EFFECT OF 2D PHC STRUCTURE PATTERNED IN LED SURFACE ON EMISSION PROPERTIES

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1. Introduction

Besides of many other applications, the photonic crystal (PhC) structures have been investigated as a potential candidate for improving the emission properties of light emitting diodes (LED). First, the light extraction efficiency can be improved by minimizing the total internal reflection in the diode surface. Second, the far-field pattern can be improved as well, if the PhC structure is optimized to the emission wavelength [1, 2].

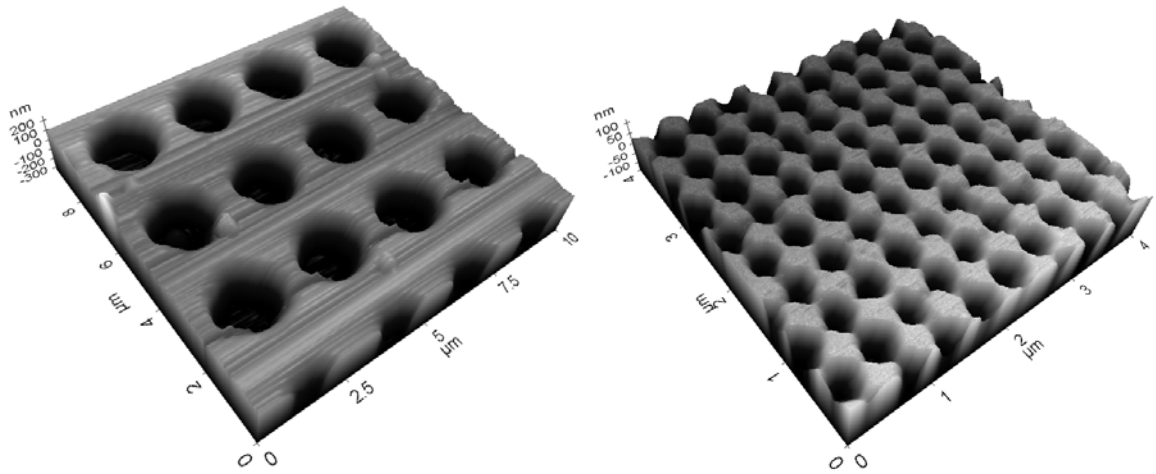
There are many techniques favorable for planar PhC fabrication in the optoelectronic device surfaces as direct laser writing [3] electron beam lithography [4], nanoimprint [5] or interference lithography [6]. Interference lithography can by used for fabrication of large areas of PhC structures using multiple exposures of an interference optical field produced by two coherent beams [6]. This multi-exposure technique can be used for fabrication of different one- and two-dimensional (2D) periodic structures in photoresist materials as well as in different III-V compounds [7].

In this work we focus on fabrication of 2D PhC structures prepared in a LED surface in order to improve the light extraction efficiency from the LED as well as the LED far-field pattern. This PhC structure can generate a photonic band gap where photons with frequencies within the gap are not allowed to propagate, resulting in an enhancement in the extraction of light in the vertical direction from LED [3]. It can improve the light extraction efficiency by diffracting waveguide modes out of the active region.

Conventional GaAs/AlGaAs based LED with triple quantum well in active region emitting at wavelength 850 nm is used for patterning. The LED surface is shaped with 2D PhC of square symmetry with different periods. Finally, patterned surface is investigated by atomic force microscope (AFM) and effect of the 2D PhC structure on the emission properties is analyzed by electrical and optical measurements.

2. Experimental

The LED structures have been grown by low pressure metal organic vapor phase epitaxy on (001) oriented n-type GaAs substrates. The LED structure consists of a 350 nm n-doped GaAs buffer layer, 1300 nm n-doped $Al_{0.60}Ga_{0.40}As$ confinement layer, the undoped quantum well (QW) active region and 650 nm p-doped upper confinement $Al_{0.60}Ga_{0.40}As$ layer. The structure was covered by 40 nm GaAs cap layer. The quantum well active region contains three 9 nm thick GaAs quantum wells separated by 24 nm thick $Al_{0.2}Ga_{0.8}As$ barriers.



a) b)

Fig. 1: *AFM image of 2D PhC structures with square symmetry patterned in the LED surface with a) 2.4 µm and b) 490 nm period.*

Patterning of 2D PhC structures has been performed using standard positive photoresist AZ 5214E. The photoresist layer of thickness 250 nm was spin-coated on GaAs substrate with post-baking at 65 ^{o}C for 2 minutes and at 103 ^{o}C for 3 minutes to remove the solvent. After exposure using interference lithography, samples were developed in AZ 400K developer for 30-50 seconds, rinsed in DI water and dried with nitrogen.

