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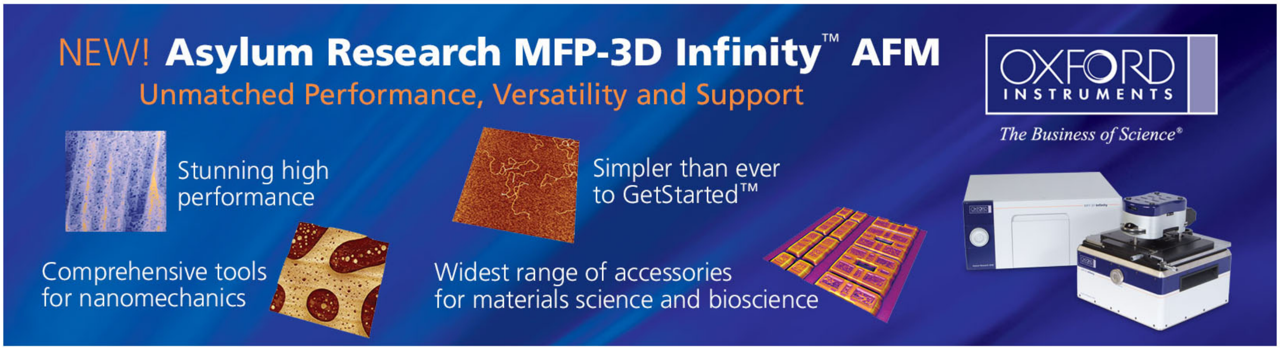

APPLIED PHYSICS LETTERS **94**, 123106 (2009)

# Directional light extraction enhancement from GaN-based film-transferred photonic crystal light-emitting diodes

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Experimental investigation of the directionality in the far-field pattern and light extraction enhancement in collected cone were performed in GaN-based film-transferred photonic crystal (PhC) light-emitting diodes (FTLEDs). Angular-resolved measurement revealed directional profile and azimuthal anisotropy in the far-field distribution with guided modes extraction. Good agreement according to Bragg's diffraction theory and free photon band structure were achieved. The light enhancement in PhC FTLEDs compared to non-PhC FTLEDs within the collection cone angle was obtained according to measured three-dimensional far-field patterns. In a ±20° collection cone, collected light was enhanced by a factor of ~2.4 for the collimated PhC FTLED. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3106109]

For next generation applications of light-emitting diodes (LEDs), further improvements of the light extraction efficiency and the directional far-field patterns are required. Directional far-field pattern of the light sources is important for many applications in projector displays, backlight displays, and automobile headlights.[1] Approaches based on the photonic crystal (PhC) have attracted much attention to achieve light extraction enhancement, polarization, and directional patterns from GaN LEDs.[2–4] Recently, an AlGaInP film-transferred (FT) resonant cavity LED combined with PhC has been reported for enhancing directional light extraction[5] in the red wavelength, as well as GaN PhC FTLEDs in the blue wavelength range for light extraction enhancement.[6,7] Nevertheless, a blue GaN PhC FTLEDs with directional light extraction has not been studied in detail.

In this paper, experimental and theoretical studies on the directional light extraction through Bragg diffraction of guided modes in GaN PhC FTLEDs will be addressed. GaN FTLEDs with different PhC lattices based on free photon band structure exhibit the corresponding directionality profiles in the far-field patterns. In addition, angular-resolved spectra have been mapped monochromatically to demonstrate the azimuthal evolution of the guided modes' diffraction behavior. Furthermore, the light enhancement of PhC FTLEDs compared to non-PhC FTLEDs within the collection cone angle was also obtained according to the measured three-dimensional (3D) far-field patterns.

The blue GaN-based LED wafer were grown by metal-organic chemical-vapor deposition onto *c*-face (0001) 2 in. diameter sapphire substrates. The LED structure consists of a 30-nm-thick GaN nucleation layer, a 4-$\mu$m-thick undoped GaN buffer layer, a 3-$\mu$m-thick Si-doped *n*-GaN layer, a 120 nm InGaN/GaN multiple quantum well active region with eight periods (dominant wavelength $\lambda = 475$ nm), a 20-nm-thick Mg-doped *p*-AlGaN electron blocking layer, and a 300-nm-thick Mg-doped *p*-GaN contact layer. The detailed wafer processing of GaN FTLEDs associated PhC is the same as in Ref. 8, using the laser lift-off technique to remove the sapphire substrate. The resulting structure was then thinned down by chemical-mechanical polishing to obtain the GaN cavity thickness of around 1.5 $\mu$m. The square-lattice PhC with circular holes was then defined by holography lithography. PhC holes were etched into the top *n*-GaN surface to a depth of around 150 nm. The lattice constant *a* of PhC were 290, 350, and 400 nm and the hole diameter *d* fixed to ratio $d/a = 0.7$. A scanning electron microscopy (SEM) image of the square-lattice PhC structure is shown in Fig. 1(a). Finally, a patterned Pt/Cr/Au electrode was deposited on *n*-GaN as the *n*-type contact layer. After fabrication, the dies were mounted on transistor outline (TO) package with encapsulant-free.

