancement of optical output has been reported for blue GaN/InGaN LED with top metal electrode designed as a mesh [1]. Mechanism responsible for the enhancement of the light extraction is related to the electric potential profile created by the mesh-like electrode. At properly chosen geometrical parameters of the meshed electrode the potential may be strong enough to promote current injection and light generation in the active region not only beneath the metal elements but in the uncovered portions as well [2]. The generated light is extracted via the mesh windows. Fig. 1a shows the emission of the LED through the windows in the mesh-like top p-electrode having a horse-shoe shape, the central dark region is occupied by the solid n-electrode. If the mesh pitch exceeds a certain value the light generation in the centers of the mesh windows may disappear. Further pitch increase may cause the squeezing of the light-generating region to a configuration mimicking that of the mesh.

To determine optimal geometrical parameters of the meshed contact leading to the maximum optical output one needs to evaluate the output optical power of the LED. Such task is usually performed by numerical simulations based on Monte Carlo ray-tracing (MC RT) or finite-difference time domain (FDTD) techniques [3], [4]. In the case of the mesh-like electrode the distributions of electric potential, injected current and intensity of generated light are spatially nonuniform along the active region which adds an extra complexity to the simulation procedure.

This paper deals with a numerical analysis of the LED with top metal electrode designed as a mesh. Numerical procedure is developed and used to simulate output optical performance of the LED at different mesh parameters.

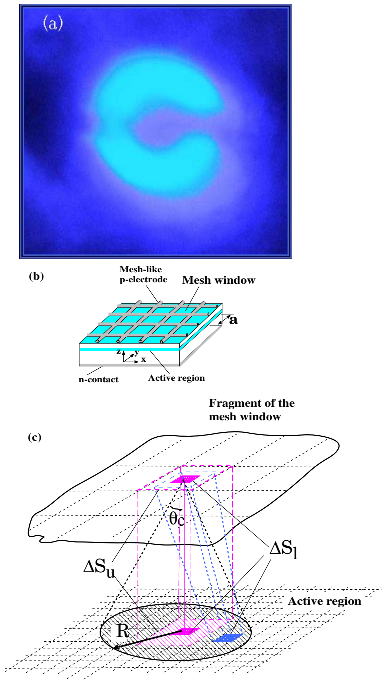

Fig. 1. (a) Emission of blue LED through the windows in the meshed top electrode. (b) Schematic structure of the LED with solid bottom n- and designed as a mesh top p-electrodes. (c) A fragment of the LED unit cell in a bi-plane representation. Lower and upper planes correspond to a light-generating layer and output semiconductor-air interface, respectively. NG-cell areas in two planes are different but related to each other.

II. Models. Simulation Strategy. Results

A simplified model of an LED with narrow-gap active region sandwiched between top and bottom wide-gap p- and n-semiconductor layers schematically shown in Fig. 1b is considered. Top metal p-electrode is designed as a mesh with pitch a, the bottom n-electrode is solid and grounded. Due to periodicity of the mesh a unit cell (UC) of the LED structure beneath a single mesh cell is considered. Computation domain of the UC is represented by a bi-plane model. Lower and upper planes correspond to a light-generating layer and output semiconductor-air interface, respectively. Areas of numerical grid (NG) cells in the lower (ΔS_l) and upper (ΔS_u) planes are set to be related to each other: $\Delta S_l = \Delta S_u \times \cos^3 \theta_c$, θ_c is the angle of total internal reflection at the semiconductor-air interface. Elementary volume ΔV of the light-generating layer corresponding to each NG-cell of area ΔS_l is treated as a point light source emitting light isotropically. However, light emitted in the lower hemisphere is assumed to be absorbed and is not taken into account.

The power of light generated in the elementary volume ΔV of the active region is related to the injected current and can be expressed in the form [5]

$$\Delta P = \frac{h\nu}{e}\eta_{in} J_0 \exp\left(\frac{e}{kT}\varphi(x_l, y_l, z_{ar})\right)\Delta x_l \Delta y_l, \qquad (1)$$

where h and ν are the Planck's constant and frequency of light; η_{in} is internal quantum efficiency, e and k are electron charge and the Boltzmann constant, T is the temperature in Kelvin, J_0 is the saturation current per unit area, $\varphi(x_l, y_l, z_{ar})$ is potential in the plane of $p-n$-heterojunction (lower plane), $z_{ar} = b - d_{ts}$, d_{ts} is the distance between upper and lower planes, b is the thickness of the LED structure. Approximating the mesh elements by wires of radius r we arrive at the following expression for the potential:

$$\varphi(x_{ln}, y_{lm}, z_{ar}) = \rho_L^2 \ln \frac{\cosh \frac{2\pi}{a}(z_{ar} - b) - \cos \frac{2\pi}{a} x_l}{\cosh \frac{2\pi}{a}(z_{ar} + b) - \cos \frac{2\pi}{a} x_l}$$

$$\times \ln \frac{\cosh \frac{2\pi}{a}(z_{ar} - b) - \cos \frac{2\pi}{a} y_l}{\cosh \frac{2\pi}{a}(z_{ar} + b) - \cos \frac{2\pi}{a} y_l}, \qquad (2)$$

where $\rho_L = \sqrt{V_1}/(2\ln(a/(2\pi r)) + 4\pi b/a)$.