2D PhC structure in the LED surface was prepared using interference lithography technique. Homogeneous one-dimensional optical field of diameter 5 mm was formed by the interference of two coherent beams of Ar ion laser (488 nm) with the intensity 60 mW/cm^2. The adequate exposure time for this type of photoresist, radiation wavelength and intensity was optimized to be 100-120 s [7]. 2D square pattern in the thin photoresist layer was achieved using the double exposure process, where the sample was rotated between individual exposures at angle 90 degree in the plane of sample surface. By setting the angle of the interfering beams, two 2D PhC structures with different periods were prepared. The 2D PhC pattern from the photoresist layer as a mask was transferred in the LED surface using reactive ion etching.

Morphology of prepared 2D PhC structures was analyzed by AFM. AFM analysis documents homogeneous square lattice of air holes shaped in the LED surface for both structures (Fig. 1). From the detailed analysis, the period of 2.4 µm and etch depth of 360 nm is documented for the first structure, shown in Fig. 1a. The structure from Fig. 1b shows 490 nm period and the pattern depth up to 220 nm.

Finally, the mesa etching and the upper p-type Be/Ni/Au circular ohmic contact of the diameter of 100 µm and n-type Ag/Sn contact were realized.

3. Results

Two-dimensional PhC structures of square symmetry were applied in the LED surface with the aim to improve light extraction efficiency. Such 2D PhC structures of sufficient depth in the LED surface can significantly improve light extraction efficiency due to the multiple reflections of photons from the interfaces of the holes etched into the surface. It should allow the more effective radiation of guiding modes in the active region in the surface emission [2].

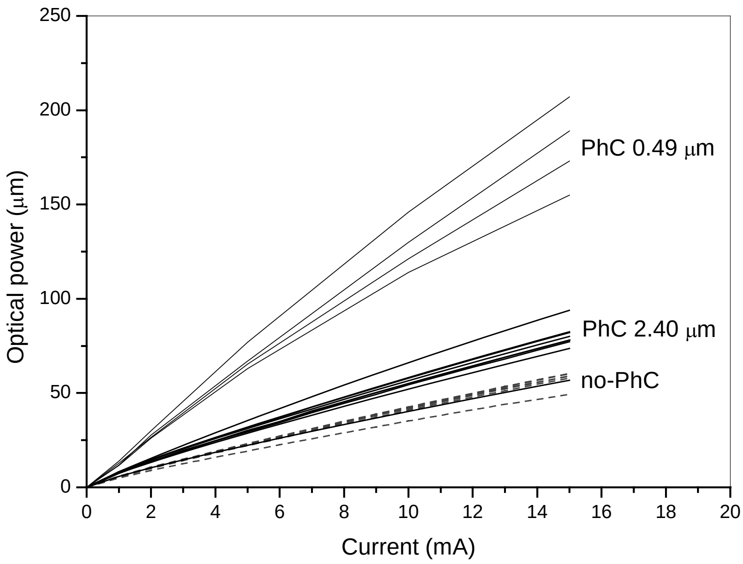


Fig. 2: *Optical power vs. current for set of 2D PhC LEDs with two different periods in comparison with set of no-PhC LEDs.*

Sets of PhC with two different periods and no-PhC diodes were investigated. The optical power - current ($L(I)$) measurement in the calibrated sphere with Si detector demonstrates considerable enhancement of light extraction efficiency from the PhC LED surface in comparison with the no-PhC LED (Fig. 2). The enhancement of light extraction efficiency between the emitted light of the 2.4 µm PhC and no-PhC LEDs is app. 1.7 in whole investigated range of driving currents. The enhancement was more significant for the optimized 490 nm PhC LEDs – up to 4.2 in comparison with no-PhC LEDs.

Optimized structure period related to the emission wavelength typically leads to an improvement of far-field radiation pattern diagram [8]. Far-field radiation pattern diagrams of PhC with 490 nm period and no-PhC LEDs were measured using optical fiber with core diameter of 10 μm placed app. 2 mm from the LED surface. The pattern was measured at different angles of fiber axis to the normal of the LED surface. Different PhC structure orientations (Γ-X, Γ-M) for far-field pattern investigation were analyzed. 2D PhC patterned LED shows slight improvement of radiation pattern diagram as can be seen from Fig. 3, where a slight narrowing of the radiation pattern diagram of PhC LED was achieved in comparison to the no-PhC LED. Effect of the sample surface orientation is also documented, where 45 degree orientation (Γ-M) shows the narrowest radiation pattern.

