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Azimuthal anisotropy of light extraction from photonic crystal light-emitting diodes

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Photonic crystal (PhC) light-emitting diodes (LEDs) exhibiting anisotropic light extraction have been investigated experimentally and theoretically. It is found that the anisotropic light extraction strongly depends on the lattice constant and orientation. Optical images of the anisotropy in the azimuthal direction are obtained using annular structure with triangular lattice. 6-fold symmetric light extraction patterns with varying number of petals are observed. More petals in multiple of 6 appear in the observed image with lattice constant increasing. This anisotropic behavior suggests a new means to optimize the PhC design of GaN LED for light extraction.

1 Introduction

Recently, the development in Gallium-nitride (GaN)-based blue light-emitting diodes (LEDs) has initiated the commercialization of LEDs in flat-panel displays and enabled applications in other displays. Further improvement in internal and external quantum efficiency can expand the market penetration and realize many new applications. Photonic crystal (PhC) has attracted a great deal of attention to enhance the brightness of light-emitting diodes (LEDs) [1, 2]. Both the intensity and the angular distribution of the light extraction can be controlled by engineering the PhC structure fabricated on the light emitting surface, [3, 4]. Many reports on the light extraction efficiency have appeared [5-7] including the periodic light extraction intensity variation in the plane perpendicular to the chip surface [8]. But the angular dependence of the light distribution, particularly in the azimuthal direction, has not been examined in detail. In this work, we present the direct imaging method to investigate the in-plane angular distribution of the extracted light using a special designed structure. The strong dependence on the orientations and lattice constants of the PhCs was observed and theoretical discussion regarding guided modes of diffraction into the air was addressed.

2 Experimental

The GaN epitaxial materials were grown by metalorganic chemical vapor deposition (MOCVD) on c- sapphire substrates. The epitaxial structure is composed of a 1 μm-thick GaN bulk buffer layer on c-sapphire substrate, a 2 μm-thick bottom n-GaN current-spreading layer, a 100 nm-thick InGaN/GaN active region consisting of multiple quantum wells (MQW), and a 130 nm-thick top p-GaN current spreading layer. Figure 1(a) shows the schematic diagram of the GaN blue PhC LED structure, where an annular PhC region with an inner/outer diameter of 100/200 μm was fabricated. The triangular-lattice PhCs were patterned by electron-beam (e-beam) lithography. The holes were then etched into the top p-GaN layer using inductively coupled plasma (ICP) dry etching. Figure 1(b) and (c) show the top and tilted views of the scanning electron microscopy (SEM) images of the PhC structures, respectively, wherein the etch depth t is 120 nm, and the ratio of hole diameter d to lattice constant a is fixed to 0.7. The light extraction properties of PhC structures are characterized by optical pumping with a 325 nm He-Cd laser at room temperature. The micro-photoluminescence (μ-PL) system is utilized in the experiment, as shown in Fig. 2(a). The sample faces toward the pump laser beam and held on the 2D stage with 3D stepping motor to align the microscopes collinearly. A 15x UV objective with numerical aperture (N.A.) of 0.32 was used to collect the on-axis emission signal from the sample. A high-resolution digital camera charge-coupled device (CCD) was employed to record the microscopic images of radiative light patterns. Incident pump power is 3.2 mW and power density at this pumping condition is about 0.2 MW/cm^2. He-Cd cut-off filter was installed in front of the CCD to avoid the backscattering of pumping light from samples.

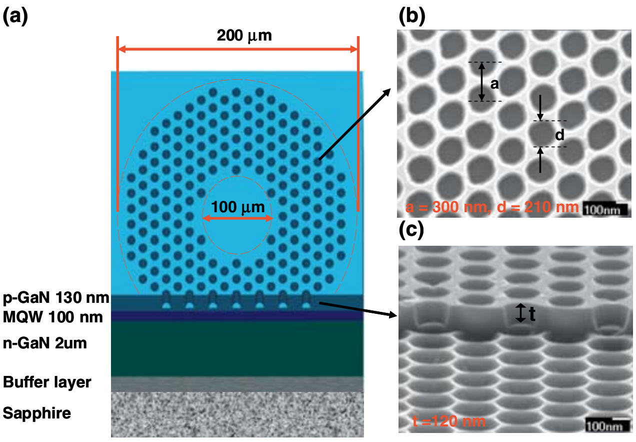

Figure 1 (a) Schematic diagram of the MOCVD-grown 470 nm GaN-based blue PhC LED structure. (b) The top-view SEM image of PhCs on blue LED with the lattice constant *a* and the diameter of air holes *d*. (c) The tilted-view SEM image of PhCs on blue LED with the etch depth *t*.