After sample preparation, angular-resolved measurement under electrical current injection was performed. A continu-

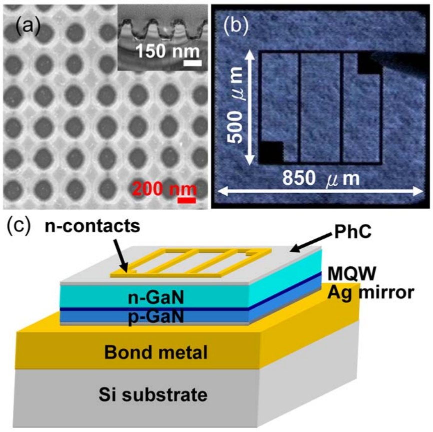

FIG. 1. (Color online) (a) The top-view SEM image of PhCs on FTLED with the lattice constant $a = 400$ nm and the diameter of air holes $d = 280$ nm fabricated with the holography lithography. Inset: the cross-section TEM image shows the PhC depth $t = 150$ nm. (b) The optical micrography showing the blue light distribution across the die operated at low injection current 5 mA. (c) Schematic diagram of the GaN FTLED structure with PhC.

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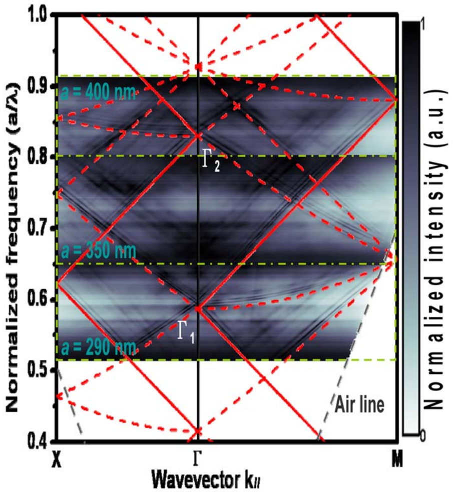

FIG. 2. (Color online) Free photon band structure calculated with $n=2.42$ for the TE modes. The red thick lines indicate the collinear coupled modes. The red dash lines indicated the noncollinear coupled bands. The air lines are shown in gray dashed lines. The boxes indicate the experiment regions observed with $a=290$, 350, and 400 nm.

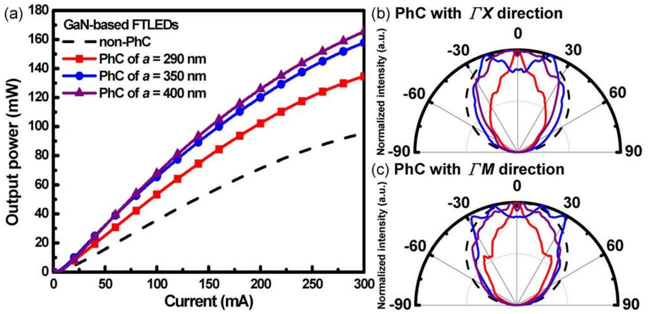

FIG. 3. (Color online) (a) Light output power-current ($L$-$I$) curve characteristic of GaN FTLED with PhC and without PhC. The far-field pattern shows the different direction (b) $\Gamma X$ and (c) $\Gamma M$ with PhC at driving current of 50 mA.

ous current of 20 mA injected into the TO mounted device at room temperature. The angular-resolved experiment setup is the same as in Ref. 9. In PhC FTLED, the far-field distribution will be significantly modified by the PhC lattice diffraction. The waveguided light traveling in the plane will be diffracted by the reciprocal wave vectors associated with the PhC. Figure 2 shows the two-dimensional (2D) free photon band structure for the TE modes with average refractive index $n=2.42$.[10] Three different $a$ values, 290, 350, and 400 nm, creates a range of $a/\lambda=0.52-0.91$ for experimental investigation as enclosed in the boxes, as shown in Fig. 2. The angular-resolved spectra are transformed into the guided mode dispersion curves, as shown in the inset as boxes in Fig. 2.[9] The image shows the normalized dispersion curves for each mode lines in the $\Gamma X$ and $\Gamma M$ directions. Above the air lines, the band structure exhibits and abundance of resonant states that will be involved in the PhC assisted by light extraction. Using the angular-resolved spectroscopic technique, most of these states can be investigated efficiently. The agreement between the experiment and calculation are good. Only the guided modes of effective refractive index $n_{\text{eff}}=2.414-2.15$ from our samples are seen. We accurately fit the lowest order mode with the free photon band structure. The other modes are shifted higher than our red line because each mode has a different photonic crystal induced effective index.[9] Additionally, the extracted guided mode corresponds with the high symmetry point along the $\Gamma$ axis of $\Gamma_1$ and $\Gamma_2$ that shows the light collimation profile. For a more detailed analysis of angular-resolved spectra for GaN film-transferred PhC LEDs, see Ref. 7.

