GaN Thickness Effect on Directional Light Enhancement from GaN-Based Film-Transferred Photonic Crystal Light-Emitting Diodes

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GaN Thickness Effect on Directional Light Enhancement from GaN-Based Film-Transferred Photonic Crystal Light-Emitting Diodes

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Directional light enhancement behavior including collimated far-field patterns sensitively depending on both photonic crystal (PhC) lattice constant and GaN thickness from GaN film-transferred light-emitting diodes (FTLEDs) with a triangular PhC lattice has been experimentally studied. Far-field pattern measurement in the Γ–M and Γ–K directions of GaN PhC FTLEDs with various lattice constants and GaN thicknesses revealed different far-field profiles as detemined on the basis of guided mode extraction of Bragg's diffraction. Additionally, three-dimensional (3D) far-field measurement revealing the PhC diffraction patterns was also demonstrated. We also used the 3D finite-different time-domain method to confirm the experimental results.

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1. Introduction

Light-emitting diodes (LEDs) have been a promising candidate for general solid-state lighting because of their being small, energy saving feature, and long lifespan. LEDs of solid-state lighting will replace conventional lighting sources within years. Recently, high brightness GaN-based LEDs have already been extensively used in projector displays, liquid crystal display (LCD) backlight, and automotive lighting.[1)] The use of photonic crystals (PhCs) to improve the light extraction and directional far-field patterns from GaN LEDs and GaN film-transferred LEDs (FTLEDs) has been investigated.[2–9)] According to Bragg's diffraction theory and the free-photon band structure, PhCs can diffract guided light into the air cone from the waveguide structure of FTLEDs leading to the formation of collimated far-field patterns.[10)] However, directional far-field patterns and light enhancement depending on GaN thickness from GaN-based PhC FTLEDs have not been studied in detail.

In this paper, the directional far-field and light enhancement sensitively depending on both the PhC lattice constant and GaN thickness of GaN PhC FTLEDs have been studied. Far-field pattern measurement in the Γ–M and Γ–K directions of a triangular PhC lattice on GaN FTLEDs revealed different far-field profiles as determined on the basis of the guided mode extraction of Bragg's diffraction. Additionally, a three-dimensional (3D) far-field measurement revealed PhC diffraction patterns. Finally, the 3D finite-different time-domain (FDTD) method was also used to discuss the experimental light enhancement behavior.

2. Experimental Methods

A blue LED wafer consists of a 30-nm-thick GaN nucleation layer, a 2-μm-thick undoped 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, and a 0.3-μm-thick Mg-doped p-GaN contact layer. The detailed wafer processing of GaN PhC FTLEDs is the same as that described in ref. 11, using the laser lift-off technique to remove the sapphire substrate. Then, the sapphire-removed samples were dipped into HCl solution to remove residual Ga on the undoped GaN. The resulting structure was then thinned by chemical–mechanical polishing (CMP) to obtain different GaN cavity thicknesses of about 1.0, 1.5, and 2.0 μm. Next, 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 n-GaN by plasma-enhanced chemical vapour deposition (PECVD). The PhC with the ellipse holes of a triangular lattice was then defined by holography lithography on the hard mask.[12)] According to the 2D free-photon band structures, two PhC lattice constants a of 380 and 450 nm have been chosen for collimated far-field patterns.[10,13)] Holes were then etched into the top n-GaN surface using inductively coupled plasma (ICP) dry etching to a depth $t = 150$ nm. The top views of scanning electron microscopy (SEM) images of the PhC are shown in Figs. 1(b) and 1(c). Finally, a patterned Ti/Pt/Au (50/50/2000 nm) electrode was deposited on n-GaN as the n-type contact layer, and Ti/Pt/Au (50/50/2000 nm) metal was deposited on the Si substrate back surface. After fabrication, the dies were mounted on the transistor outline (TO) package. A schematic diagram of the structure of GaN PhC FTLED is shown in Fig. 1(a).

