FAR FIELD MEASUREMENTS OF PHC LED PREPARED BY E-BEAM LITHOGRAPHY

Pavol Hronec[1], Jaroslava Škriniarová[1], Dušan Pudiš[2], Jaroslav Kováč[1], Anna Benčurová[3], Pavol Nemec[3]

[1] Institute of Electronics and Photonics, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in Bratislava, Ilkovičova 3, 812 19 Bratislava, Slovak Republic,

[2] Dept. of Physics, Faculty of Electrical Engineering, University of Žilina, Univerzitná 1, 010 26, Žilina, Slovak Republic

[3] Institute of Informatics, Slovak Academy of Sciences, Dúbravská cesta 9, 84507 Bratislava, Slovak Republic

E-mail: pavol.hronec@stuba.sk

Received 24 May 2014; accepted 28 May 2014

Abstract The paper deals with optical characterization of the $Al_{0.295}Ga_{0.705}As$/GaAs multi-quantum well light emitting diode (LED) structure with patterned photonic crystal (2D PhC). The 2D PhC was patterned on the top of the structure using Electron Beam Direct Write Lithography (EBDWL). The LEDs light-current characteristics were measured by using integrating sphere, where extracted light intensity increase was observed at 10 mA forward current as 24.2 %. Also far field measurements were performed at forward current of 10 mA. Comparison of reference LED and PhC LED far fields shows increase in whole emission area. As a complementary method for extracted light intensity increase evaluation, relative light intensity distributed in the far field was integrated in range of ±60° in both θ and φ coordinate of spherical coordinate system. This method shows increase of extracted light intensity as 35.6 %. We suggest this method as more suitable for evaluation of extracted light intensity increase because it omits emission from edges of the LED and thus light is measured only from the area where PhC is patterned.

Keywords *electron beam direct write lithography, photonic crystal, far field*

1. Introduction

Since the first light emitting diode (LED) was created, there is a worldwide effort to constantly improve its optical power output and thus improving extracted light intensity because a high fraction of the generated light is back reflected due to a total internal reflection at semiconductor-air interface. For this purpose, currently is very widely used approach based on using photonic crystals (PhC) on the top or buried in the LED structure [1, 2]. To quantify improvement of the LED optical properties, there are needed optical characterization methods such as light-current measurements, near- [3] and far-field measurements. Far-field distribution of PhC LEDs were studied in [4, 5] where plane distribution of emitted light and photonic crystal properties were primarily investigated. However, extracted light intensity increase can be determined from far-field measurements. This approach is presented in the next and can be effectively used especially for PhC LEDs.

2. Experiment

The patterned $Al_{0.295}Ga_{0.705}As$/GaAs LED structure consists of $Al_{0.295}Ga_{0.705}As$ active region with three GaAs quantum wells. The emitted central wavelength of the LED is

at 845 nm. Two-dimensional (2D) PhC with pillars was patterned using Electron Beam Direct Write Lithography (EBDWL). For our purpose the XR 1541-006 e-beam patternable resist was chosen for its suitable resistance in the RIE etching and at the same time for its high pattern resolution.

The fabrication of LED with PhC structure (Figure 1b) consisted of a whole series of technological operations, such as: cleaning of the sample surface, photolithography, metallization, wet chemical etching. The following processing steps were employed for the realization of the device structures: upper ring metallization (p-type ohmic contact); bottom metallization (n-type ohmic contact); contacts annealing, and MESA etching (Figure 1a).

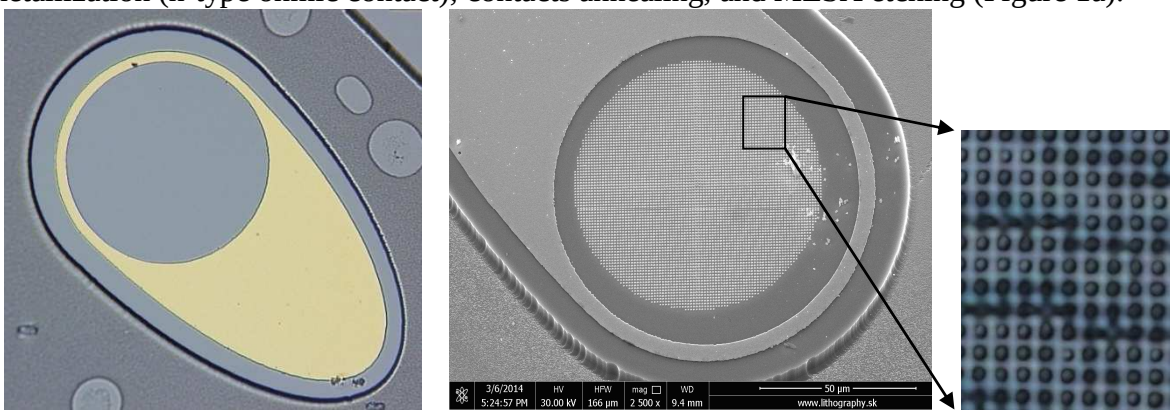

Fig. 1. *SEM image of the investigated LED a) without PhC, and b) with PhC structures.*

