LED WITH 2D IRREGULAR STRUCTURE IN THE SURFACE PREPARED BY NSOM LITHOGRAPHY

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1. Introduction

Light emitting diodes (LEDs) are rapidly emerging as an alternative for future lighting due to their potential superior efficiency. By implementation of PhC structures in LED surface, the modification of optical properties has been proven. PhC structures implemented in LED surface can generate a photonic band gap where photons with frequencies within the gap are not allowed to propagate, which results in modification of LED directionality or far-field profile of irradiated optical field [1].

On the other hand, for LEDs with PhC structures, the enhancement of light extraction efficiency has also been confirmed [2, 3]. While geometric factors of the 2D PhC structure – such as lattice shape, air hole size, and dielectric constants of used materials – play a role in determining the directionality and the far-field pattern, for the light extraction efficiency the etch depth of the structure is important [4].

Thanks to implementation of 2D structure (not necessarily regular) in LED emitting surface, the total internal reflection from the diode surface is minimized. In a conventional unpatterned LED, the majority of light emitted from the quantum well active region due to the total internal reflection from the LED surface is back-reflected and absorbed. The 2D structure influences cross-coupling between waveguide modes in an active region and radiated modes associated with the 2D surface pattern depending on the etch depth of the structure [4].

One of the most promising technologies for 2D structure fabrication is near-field scanning optical microscope (NSOM) lithography. The method consists in employing the NSOM in illumination mode, where patterning of structures is done through a direct writing process which is performed by the optical near-field produced at the tip of a fiber probe [5].

We present a triple quantum well (QW) LED with irregular 2D structure in the surface prepared by NSOM lithography. Prepared structures are investigated by atomic force microscope (AFM). In agreement with published results on GaAs-based LEDs, the enhancement of emission from the shaped air hole regions in comparison with the surrounding surface and thus the local increase of the light extraction efficiency of the patterned LED surface is presented. The enhancement is documented by optical field analysis using Spiricon system.

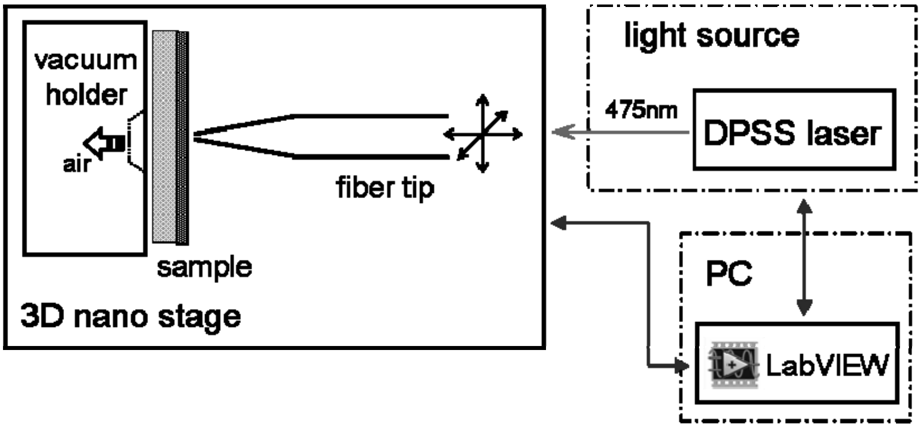

Fig.1: *Experimental arrangement for non-contact NSOM lithography.*

2. Experimental

The LED samples were grown by low-pressure MOVPE on (001) oriented n-type GaAs substrate. The 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 QW active region and 800 nm p-doped upper confinement $Al_{0.60}Ga_{0.40}As$ layer. The active region contains three 9 nm thick GaAs QWs separated by 24 nm thick $Al_{0.2}Ga_{0.8}As$ barriers. The structure was covered by 40 nm p-doped GaAs cap layer.

In the next step, the contact operations using upper p-type Be/Ni/Au circular ohmic contact with the diameter of 100 µm were realized. On such prepared LED structure, 2D structure was patterned in the emitting part of the LED using NSOM lithography.

Experimental arrangement for NSOM lithography is shown in Fig. 1. Experimental stage for NSOM lithography requires high resolution 3D nanoposition system controlled by computer. Because of the photoresist sensitivity in the violet-blue wavelength range, a modulated 473 nm DPSS laser was used as a exposing light source. The laser beam was coupled to the fiber probe fixed on the 3D axis nanoposition piezosystem. The non-contact mode of NSOM lithography was performed in this experiment, where the fiber tip realized the in plane movement over the sample without touching the sample surface.

The 450 nm thin standard positive photoresist AZ 5214E was spin-coated on the sample surface with post-baking at 65°C for 2 minutes and at 103°C for 3 minutes to remove the solvent. The LED sample was fixed on a holder using a vacuum system. Patterning of the photoresist was carried out by moving the fiber probe over the sample. The laser light irradiated the sample through the fiber probe aperture at desired positions. After exposure, the sample was developed in AZ 400K developer for 30 s and rinsed in deionized water.

The 2D structure patterned in the photoresist layer deposited on the LED surface works as a mask layer for next etching process. By reactive ion etching, the pattern was transferred into the upper confinement layer. To finalize the LED device, the MESA etching and n-type Ag/Sn contact was realized.

The emission properties of prepared LED with 2D irregular structure in the emitting part were investigated by Spiricon system.

