

# FAR FIELD MEASUREMENTS OF PhC LED PREPARED BY E-BEAM LITHOGRAPHY

Pavol Hronec<sup>\*</sup> — Jaroslava Škriniarová<sup>\*</sup> — Anna Benčurová<sup>\*\*\*</sup> —  
Pavol Nemec<sup>\*\*\*</sup> — Dušan Pudiš<sup>\*\*</sup> — Jaroslav Kováč<sup>\*</sup>

The paper deals with optical characterization of the  $\text{Al}_{0.295}\text{Ga}_{0.705}\text{As}/\text{GaAs}$  multi-quantum well light emitting diode (LED) structure with photonic crystal (2D PhC) patterned on the top of the structure using Electron Beam Direct Write Lithography (EBDWL). Light-current characteristics measured by integrating sphere shows increase of extracted light intensity as 21.1 %. Additionally, extracted light intensity was studied by far-field measurements as a complementary method to light-current characteristics. The far-field measurements show increase of extracted light intensity as 31.2 %. We suggest this method as more suitable for evaluation of extracted light intensity because it omits emission from edges of the LED and thus light is measured only from the area where PhC is patterned.

**Key words:** LED, Electron beam direct write lithography, photonic crystal, far field, light extraction

## 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 intensity distribution of PhC LEDs was studied in [4, 5] where distribution of emitted light and photonic crystal properties were primarily investigated. However, also extracted light intensity increase can be determined from far-field measurements. This approach is presented in this paper and can be effectively used especially for PhC LEDs.

## 2 THEORY

LED far-field measurements were performed as a relative light intensity distribution in spherical coordinate system  $(\phi, \theta, r)$ . To determine the effect of PhC on far-field pattern of LEDs as well as extracted light intensity increase, the following steps were needed:

- (i) transformation of the measured data into the Cartesian coordinate system,

- (ii) interpolation using Thin plate spline interpolating method [6].

- (iii) (iii) far-field distribution volume integration, which gives the relative output power of the LEDs.

## 3 EXPERIMENT

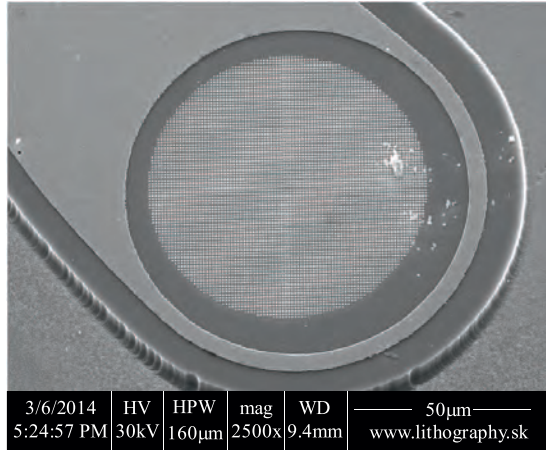
The patterned  $\text{Al}_{0.295}\text{Ga}_{0.705}\text{As}/\text{GaAs}$  LED structure consists of  $\text{Al}_{0.295}\text{Ga}_{0.705}\text{As}$  active region with three GaAs quantum wells. The emitted central wavelength of the LED is at 845 nm. Two-dimensional (2D) PhC with pillars was patterned using Electron Beam Direct Write Lithography (EBDWL). For our purpose the XR 1541-006 e-beam patternable resists 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 (Fig. 1) 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.

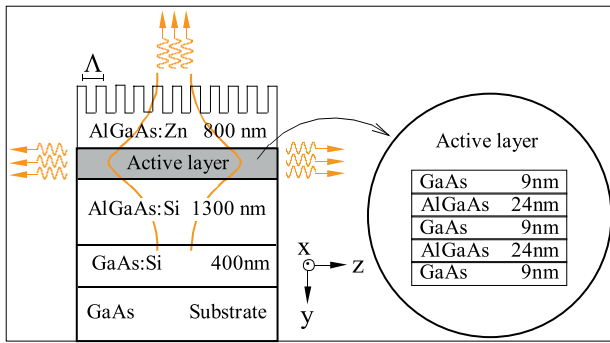
The aim of the experiment was to determine how PhC patterned on the top of the LED structure affects light extraction from the structure surface. Structure without PhC was used as a reference structure and optical measurements were performed by two methods.