3 Results and discussion

The observed the images shown on the CCD are due to the scattered PL light at 470 nm by the PhC generated by the 325 nm He-Cd laser beam normally incident into the central area of the annular structure. As light generated in the central area travels radially outward to enter the surrounding PhC region, it is extracted by the PhCs and the distribution of the light is imaged by the CCD. The observed images show a 60° rotational periodic variation light extraction pattern, as shown in the inset of Fig. 2(a). The light intensity distribution of GaN blue LEDs with PhC patterns is imaged as shown in the Fig. 2(c). The images without the PhC regions are shown in Fig. 2(b) for reference. It can also been seen that the light extraction from the PhC is anisotropic and forms a 6-fold rotational symmetry light extraction pattern. Light emission intensity from the sample with PhC is stronger than that from the one without PhCs. In addition, the light extraction intensity in the Γ-M direction of PC LED structure is larger than that in the Γ-K direction as shown in the Fig. 2(c). Some of the light propagation inside the PhC region exhibits a focusing behavior.

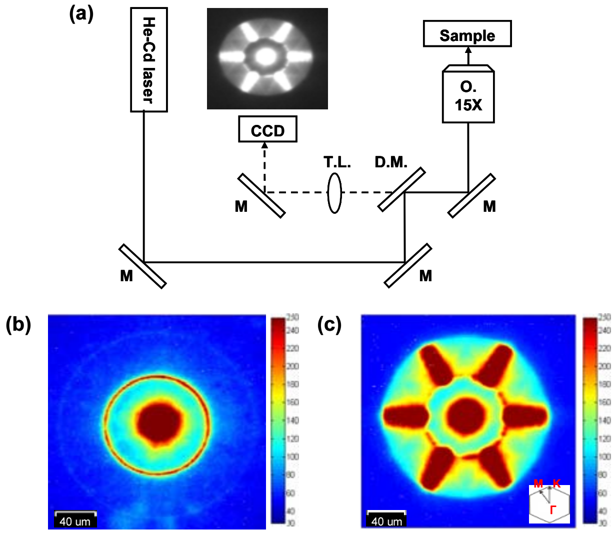

Figure 2 (a) Schematic representation of the experimental setup for μ-PL system. M mirror; T.L. tube lens; D. M. dichroic mirror; O. objective The CCD images of GaN blue LEDs at 3.2 mW He-Cd laser power injections the inner circle, as shown inset. The intensity distribution images of GaN blue LEDs at 3.2 mW He-Cd laser power injections (b) without PhCs, (c) with PhCs (*a* = 300 nm), the inset shows the reduced BZ.

The observed anisotropic light extraction patterns can be explained using Bragg theory and considering their reciprocal lattice. Diffraction can be represented in the wavevector diagram, as shown in the Fig. 3. Figure 3 shows to scale the reciprocal lattice with the appropriate air disk (in red color) and the guided mode circles (in blue and purple color) for lattice constant *a* = 300 nm. Guided mode propagating in the 2D PhC region can couple with the reciprocal wavevectors and diffracted toward the extraction cone (ec) which is the air disk for the present case. When the resultant wavevector falls inside the ec, the diffracted light can escape into air. However to be observed with the microscopy, the light propagation must fall in the numerical aperture (NA) of the objective lens. The circle (in brown color) inside the ec represents the zones where the light will fall into the NA. The solid blue arcs inside the ec are all the wavevectors that fell into the ec. These arcs are all from the coupling to the unit reciprocal vectors $G_{\Gamma\text{-}M}$.