Aim of the experiment was to determine how PhC patterned on the top of the LED structure affects light extraction from the structure surface. Structure without PhC was used as a reference structure and optical measurements were performed by two methods.

First one was the standard light-current measurement using current source from semiconductor parameter analyzer Agilent 4155C and universal optical power meter with integrating sphere Melles Griot 13 PDC 001. Since the investigated structure is composed of active layer with quantum wells, these act as a planar waveguide. In such a structure active layer can be approximated by the effective refractive index which is higher than refracting index of boundary layers. [6, 7, 8] Thus, structure emits light from the top of the structure as well as from its edges due to generated guided modes (depicted in Fig. 2). The standard light-current measurement includes both the light emitted from the LED surface and those emitted from the edges. For investigations of the PhC influence on the LEDs light extraction from the surface we proposed the second method based on measuring far-field patterns of LEDs.

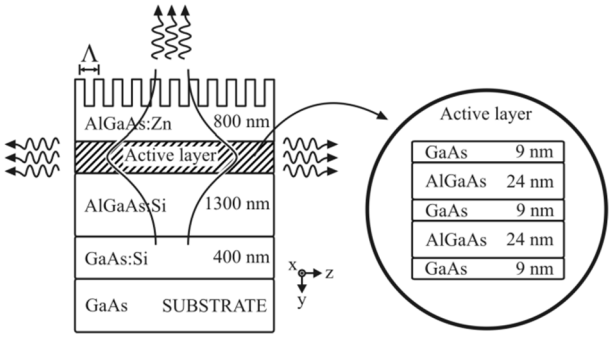

Fig. 2 *AlGaAs/GaAs LED structure.*

The far-field patterns were measured at 10 mA forward current by motorized precision rotation stage Thorlabs PRM1/MZ8E, photodiode, and lock-in amplifier Stanford Research Systems SR830. As a result, relative light intensity distributed in spherical coordinate system is measured. This measurement is then transformed to Cartesian coordinate system and plane defined by measured points is interpolated using Thin Plate Spline 2D interpolation method. Relative integrated light intensity is then calculated as a volume integral under the interpolated plane. The motivation for using this method is to omit the light emitted from the edges of PhC LED.

3. Results

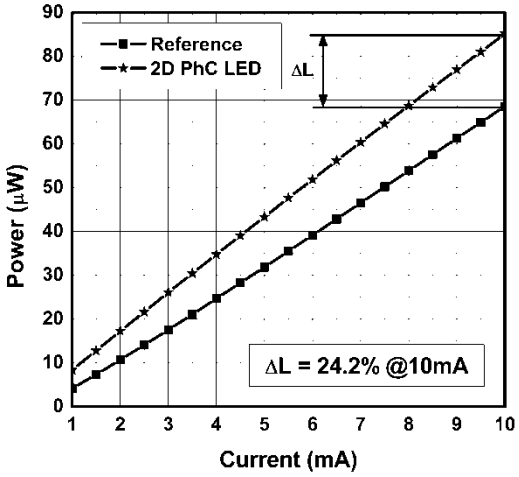

Fig. 3 *Light - current characteristics measured by standard method using integrating sphere.*