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<sup>\*</sup> Institute of Electronics and Photonics, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in Bratislava, Ilkovičova 3, 812 19 Bratislava, Slovakia, pavol.hronec@stuba.sk; <sup>\*\*</sup> Dept. of Physics, Faculty of Electrical Engineering, University of Žilina, Univerzitná 1, 010 26 Žilina, Slovakia, <sup>\*\*\*</sup> Institute of Informatics, Slovak Academy of Sciences, Dúbravská cesta 9, 845 07 Bratislava, Slovakia,



**Fig. 1.** SEM image of the investigated LED with patterned PhC



**Fig. 2.** AlGaAs/GaAs LED structure

The 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. [7–9] Thus, structure emits light from the top of the structure as well as from its edges due to generated guided modes, Fig. 2.

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 intensity distributions of LEDs.

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 mea-

sured points is interpolated using Thin Plate Spline 2D interpolation method. The relative integrated light intensity is then calculated as a volume integral under the interpolated plane.

The near-field patterns were measured by COHU 4910 camera. As a result, an 8-bit gray-scaled image is measured, where the relative optical output is distributed in pixels in two dimensions. Image processing is required to evaluate the measurements by integrating over all image pixels. Each pixel has a grey-scale value coded in 8 bits, which gives a value range of 0 to 255. The total relative optical output in arbitrary units can be expressed as

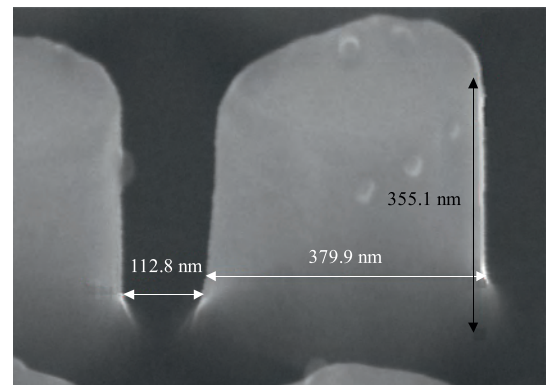
$$L = \sum_{j=1}^N \sum_{i=1}^M L_{ij}$$

where  $M \times N$  is image resolution,  $i, j$  are numbers of pixels in both directions and  $L_{i,j}$  is the relative optical output in a given pixel. Motivation for using these methods is to omit the light emitted from the edges of the PhC LED.

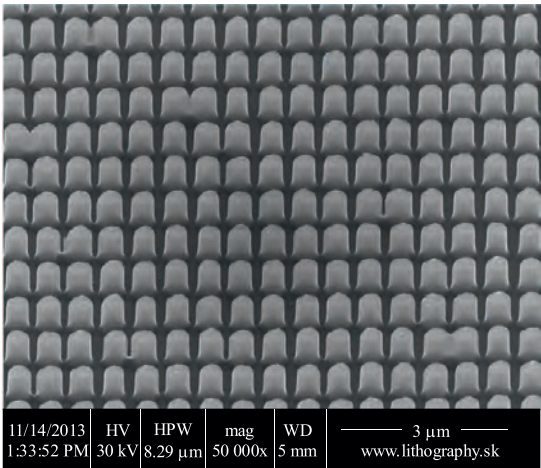
## 4 RESULTS

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 500 nm as shown in Fig. 3. Height of the pillars was  $\sim 350$  nm.

