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Divergent Far-Field Pattern from GaN-Based Film-Transferred Photonic Crystal Light-Emitting Diodes

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1. Introduction

For the application of next-generation LEDs, further improvements of the light extraction efficiency and the far-field patterns are required [1]. Directional and divergent far-field pattern of the light sources are important for many applications in projector displays, backlight displays, and automobile headlights. Approaches based on the photonic crystal (PhC) have attracted much attention to achieve light extraction enhancement, and directional patterns from GaN film-transferred (FT) LEDs [2-3]. Nevertheless, a blue emitting GaN PhC FTLEDs with divergent far-field pattern of light extraction has not been studied in details.

In this paper, experimental and theoretical studies on the divergent far-field from the directional light extraction in GaN PhC FTLEDs have been addressed. Angular-resolved measurement in the Γ-M and Γ-K directions was revealed guided modes extraction behavior based on Bragg's diffraction. GaN PC FTLEDs based on free photon band structure exhibit the corresponding divergent profiles in the far-field pattern. In addition, angular-resolved spectra have been mapped monochromatically to demonstrate the azimuthal evolution of the guided modes' diffraction behavior. Furthermore, the light output efficiency of PhC FTLEDs was significantly higher than that of non-PhC FTLEDs.

2. Experiment

The schematic diagram for the structure of GaN FTLED associated PhC was shown in Fig. 1(a). The GaN-based blue LED wafer consists of a 30-nm-thick GaN nucleation layer, a 4 μm thick un-doped GaN buffer layer, a 3 μm thick Si-doped n-GaN layer, a 120 nm InGaN/GaN multiple quantum well (MQW) active region, a 20-nm-thick Mg-doped p-AlGaN electron blocking layer, a 0.3 μm thick Mg-doped p-GaN contact layer. The detailed wafer processing of GaN FTLEDs associated PhC is the same as in Ref. 4, using the laser lift-off technique to remove the sapphire substrate. Then the sapphire-removed samples were dipped into HCl solution to remove the residual Ga on the un-GaN. The resulting structure was then thinned down by chemical-mechanical polishing to obtain the GaN cavity thickness about 1.23 μm. In order to fabricate PhC on the n-GaN surface, we first deposited a 200-nm-thick layer of SiN to serve as a hard mask on the n-GaN by plasma-enhanced chemical vapour deposition (PECVD). The PhC with a triangular lattice of ellipse holes was then defined by holography lithography on the hard mask. Holes were then etched into the top n-GaN surface using inductively coupled plasma (ICP) dry etching to a depth t = 150 nm. The lattice constant of PhC was to be 310 nm. The top view of the scanning electron microscopy (SEM) image of the PhC was shown in Fig. 1(b). Finally, a patterned Cr/Pt/Au (20/30/1400 nm) electrode were deposited on n-GaN as the n-type contact layer and Cr/Au (50/1400 nm) metal was deposited on Si substrate backside. After fabrication, the dies were mounted on transistor outline (TO) package with encapsulant-free.

After sample preparation, we performed electroluminescence (EL) measurement by injecting a continuous current into the devices at room temperature. We first measured the angular distribution radiation patterns of the light output from a GaN PhC FTLEDs and GaN non-PhC FTLEDs at a driving current of 50 mA, as shown in Fig. 2. The GaN PhC FTLEDs show higher extraction efficiency with the divergence angle in the Γ-M and Γ-K directions. The measured far-field pattern of non-PhC FTLED was nearly Lambertian. In addition, the three-dimensional (3D) far-field pattern from the GaN PhC FTLED was shown in Fig. 2(b) which reveals the PhC diffraction patterns with six-fold symmetry due to triangular lattice. Additionally, the intensity-current-voltage (L-I-V) characteristics were measured by using an integration sphere with Si photodiode that the GaN PhC FTLEDs shows output power enhancement by 140% at a driving current of 150 mA, when compared to the GaN non-PhC FTLEDs. The turn on voltage was around 3V.

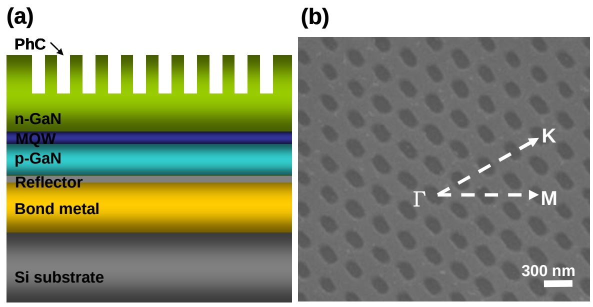

Fig. 1 (a) Schematic diagram of GaN PhC FTLED structures. (b) Top-view SEM image of triangular lattice PhC with the lattice constant a =310 nm.