In addition, the intensity-current-voltage ($L$-$I$-$V$) characteristics were measured by using an integration sphere with Si photodiode. The turn on voltage is about 2.7 V. The light output power of the GaN PhC FTLEDs with various $a$ values of 290, 350, and 400 nm at a driving current of 200 mA shown in Fig. 3(a) reveals output power enhancement by a percentage of 45%, 68%, and 77%, respectively, compared to the GaN FTLED without PhC (non-PhC FTLED). At 200 mA driving current, the forward voltages of the GaN PhC FTLED with $a$ of 290, 350, and 400 nm are 6.2, 6.4, and 6.5 V, respectively. The high forward voltages could attribute to high series resistance in such thin PhC device. Furthermore, due to the discrete nature of the guided modes, this diffraction light will exhibit anisotropy in the far-field pattern both in the zenith directional and the azimuthal direction. The far-field patterns in the zenith direction were measured at a driving current of 50 mA, normalized with the peak intensity, as shown in Figs. 3(b) and 3(c). The samples with $a$ of 290 and 400 nm have collimated far-field patterns that both are peaked near normal to the FTLED surface and have small far-field angle at half intensity of ±31.7° (±41.05°) and ±42.45° (±49.7°) in $\Gamma X$ ($\Gamma M$) orientation of PhC lattice, respectively, which are much smaller than that of a typical Lambertian cone, ±60°. The measured far-field pattern of the GaN non-PhC FTLED is nearly Lambertian. In addition, the $a$ of 350 nm sample has lobes at around ±17° (±15°, ±30°) in $\Gamma X$ ($\Gamma M$) orientation. Therefore, in GaN PhC FTLED, the far-field distributions will be significantly modified by the PhC structure, i.e., lattice constant $a$. With comparing to the encapsulant-free PhC FTLED, the encapsulated PhC FTLED has similar far-field characteristics in our study. As a result, the GaN PhC FTLEDs can be encapsulated to increase light enhancement,[6] while retaining the directional patterns.

The azimuthal anisotropy of the far-field distribution is measured as a function of the azimuthal angles by using the angular-resolved setup. Figures 4(a)–4(c) plot the far-field distributions monochromatically in the azimuthal direction at a fixed wavelength of $\lambda=475$ nm with $a$ of 290, 350, and 400 nm, respectively. Different guided mode with different index will trace out an arc with the radius corresponding to the respective waveguide circle, which are well fitting by Ewald's construction of Bragg's diffraction theory.[11] The several lower guided mode extracted by PhC lattice is shown in Fig. 4. Additionally, we also measured the 3D far-field patterns of three different $a$ values, 290, 350, and 400 nm, in top view, which revealed the PhC diffraction patterns with fourfold symmetry due to square lattice, as shown in Figs. 4(d)–4(f), respectively.

The light enhancement in the PhC FTLEDs compared to non-PhC FTLEDs at a driving current of 50 mA can be charted in Fig. 5 in which the light enhancement is defined as the ratio of the light output of the PhC FTLED divided by non-PhC LED, and the power is collected from ±0° to ±90°. The light enhancements in collection angles strongly depending on the far-field patterns of GaN PhC FTLEDs are obtained. The collimated PhC FTLED in a ±20° collection