The optical properties of AlGaAs/GaAs MQW LED structure and its guided mode light extraction are described more detailed in [10]. Calculations showed that in such a structure there is one guided mode for TE and one for TM polarization with different penetration depths. As the most suitable PhC period for light extraction from studied AlGaAs/GaAs MQW LED structure was calculated period of 249 nm. However, also second order of coupling grating can extract guided modes but with less efficiency. Extraction efficiency is also strongly dependent on PhC symmetry. For ideal light extraction 2D PhC should have circular irreducible Brillouin zone [10].

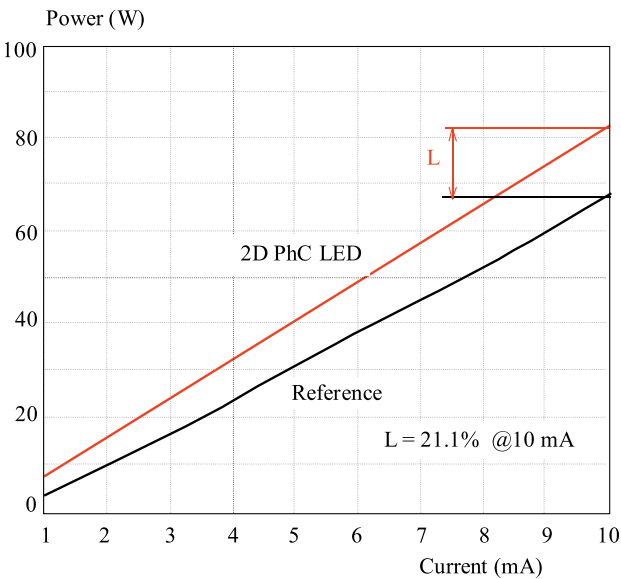


**Fig. 3.** SEM image of PhC patterned on the top of LED

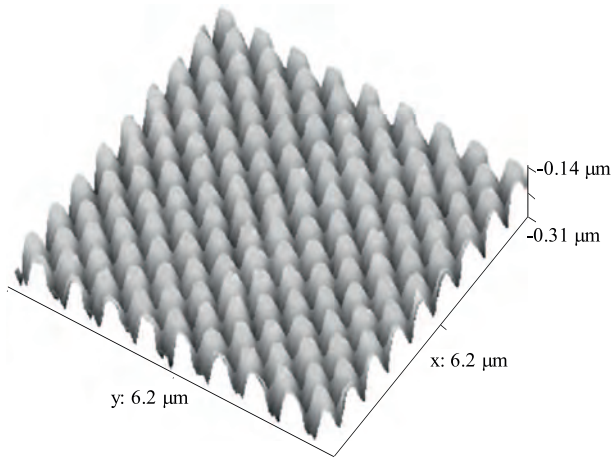


**Fig. 4.** Light-current characteristics of the reference LED without a PhC and of a 2D PhC LED

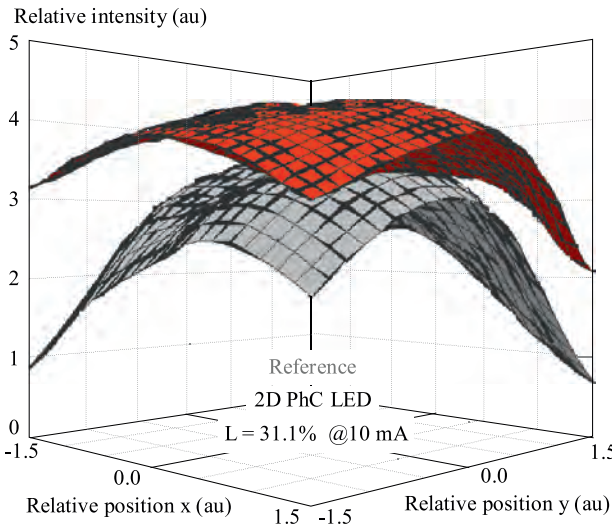
The light-current measurements from Fig. 4 show comparison of light output power of reference and 2D PhC LED in dependence of driving current. It was found that PhC on the top of the LED structure improves the extracted light intensity from LEDs. Extracted light intensity increase was evaluated at 10 mA forward current as 24.2 %. However, in comparison to light-current measurements, 2D PhC LED shows higher light extraction increase by using method of far-field LED light intensity distribution is shown in Fig. 5. The measurement range in Cartesian coordinate system represents range of  $\pm 60^\circ$  in  $\theta$  and  $\phi$  coordinates of spherical coordinate system. The bottom far-field pattern represents reference LED, top far-field pattern represents 2D PhC LED. The increase in extracted light intensity increase of 2D PhC LED evaluated from volume integral of far-field pattern was 35.6 %.