The solid blue arcs inside the ec in Fig. 3 represent diffraction only the Γ-M direction that wavevectors fell into the ec. These arcs are all from the coupling to the unit reciprocal vectors $G_{\Gamma\text{-}M}$ so that there are six extracted light petals parallel to the Γ-M direction of PhC orientation, as shown in the Fig. 2(c). Each point on the arc represents the in-plane component for the possible escape vector. It can be seen that the light propagating in the Γ-K direction couples to the unit reciprocal vector $G_{\Gamma\text{-}K}$ resulted in the in-plane component that fell “outside” the ec. Thus for light travel in the Γ-K directions, there is no diffracted petal that can escape into air as is observed in the Fig. 2(c).

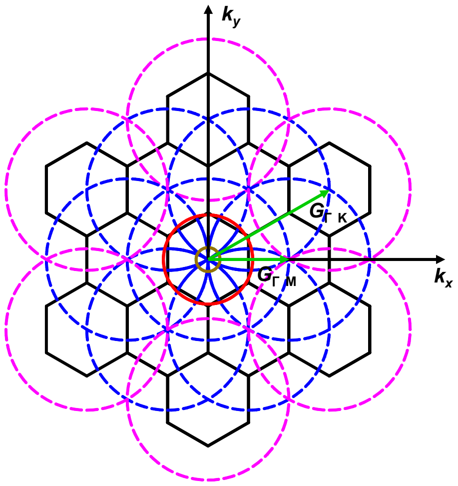

Figure 3 Schematic scale the reciprocal lattice with the appropriate air disk (in thick red color) and the guided mode circles (in blue and purple color) for lattice constant a = 300 nm.

Following the same reasoning as for Fig. 3, for larger lattice constants there are more possibilities for the coupling back into the ec, the observed number of petals in the images increased. The pattern becomes more isotropic. Figure 4 is a diagram to illustrate the regions where patterns with different number of petals are observed. As lattice constants increases, more petals in multiple of 6 appear in the observed image. The insets of Fig. 4 shows the images with 6 and 12 petals for a = 300 and 450 nm samples respectively. Pattern with up to 24 petals has been observed with the present setup. The formula for the boundary of different regions have been derived and are shown in the figure.

4 Conclusion

In conclusion, we have investigated the anisotropic light extraction in the azimuthal direction of PhC LEDs. Optical measurement images of the anisotropy in the azimuthal direction are obtained using annular structure with triangular lattice and shown the 6-fold symmetric light extraction patterns with varying number of petals. More petals in multiple of 6 appear in the observed image with increasing lattice constant. The present imaging approach can be used to study the propagation of light in the PhC slabs and provides information important for designing LED and other photonic devices to take full advantages of what the PhC can offer.

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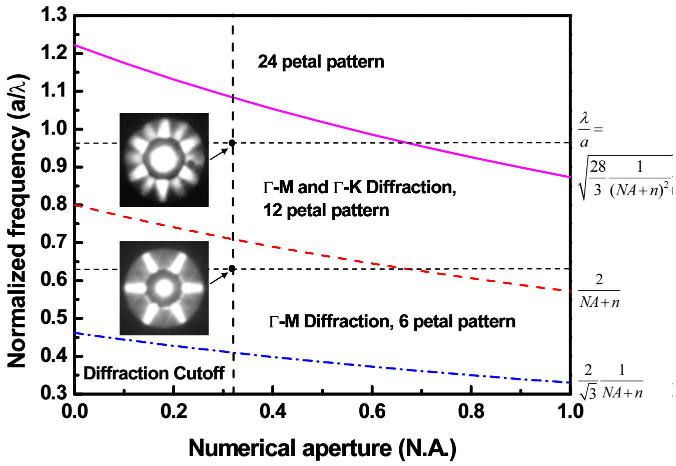

Figure 4 illustrates with the formula for the boundary of different regions where patterns with different number of petals. Inset showed the 6-fold (a = 300 nm, a/λ = 0.638) and 12-fold (a = 450 nm, a/λ = 0.957) symmetric light extraction patterns.

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