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Divergent Far-Field III–Nitride Ultrathin Film-Transferred Photonic Crystal Light-Emitting Diodes

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The divergent far-field distribution of III–nitride ultrathin film-transferred light-emitting diodes (FTLEDs) with ellipse holes of triangular photonic crystal (PhC) lattice have been experimental and theoretical studies. Angular-and-spectral-resolved measurement revealed guided modes extraction behaviors which obtain good agreement with theoretical model according to two-dimensional free photon band structure. The azimuthal evolution of the guided modes' diffraction behavior according to Bragg's diffraction has also been discussed by angular-resolved monochromatical mapping. Finally, the PhC FTLEDs show light enhancement with the divergence far-field pattern that exhibited 130% at a driving current of 200 mA as compared with non-PhC (without PhC) FTLEDs. This could lead to promising LEDs with unusual divergent far-field properties for specific applications.

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1. Introduction

Recently, for the benefit of application to next-generation LEDs, further improvements in the light extraction efficiency and the far-field patterns are required.[1)] At present, a tremendous progress in III–nitride film-transferred light-emitting diodes (FTLEDs) attached the photonic crystal (PhC) has achieved high light extraction efficiency.[2)] Due to high-efficiency white LEDs made with blue LEDs and phosphors have attracted much attention because the replacement of incandescent, fluorescent for general lighting could be realistic.[3)] Directional far-field pattern of the light sources are important for many applications such in projection displays. In addition, divergent far-field patterns have many applications in down light of general lighting, automatic headlight, and liquid crystal display (LCD) backlight. In the past work, employing the PhCs has achieved light extraction enhancement and directional far-field patterns from III–nitride FTLEDs.[4)] Nonetheless, III–nitride PhC ultrathin FTLEDs with light enhancement and divergent far-field patterns has not been investigated in details.

In this work, experimental and theoretical studies on the divergent far-field distribution from triangular PhC lattice with the ellipse holes in III–nitride PhC ultrathin FTLEDs were discussed. Angular-and-spectral resolved measurement in the Γ–M, Γ–K, Γ–M′, and Γ–K′ directions of the PhC were revealed guided modes extraction behavior based on Bragg's diffraction, which is consistent with two-dimensional (2D) free photon band structure and exhibits the corresponding divergent profiles in the far-field pattern. Further, angular-resolved spectra were mapped monochromatically to demonstrate the azimuthal evolution of the guided modes' diffraction behavior. Finally, the light output enhancement of PhC FTLEDs was significantly higher than that of non-PhC (without PhC) FTLEDs.

2. Experiments

The III–nitride blue LED wafers used in this study were grown by low-pressure metal organic chemical vapor deposition (MOCVD) onto *c*-face (0001) 2-in. diameter sapphire substrates. The LED structure consisted of a 30-nm-thick GaN nucleation layer, a 1-μm-thick undoped GaN layer, a 3-μm-thick Si-doped n-type GaN cladding layer which consists a 10 periods of 150-nm AlGaN/GaN short period super lattice (SPS) structure, an unintentionally doped active region of 470 nm emitting wavelength with 5 periods of 100-nm-thick InGaN/GaN multiple quantum well (MQW), a 120-nm-thick Mg-doped p-AlGaN electron blocking layer, and a 110-nm-thick Mg-doped p-GaN cladding layer. Figure 1(a) is a schematic diagram for our III–nitride ultrathin FTLEDs with PhC structures. The details of the wafer bonded and laser lift-off (LLO) processing from III–nitride FTLEDs were described as the same in ref. 5, where bonded metal using Cr/Pt/Au (30/40/2000 nm). Then the sapphire-removed samples were dipped into HCl solution to remove the residual Ga on the undoped GaN. Figure 2 is the detailed process flow schematic diagram for PhC fabrication. Step 1: the resulting structure was thinned down by chemical-mechanical polishing (CMP) to obtain the GaN cavity thickness about 0.6 μm (∼3λ). Next the chemical particle residue was removed with an oxygen reactive ion etch (RIE); this process was found *not* to affect the current spreading over n-GaN layer.[4)] Step 2: in order to fabricate PhC on the n-GaN surface of ultra-thin FTLEDs, we first deposited a 200-nm-thick layer of SiN to serve as a hard mask on the n-GaN by plasma-enhanced chemical