**Fig. 6.** Light-current characteristics of reference LED without 2D PhC and 2D PhC LED



**Fig. 5.** Far field pattern for the reference LED (bottom, light colour) and for the 2D PhC LED (top, dark colour)



**Fig. 7.** Far field pattern for reference LED (bottom, light grey) and 2D PhC LED (top, dark grey)

Similar results like in far-field measurements were observed using the method of near-field measurements. Fig. 6 shows a comparison of light intensity in dependence on the driving current. PhC on the top of LED structure improves the light extraction of LEDs. The increase in the extracted light evaluated from near-field measurements was 34.7%. The higher light extraction improvement in the case of near- and far-field measurement in comparison with measurement by the integrating sphere was due to the fact that light emitted from the LED is measured only from the top of the structure and light emitted from the edges does not affect the measurement.

### 5 CONCLUSIONS

The extracted light intensity increase of a LED containing a 2D PhC was investigated and compared with

a reference LED without the PhC using three different methods. Besides conventional LED light-current measurement using an integrating sphere, two complementary methods were performed. The first one was far-field LED light intensity measurement performed at 10 mA of driving current. The second one was light-current measurement evaluated from near-field patterns at a driving current varying from 1 to 10 mA. The results confirmed that the LED extracted light intensity increased when a 2D PhC was patterned on the top of the LED structure. PhC light extraction enhancement was 24.2% using standard light-current measurements by the integrating sphere. Light extraction enhancement of 35.6% was achieved in the case of far-field measurement and 34.7% in the case of near-field measurement. These two methods show similar results because both collect only the light emitted from the top of the structure. In this case, unlike in measurements by the integrating sphere, edge emission does not affect the measurement. Therefore, we suggest these methods as more suitable for optical characterization of PhC LEDs.

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**Pavol Hronec** (Ing), born in Komárno, Czechoslovakia, in 1987, graduated from Faculty of Electrical Engineering and Information Technology, Slovak University of Technology, Bratislava, from Microelectronics, in 2011. He is currently PhD student at the Institute of Electronics and Photonics of Faculty of Electrical Engineering and Information Technology. His main activities are teaching and research in the area of electrical and optical characterization of light-emitting diodes as well as development of these characterization techniques.

**Jaroslava Škriniarová** (Ing, CSc) received her Ing (MSc) and CSc degree from the Slovak University of Technology (STU), Bratislava, in 1977 and 1986. In 1993 she joined the Microelectronics Department of STU, at present she is there engaged in the research of optoelectronic devices. Her scientific interests include chemical processing of semiconductor materials, thin films and surfaces.

**Dušan Pudiš** (doc, Ing, PhD) received degrees from the Faculty of Electrical Engineering, Slovak University of Technology Bratislava, MSc (Ing) in 1997, PhD in 2001 and doc (Assoc. prof) in 2007, FEI STU. From 2002 he works in Physics Department in University of Žilina in the field of semiconductor devices and photonic structures.

**Jaroslav Kováč** (Prof, Ing, PhD) was born in Tornala, Slovakia, in 1947. He graduated from the Slovak University of Technology, Faculty of Electrical Engineering and Information Technology (FEI STU), Bratislava, in 1970. Since 1971 he has been engaged in the research of optoelectronic devices technology at the Microelectronics Department of FEI STU. He received a PhD degree (1983) and professor degree (2001) at STU Bratislava. Since 1991 he has been the team leader of the Optoelectronic group at the Institute of Electronics and Photonics.