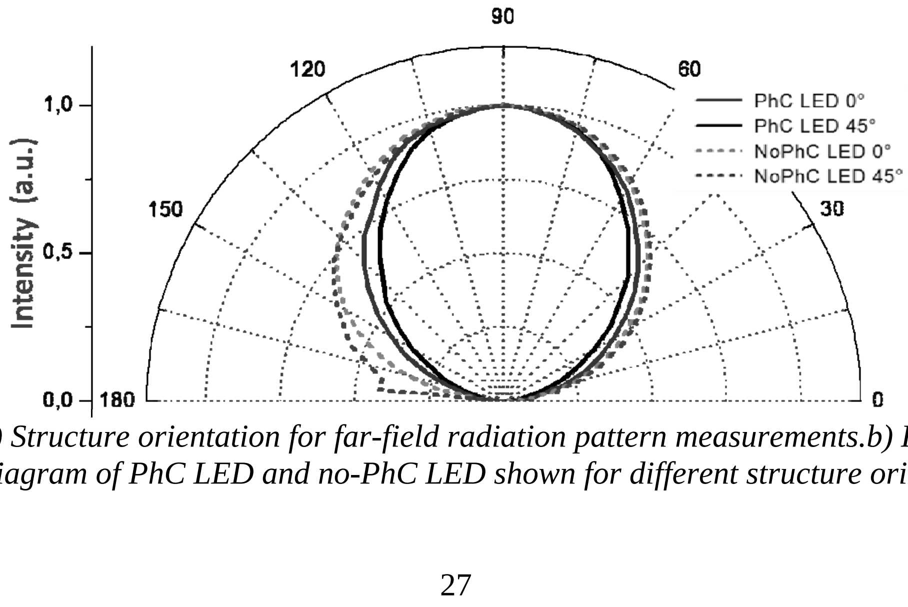


Fig. 3: *a) Structure orientation for far-field radiation pattern measurements.b) Radiation pattern diagram of PhC LED and no-PhC LED shown for different structure orientations.*

4. Conclusion

Two beam interference method was successfully examined for preparation of 2D PhC structures in a LED surface. The 2D PhC LEDs in square symmetry with two different periods 2.4 µm and 490 nm of etch depths higher than 220 nm were prepared. This PhC LED shows considerable enhancement of light extraction efficiency from the diode surface given by the effective extraction of guided modes from active region. The light extraction efficiency 4.2 higher was documented for the 490 nm PhC LED in comparison with no-PhC LED. Also slight narrowing of far-field radiation pattern was documented for the PhC LED with optimized structure period.

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References:

[1] M. L. Hsieh, K. C. Lo, Y. S. Lan, S. Y. Yang, C. H. Lin, H. M. Liu, H. C. Kuo: *IEEE Photonic. Tech. L.*, **20**, 141 (2008).

[2] A. M. Adawi, R. Kullock, J. L. Turner, C. Vasilev, D. G. Lidzey, A. Tahraoui, P. W. Fry, D. Gibson, E. Smith, C. Foden, M. Roberts, F. Qureshi, N. Athanassopoulou: *Org. Electron*, **7**, 222 (2006).

[3] M. Deubel, G. von Freymann, M Wegener, S. Pereira, K. Busch, C. M. Soukoulis: *Nature materials*, **1038**, 1155 (2004).

[4] H.X. Tang, Y.H. Zuo, J.Z. Yu, Q.M. Wang: *Chin. Phys. Lett.*, **23**, 10 (2006).

[5] A. Chen, S. J. Chua, C.G. Fonstad, B. Wang, O. Wilhelmi: *Advanced Materials for Micro- and Nano-Systems*, **01**, 7374 (2005).

[6] N. D. Lai, W. P. Liang, J. H. Lin, C. C. Hsu, C. H. Lin: *Opt. Express*, **13**, 9605 (2005).

[7] D. Pudis, J. Skriniarova, I. Martincek, J. Kovac jr., N. Tarjanyi, S. Hascik: *J. Electr. Eng.*, **60**, 166 (2009).

[8] E. Mattioli, C. Weisbuch: *J. Phys. D: Appl. Phys.*, **43**, 354005-1-22 (2010).