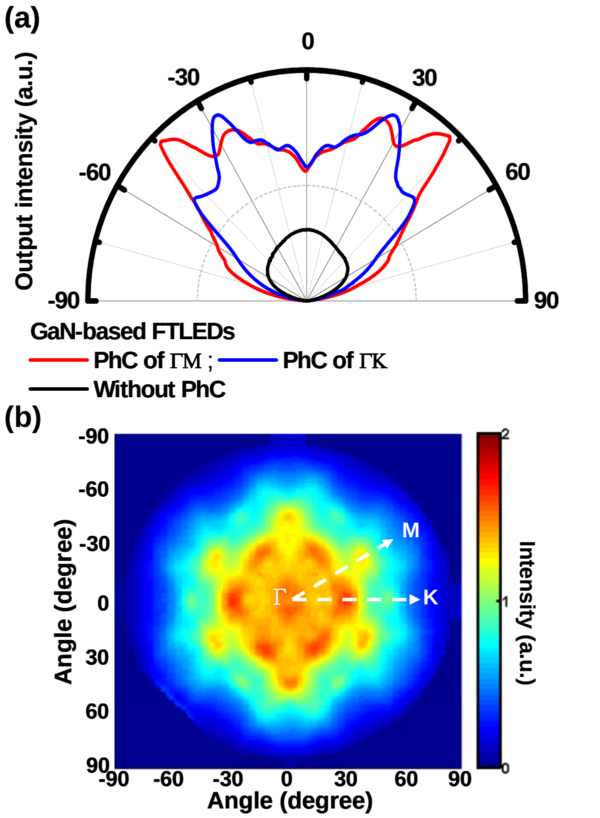

Fig. 2 (a) Radiation patterns of the GaN PhC FTLED and GaN FTLED without PhC. The device without PhC has a near Lambertian radiation pattern while that GaN PhC FTLEDs was heavily modified. (b) Top-view 3D far-field patterns of the GaN PhC FTLED with the triangular lattice.

Figure 3 shows the angle-resolved spectra of the GaN PhC FTLED, for which light was collected along the with Γ-M and Γ-K directions of the triangular lattice [5]. The additional sharp emission lines observed for the GaN PhC FTLED resulted from the coupling of guided modes to PhC modes above the light line of air. Numerous guided modes were supported in the GaN layer according to its thickness, and their diffraction angle varies with wavelength based on free photon band structures [3]. The PhC extraction of guided modes as a result of the presence was clearly observed as shown in Fig. 3(a). The azimuthal anisotropy of the far-field distribution is measured as a function of the azimuthal angles by using the angular-resolved setup. Fig. 3(b) plot the far-field distribution monochromatically in the azimuthal direction at a fixed wavelength of λ = 470 nm. 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 with effective refractive index n_{eff} = [2.44, 2.20]. The two lower guided mode extracted by triangular lattice PhC were shown in Fig. 3(b). According to the free photon band structure could be obtain the more divergent far-field patterns.

3. Conclusions

In summary, GaN-based PhC FTLEDs were fabricated and studied. Angle-resolved measurement

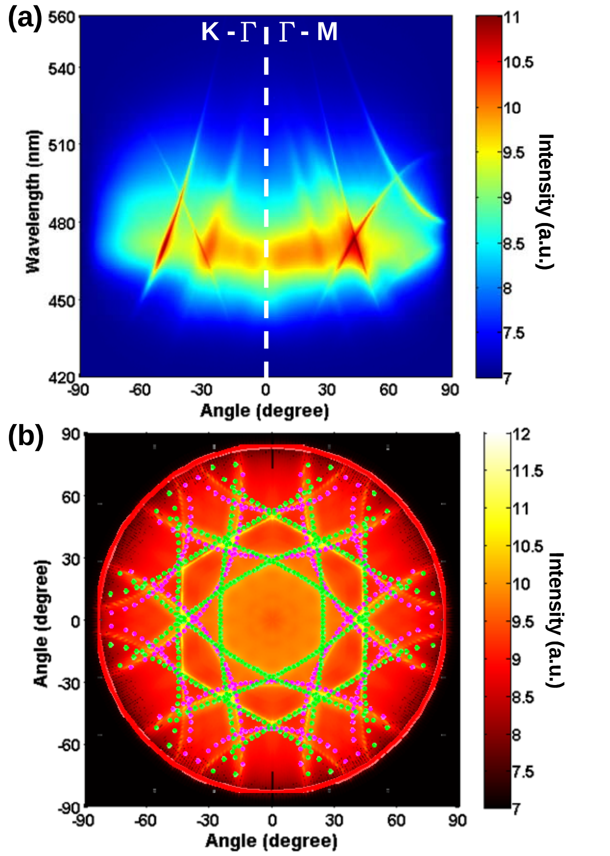

Fig. 3 (a) Angle-resolved EL measurement of the GaN PhC FTLED with Γ-K (left) and Γ-M (right) directions. (b) The map of intensity of the extracted light at a fixed wavelength λ = 470 nm. Inset: the tittles show Bragg's diffraction theory fitting.

revealed a strong PhC effect in the GaN FTLEDs, and could lead to much stronger extraction enhancement and directional far-field pattern, e.g. divergent patterns. This could lead to promising LEDs with unusual divergent far-field properties for specific applications.

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