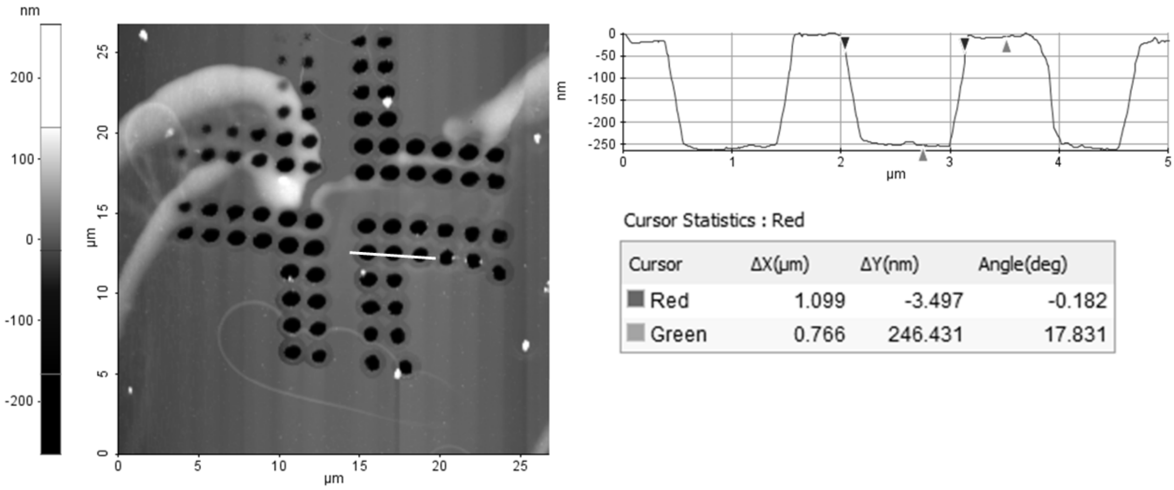

Fig.2: *Irregular 2D structure in the emitting part of the LED chip patterned in the upper confinement layer, AFM line profile analysis. The air hole diameter is about 1 µm (ΔX value for the red cursor pair) and the depth is about 245 nm (ΔY value for the green cursor pair).*

3. Results

Published results for GaN-based structures with 2D surface pattern document improvement of extraction efficiency from 1.3 to 2.4 with 1200 nm surface pattern period for different etch depth and symmetries [6, 7]. In these structures, the mechanism of light extraction enhancement is mainly related to surface diffraction of guided modes on the surface roughness. Similar results were shown for GaAs-based structures, where the $L(I)$ measurements demonstrated an enhancement of light extraction efficiency between the emitted light of the PhC and non-PhC LED app. 1.39 times [3].

NSOM lithography differs from other conventional lithography techniques in the flexibility of the design of the exposed structure. A cross-shaped 2D irregular structure was designed in the grid with 1.5 µm period in both horizontal and vertical directions. Using NSOM lithography process the irregular structure was patterned in the photoresist layer deposited in the LED surface. In the next step, the cross-shaped 2D structure was successfully transferred into the substrate layer. Its morphology and depth profile after etch was analyzed by employing of AFM.

The AFM image of the structure transferred in upper confinement layer is shown in Fig. 2. The detailed line profile AFM analysis reveals the air hole diameter app. 1 µm and the depth of the structure to be about 245 nm. According to the published results, the etch depth should be sufficient to allow the guided modes to be extracted [1 – 3].

The emission properties of prepared LED with 2D irregular structure in the emitting part were investigated by Spiricon system. In Fig. 3, there is shown the image of the LED under radiation at driving current of 10 mA. From the Spiricon image, there is clearly visible the enhancement of radiation from the air hole irregular pattern. From the intensity scale, app. 1.6 times local enhancement is estimated from the patterned irregular cross-shaped 2D structure comparing to the surrounding surface.

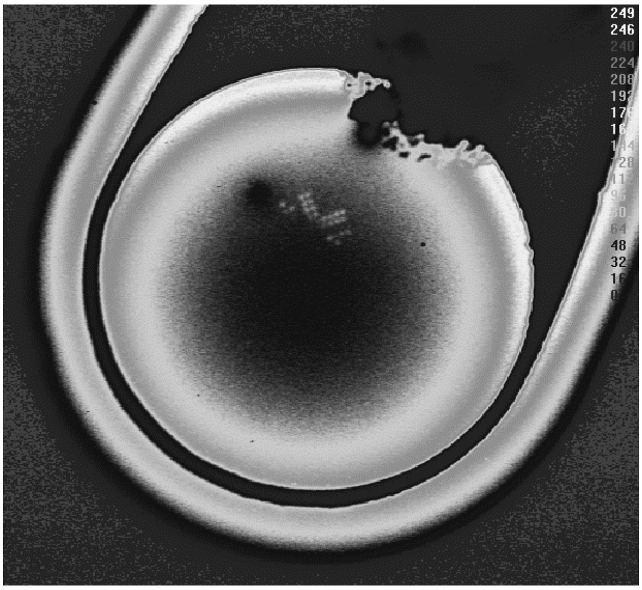

Fig.3: *LED with 2D irregular structure in the emitting part under radiation, at driving current of 10 mA, Spiricon image, top view.*

4. Conclusion

Previously published enhancement of light extraction efficiency due to the diffraction on the shaped air hole regions inspired creation of 2D irregular structure in the LED surface. Using NSOM lithography, the cross-shaped 2D irregular structure was patterned in the emitting surface of the LED. By etching process, this was transferred into the upper confinement layer of the LED. Further analysis by Spiricon revealed the local enhancement of the radiation from the 2D structure comparing to the surrounding region.

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