Light photons coming to the upper plane at the angles $\theta_i \leq \theta_c$ can be successfully extracted. To calculate the power of light photons which can escape from each NG-cell in the upper plane we sum the contributions of all NG-cells within the circle area (Fig. 1c) of radius $R = d_{ts} \tan\theta_c$.

$$P(x_u, y_u) \propto \frac{\Delta S_l}{4\pi d_{ts}^2} J_0$$

$$\times \sum_{lm,ln} \mathcal{F}_{ATA} T(\theta) \exp\left[\frac{e}{kT}\varphi(x_l, y_l, z_{ar})\right]\Delta S_l. \qquad (3)$$

Here $T(\theta)$ is transmission coefficient. Light photons coming from the NG-cells in the center of the circle and from its rim cover different portions of the of the area ΔS_u, as it is shown in Fig. 1c. To promote the complete "collection" of light by simulation procedure we introduce function $\mathcal{F}_{ATA}$ playing the role of angular-dependent aperture

$$\mathcal{F}_{ATA} = \left(\frac{\cos\theta_i}{\cos\theta_c}\right)^3. \qquad (4)$$

The developed procedure was used to simulate spatial distributions of output optical power at different geometrical parameters of the mesh. The distribution of output optical power along the mesh window is shown in Fig. 2a at mesh pitch $a = 600$ nm, $V_1 = 6.25$ V, $b = 800$ nm, $d_{ts} = 200$ nm, $n = 2.5$. To find the total output power of the LED we need to sum the output power over all NG-cells in the window of one UC and then multiply by the number of the UCs. Normalized total output optical power versus mesh pitch a shown in Fig. 2b for different wire radii r.

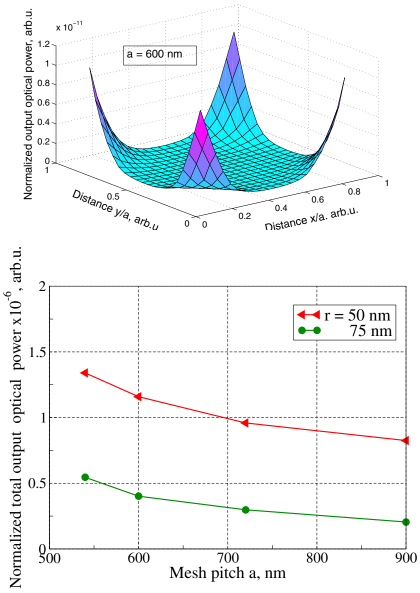

Fig. 2. (a) Spatial distributions of normalized output optical power along mesh window at mesh pitches $a = 600$ nm; (b) Total normalized output optical power versus mesh pitch a at different width of the mesh elements.

III. Conclusions

Numerical model and simulation strategy are developed to evaluate optical output performance of the LED with the top metal electrode patterned as a mesh. In the model the light-generating layer has been represented as a system of point light sources with isotropic emission. Bi-plane computation domain has been introduced. NG-cell areas in the two planes of the computation domain are set to be related to each other. Angle-tuned aperture function is introduced to adjust the light "collection" by numerical procedure. The developed procedure is used to simulate spatial distributions of output optical power along the mesh windows and total optical power of the LED. The numerical model and procedure can be used in optimization of the LED output optical performance.

References

[1] S. Shapoval, M. Barabanenkov, V. Sirotkin, E. Polushkin, L. Saptsova, A. Kovalchuk, et al., "High efficiency LED with optoelectronically optimized p-contact" Proc. of WOCSDICE 2007, Venice, Italy, p. 29, 2007.

[2] A. Konishi, R. Yamase, I. Khmyrova, J. Kholopova, E. Polushkin, A. Kovalchuk, V. Sirotkin, and S. Shapoval, "Analytical model of light-emitting diodes with patterned contact " Opt. Rev., vol. 20, 214-217 2013.

[3] V. Zabelin, D. A. Zakheim, and S. A. Gurevich, "Efficiency improvement of AlGaInN LEDs advanced by ray-tracing analysis", IEEE J. Quant. Electron., vol. 40, 1675-1686, 2004.

[4] Y. Kawaguchi, K. Nishizono, J.-S. Lee, and H. Katsuda, Light extraction simulation of surface- textured light-emitting diodes by finite-difference time-domain method and ray-tracing method, Jpn. J. Appl. Phys., vol. 46, 31-34, 2007.

[5] M. Fukuda, *Optical Semiconductor Devices*, New York: Wiley, 1999, p. 77-100.