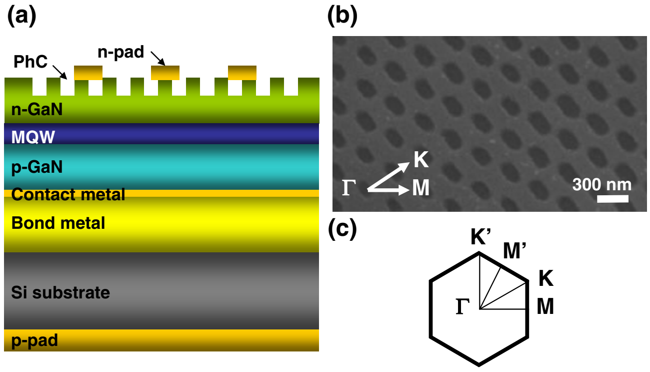

Fig. 1. (Color online) (a) Schematic diagram of III–nitride PhC ultrathin FTLED structures. (b) Top-view SEM image of triangular PhC lattice with the ellipse holes and the lattice constant $a = 310$ nm. (c) The first Brillouin zone with the symmetry points indicated.

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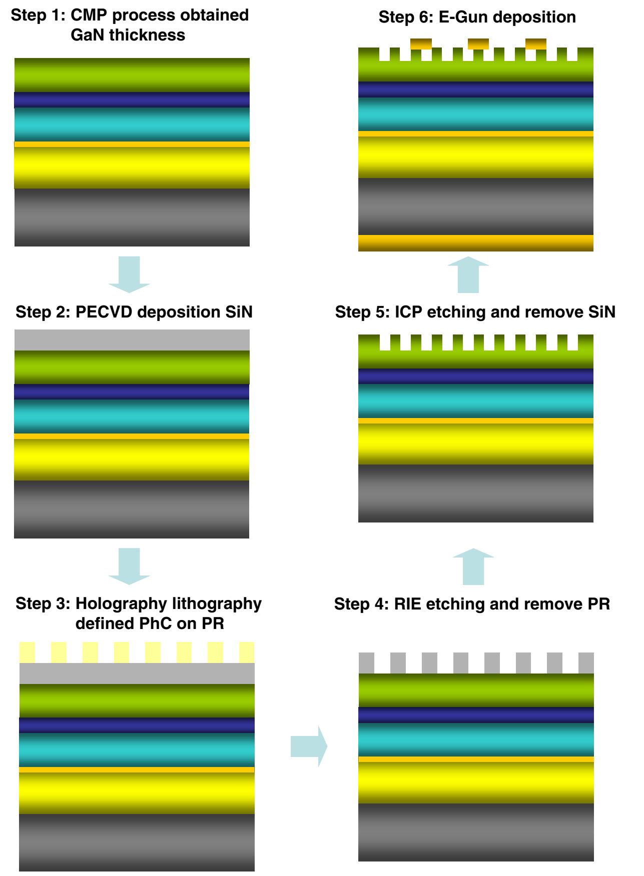

Fig. 2. (Color online) Schematic diagram of process flow for PhC fabrication on III–nitride ultrathin FTLED structures.