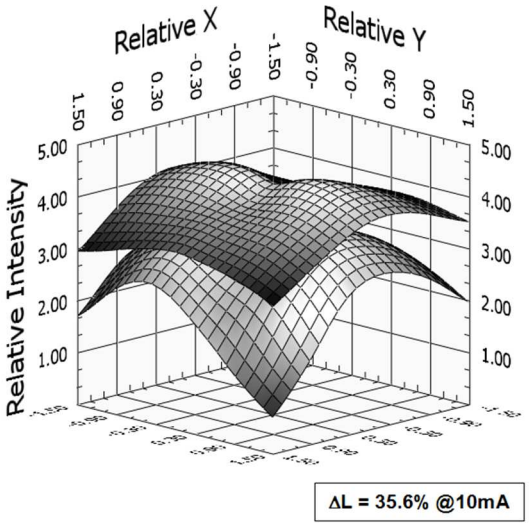

Fig. 4 *Far field pattern for a) bottom: reference LED, b) top: 2D PhC LED.*

LED samples with 2D PhC structure was compared to the reference plane LED sample without PhC. PhC structures consist of 2-dimensional pillars with square symmetry and period of 700 nm. Height of the pillars was ~340 nm. It was found that PhC on the top of the LED structure improves the extracted light intensity from LEDs Measurement from Fig. 3 shows comparison of light output power in dependence of driving current measured by method were integrating sphere is used. Extracted light intensity increase was evaluated at 10 mA forward current as 24.2 %. However, better results were achieved using method of far-field measurements showed in Fig. 4. Measurement range in Cartesian coordinate system represents range of ±60° in θ and φ coordinates of spherical coordinate system. Bottom far-field pattern represents reference LED, top far-field pattern represents 2D PhC LED. Extracted light intensity increase evaluated from volume integral of far-field pattern was 35.6 %. This is caused due to fact that light emitted from the LED is measured only from top of the structure and the light emitted from the structure edges doesn't affect the measurement. This is the reason why this method is more suitable for evaluation of PhC LED extracted light intensity increase. Measurement is affected only by the light, which is emitted from the area where PhC is patterned.

4. Conclusions

In the paper, extracted light intensity increase of LED including 2D PhC was investigated. Except for standard method using integrating sphere method using far-field measurements were performed. The results confirmed that the LED extracted light intensity increased when 2D PhC is patterned on the top of the LED structure. It was found that extracted light intensity is higher when evaluated from far-field measurements. This is due to fact that only light emitted from the LED surface is measured while light emission from edges doesn't affect the measurement. Therefore this method is more suitable for characterization of 2D PhC LED extracted light intensity increase, because it comprises only those emission areas, where PhC is patterned.

Acknowledgement

This work was financially supported by projects APVV -0395-12, VEGA 1/0439/13, and VEGA-2/0021/12.

References:

[1] Pudiš, D., Šušlik, Ľ., Kubicová, I., Škriniarová, J., Martinček, I. *Advanced optical methods for patterning of photonic structures in photoresist, III-V semiconductors and PMMA.* Proc. of SPIE, 7746, pp. 774616-1-6, 2010

[2] Kubicová, I., Pudiš, D., Šušlik, Ľ., Škriniarová, J., Slabeyciusová, S., Martinček, I. *Structures patterning by non-contact NSOM lithography.* Proc. of SPIE, 7746, pp. 774608-1-6, 2010

[3] Hronec, P., Kováč, J., Škriniarová, J.: *Investigation of the LED with PhC prepared by e-beam lithography.* ADEPT 2014, [not published yet]

[4] Chun-Feng, L., Jim-Yong, C., Hao-Chung, K., Hsi-Hsuan, Y., Chia-En, L., Chia-Hsin, C., Wen-Yung, Y., Tien-Chang, L.: *Far–Field and Near–Field Distribution of GaN-Based Photonic Crystal LEDs With Guided Mode Extraction.* IEEE Journal of Selected Topics in Quantum Electronics, Vol. 15, No. 4, 2009

[5] Chun-Feng, L., Jim-Yong, C., Hao-Chung, K., Hsi-Hsuan, Y., Chia-En, L., Chia-Hsin, C., Han-Tsung, H., Wen-Yung, Y.: *Far–Field of GaN film-transferred green light-emitting diodes with two dimensional photonic crystals.* OPTICS EXPRESS, Vol. 17, No. 11, 2009

[6] Alman, G. M., L. A. Molter, H. Shen, M. Dutta: *Refractive Index Approximations from Linear Perturbation Theory for Planar MQW Waveguides.* IEEE Journal of Quantum Electronics. vol. 28, no. 3, pp. 650-657, 1992

[7] Saini, M., Sharma, E. K.: Equivalent *Refractive Index of MQW Waveguides.* IEEE Journal of Quantum Electronics. vol. 32, no. 8, pp. 1383-1390, 1996

[8] Sonek, G. J., Ballantyne, J. M., Chen, Y. J., Carter, G. M., Brown, S. W., Koteles E. S., Salerno, J. P.: *Dielectric Properties of GaAs/AlGaAs Multiple Quantum Well Waveguides.* IEEE Journal of Quantum Electronics. vol. QE-22, no. 7, pp. 1015-1018, 1986