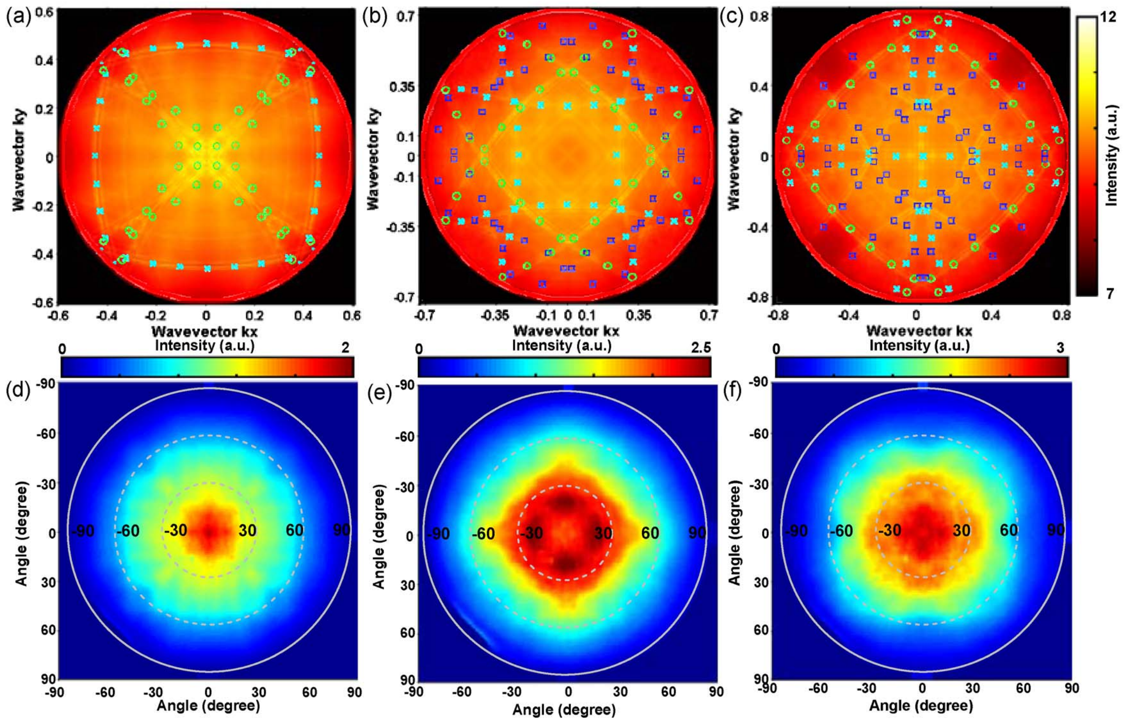

FIG. 4. (Color online) The map of intensity of the extracted light at a fixed wavelength λ=475 nm. The wavelength was kept at a constant corresponding to (a) $a$=290 nm, (b) $a$=350 nm, and (c) $a$=400 nm, respectively. Inset: the tittles show Bragg's diffraction theory fitting with effective refractive index $n_{\text{eff}}$ =2.414 (cyan X of Γ$X$ direction, green O of Γ$M$ direction, and blue □ of Γ$X$Γ$M$ direction). The top view of 3D far-field pattern shows three different $a$ value (d) 290 nm, (e) 350 nm, and (f) 400 nm, respectively.

cone achieves the light enhancement of ~2.4. For collimated patterns, the light enhancement increases with collection angle shrinking. The divergent profile of PhC with $a$ =350 nm reveals little light enhancement in a small collection angle. Therefore, the collimation profile of far-field pattern could contribute to the stronger directional light enhancement in many applications, especially for etendue limited applications. Additionally, the extraction enhancement is not only a function of the PhC parameters, but also on other variables such as the GaN thickness and QW placement, as shown in Ref. 7.

In conclusion, the far-field directionality and light extraction enhancement in collected cone in GaN-based PhC FTLEDs with three different square PhC lattice have been experimentally investigated. Angular-resolved measurements revealed directional profile and azimuthal anisotropy in the far-field distribution with guided modes extraction based on the Bragg's diffraction. The extracted guided mode corresponds with the high symmetry point along the Γ axis of $\Gamma_1$ and $\Gamma_2$ that shows the light collimation profile. The light enhancement in PhC FTLEDs compared to non-PhC FTLEDs within the collection cone angle was also obtained according to measured 3D far-field patterns. In a ±20° collection cone, collected light was enhanced by a factor of ~2.4 for the collimated PhC FTLED. The collimated PhC FTLED is a promising candidate for etendue limited applications, such as projecting display.

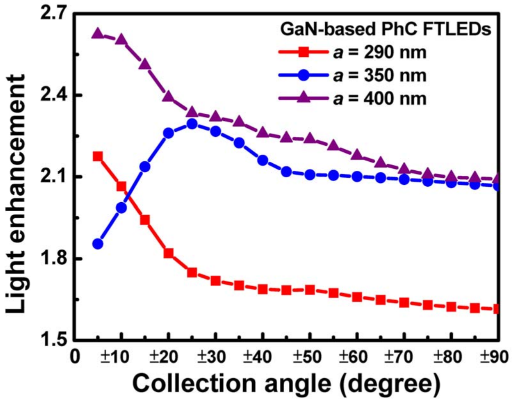

FIG. 5. (Color online) Light enhancement recorded at various output collection angle for GaN PhC FTLEDs with three different $a$.

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