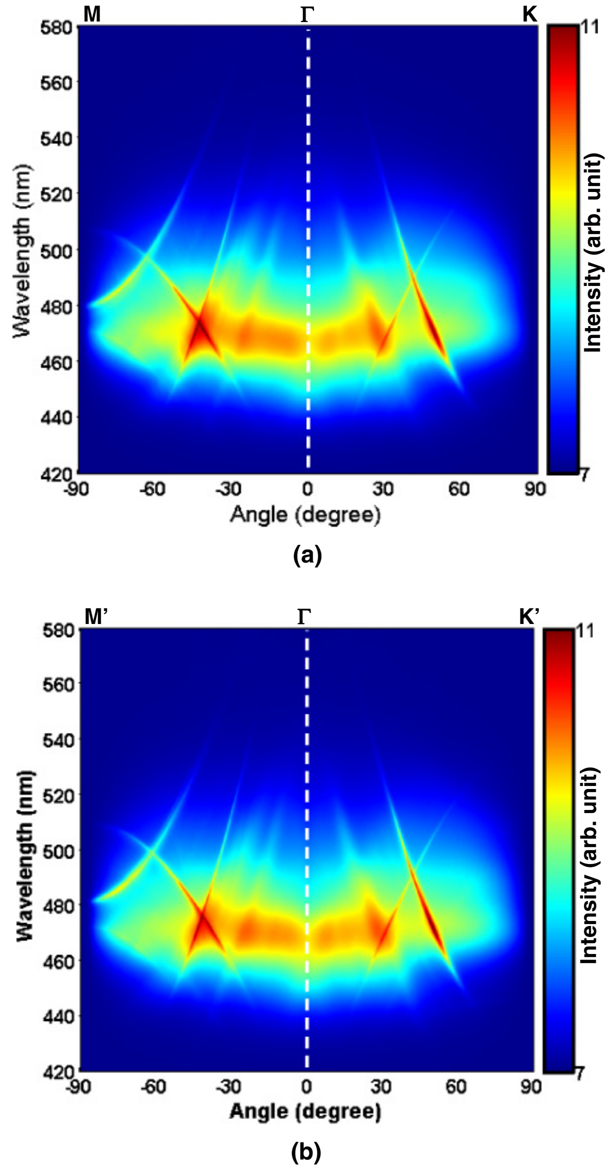

Fig. 3. (Color online) Angular-resolved EL measurement of III–nitride PhC ultrathin FTLED with (a) Γ–M (left) and Γ–K (right) directions; (b) Γ–M′ (left) and Γ–K′ (right) directions.

vapor deposition (PECVD). Step 3: the PhC with the ellipse holes of triangular lattice was defined by holography lithography on the photo-resistance (PR). Step 4: then use RIE to transfer PhC pattern on hard mask.[6] Step 5: holes were then etched into the top n-GaN surface using inductively coupled plasma (ICP) dry etching to obtain a depth $t = 100$ nm. The lattice constant of PhC was chosen to be 310 nm in order to obtain the divergent far-filed pattern. Step 6: a patterned Ti/Pt/Au (50/50/2000 nm) electrode were deposited on n-GaN as the n-type contact layer and Ti/Pt/Au (50/50/200 nm) metal was also deposited on Si substrate backside as an anode. After fabrication, the dies were mounted on transistor outline (TO) package with encapsulant-free. The top-view of scanning electron microscopy (SEM) image of triangular PhC lattice with ellipse holes on III–nitride ultrathin PhC FTLEDs is shown in Fig. 1(b).

3. Results and Discussion

After sample preparation, we performed electroluminescence (EL) measurement by injecting a continuous current into the devices at room temperature. First, the guided mode extraction behavior was analyzed from the III–nitride PhC ultrathin FTLEDs. A continuous current of 50 mA injected into the TO mounted device at room temperature. The angular-resolved experiment setup was described as the same in ref. 7. Figures 3(a) and 3(b) shows the angular-resolved spectra of the PhC ultrathin FTLED, in which light was collected along with the Γ–M, Γ–K, Γ–M′, and Γ–K′ directions due to the triangular PhC lattice with ellipse holes. We observed the angular-resolved spectra in the Figs. 3(a) and 3(b) that are *not* different. Further, the angular-resolved spectra was be transformed into the guided mode dispersion curves, as shown in Fig. 4(a). The image showed the normalized dispersion curves for each mode in the Γ–M and Γ–K directions. Due to the shallow etching of the present sample that result in a negligible narrow bandgap, the observed dispersion in this study was in good agreement with the calculated 2D free-photon band structure. The 2D free-photon band structure was calculated for transverse electric (TE) modes that the present MQW structure generates TE-polarized light propagating in the waveguide plane due to the valence band mixing of the QW emission.[8] We accurately fit the lower-order guided modes with the 2D free photon band structure using the effective refractive index $n_{\mathrm{eff}} = 2.42$ and 2.20, only two guided modes from our samples were seen, as shown in Fig. 4(a). The agreement between the experiment and calculation are good. Addition-

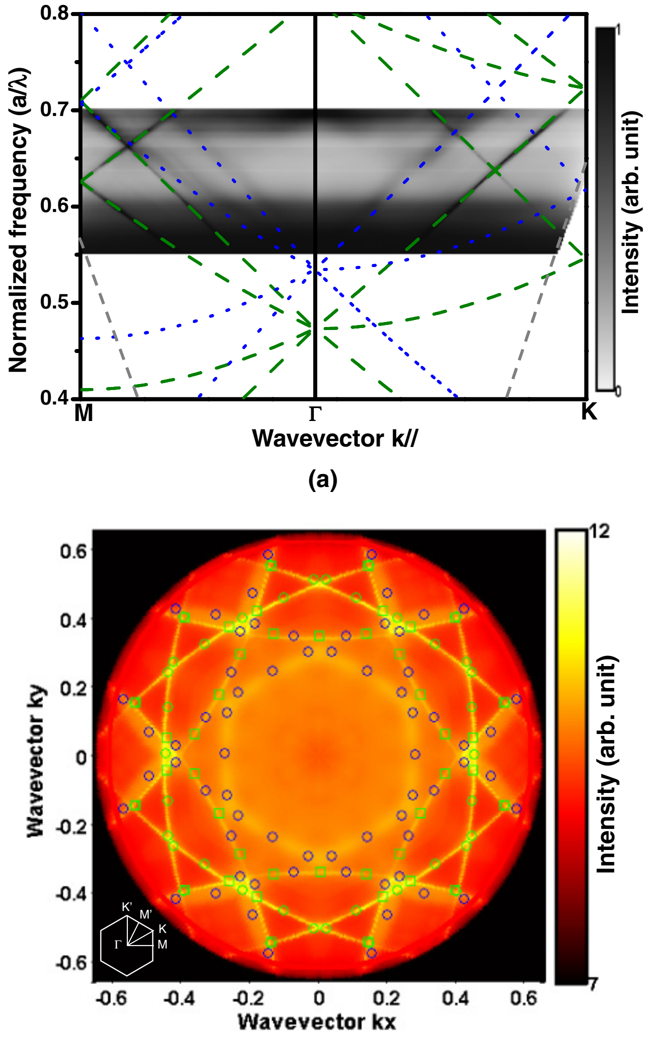

Fig. 4. (Color online) (a) Mode dispersion curves for $a = 310$ nm determined from the data shown in Fig. 2(a) and compared with the 2D free photon band diagram. The superimposed lines were the free photon band diagram that calculated with effective refractive index $n_{eff} = 2.44$ (green dashed lines) and 2.20 (blue dashed lines) for the TE modes. The air lines are shown in gray dashed lines. (b) The map are the intensity of the extracted light at a fixed wavelength $\lambda = 470$ nm around the azimuthal direction with 1° resolution. Inset: the tittles shown Bragg's diffraction theory fitting with $n_{eff} = 2.44$ (green) and 2.20 (blue), where circles (◯) of Γ–M direction and squares (□) of Γ–K direction.

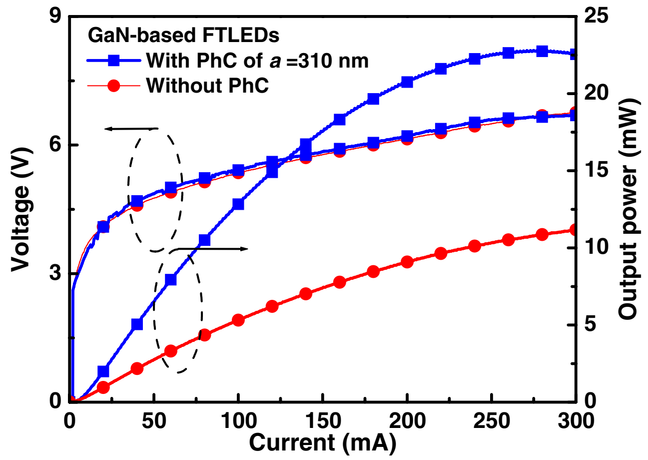

Fig. 5. (Color online) *L–I–V* curves characteristics of III–nitride ultra-thin FTLEDs with and without PhC structures.

ally, the extracted guided mode corresponding with the band diagram apart from Γ shows the light divergent far-field profile; in contrast, directional collimated far-field patterns in ref. 4 have been discussed. However, there exits five guided modes in the 3λ GaN cavity, the rest of guided modes were not observed from our sample except two extracted guided mode of $n_{eff} = 2.42$ and 2.20. This might be caused from the ellipse holes of triangular PhC lattice. In addition, the hole shapes only affect the extracted guided mode number but diffracted guided mode dispersion relation still approaches the free-photon band structure on GaN PhC ultrathin FTLEDs. This part will be discussed careful on elsewhere.

Next, in order to examine the azimuthal anisotropy of the far-field distribution, the angular-resolved spectra of the out-coupled modes are measured as a function of the azimuthal angles with the sample rotated around the axis perpendicular to the sample surface with 1 degree resolution. Figure 4(b) plot the far-field distribution monochromatically in the azimuthal direction at a fixed wavelength of 470 nm. The angular-resolved spectra of different azimuthal angles showed the extraction guided modes evolution of the collinearly and non-collinearly guided modes coupled.[9] For example, as the sample rotates around the vertical axis from the Γ–M direction, the alignment of the propagation direction to the $G_{\Gamma M}$ wavevector was changing from collinear to non-collinear guided modes. Additionally, different guided mode with different index will trace out an arc with the radius corresponding to the respective waveguide circle, which were well fitting by Ewald's construction of Bragg's diffraction theory with effective refractive index $n_{eff} = 2.44$ and 2.20.[10] The two lower-order guided modes extracted by triangular PhC lattice are shown in Fig. 4(b). Therefore, according to the free photon band structure could be design to obtain the more divergent far-field patterns.

The intensity–current–voltage (*L–I–V*) curves characteristics of III–nitride ultrathin FTLEDs with and without PhC structures were measured by using an integration sphere with Si photodiode, as shown in Fig. 5. The turn on voltage was around 3 V. At a driving current of 200 mA, the forward voltage (V_f) of the III–nitride FTLEDs with and without PhC were 6.12 and 6.11 V, respectively. The high V_f could attribute to high series resistance in such thin PhC device. Additionally, it is clearly observed that the III–nitride PhC FTLEDs shown about 130% output power enhancement compared to the non-PhC FTLEDs at a driving current of 200 mA.

To further investigate the angular distribution radiation patterns from the PhC ultrathin FTLEDs and non-PhC ultrathin FTLEDs at a driving current of 50 mA. In PhC FTLEDs, the far-field distribution will be significantly modified by the triangular PhC lattice with ellipse holes diffraction behavior in PhC ultrathin FTLEDs. Due to the waveguided light traveling in the plane will be diffracted by the reciprocal wave vectors associated with the PhC.[11] The PhC ultra-thin FTLEDs show higher extraction efficiency with the divergence angle in the Γ–M (red line) and Γ–K

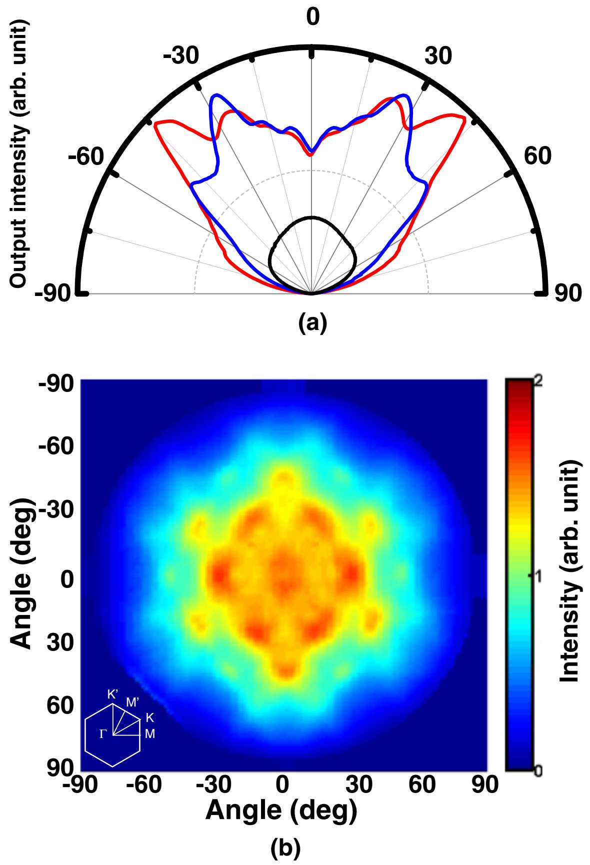

Fig. 6. (Color online) (a) Radiation patterns of III–nitride ultrathin FTLEDs with PhC (red and blue lines) and without PhC (black line). The red line is the Γ–M direction and the blue line is the Γ–K direction. (b) Top-view 3D far-field patterns of GaN-based FTLEDs with triangular PhC lattice.

(blue line) directions of triangular PhC lattice, as shown in Fig. 6(a). The measured far-field pattern of non-PhC FTLED was nearly Lambertian (black line). Furthermore, the three-dimensional (3D) far-field pattern from the PhC FTLED was also measured as shown in Fig. 6(b) which reveals the PhC diffraction patterns with six-fold symmetry due to triangular PhC lattice.

4. Conclusions

In conclusion, III–nitride ultrathin film-transferred LEDs incorporated with PhC structue were fabricated and investigated. Angle-resolved measurement revealed the PhC diffraction effect from the III–nitride ultrathin FTLEDs based on the Bragg's diffraction and 2D free photon band structure, and could lead to much stronger extraction enhancement and directional far-field pattern, e.g., divergent patterns. The III–nitride PhC ultrathin FTLEDs exhibited about 130% output power enhancement compared to that of non-PhC FTLEDs at a driving current 200 mA. This could lead to promising LEDs with unusual divergent far-field properties for specific applications such as in down light of general lighting, automatic headlight, and LCD backlight.

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