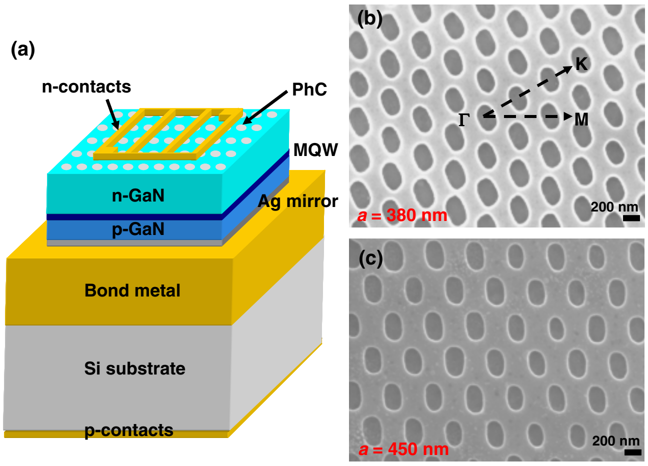

Fig. 1. (Color online) (a) Schematic diagram of GaN PhC FTLED structures. Top-view SEM image of triangular lattice PhC with the lattice constants (b) $a = 380$ nm and (c) $a = 450$ nm.

3. Results and Discussion

After the sample preparation, we performed electrolumines-

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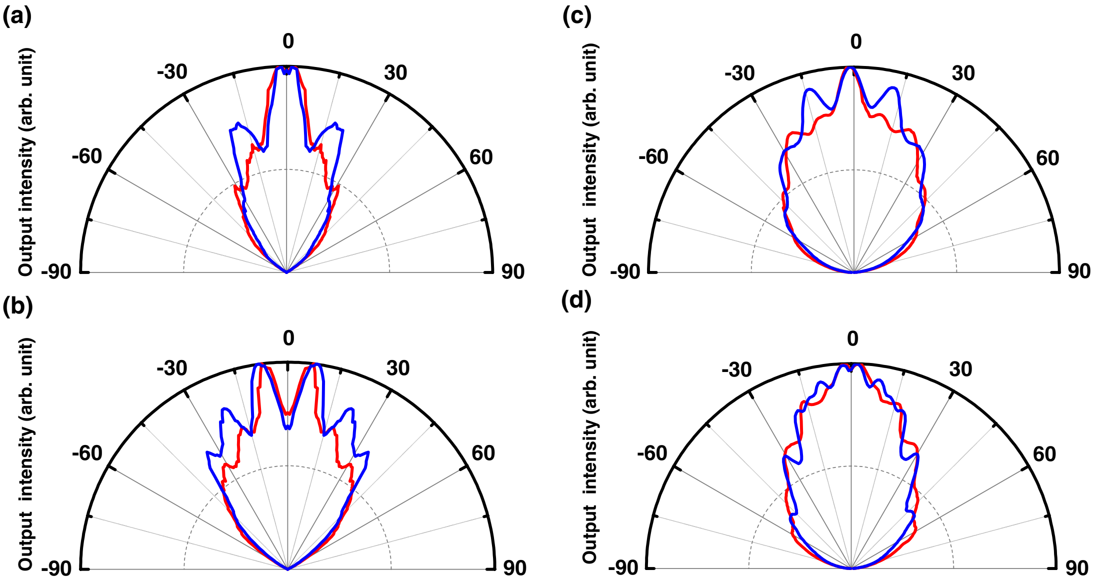

Fig. 2. (Color online) Far-field patterns of the GaN PhC FTLED: GaN thicknesses of (a) 1.0 μm and (b) 1.5 μm with the same PhC lattice constant $a = 380$ nm of PhC; GaN thicknesses of (c) 1.0 μm and (d) 2.0 μm with PhC lattice constant $a = 450$ nm. The red line indicates the Γ–M direction and the blue line indicates the Γ–K direction.

cence (EL) measurement by injecting a continuous current into the devices at room temperature. We first measured the angular distributive far-field patterns for different lattice constants and GaN thicknesses of GaN PhC FTLEDs at a driving current of 200 mA, as shown in Fig. 2. The GaN PhC FTLEDs have different directional far-field patterns owing to PhC diffraction of numerous guided modes propagating through the GaN waveguide with various GaN thicknesses in the Γ–M and Γ–K directions of the triangular PhC lattice. In addition, the triangular PhC lattice with ellipse holes will reduce the number of extracted guided modes. Therefore, the hole shape only affects the extracted guided mode number, but the diffracted guided mode dispersion relation still approaches the free-photon band structure on GaN PhC FTLEDs. This issus will be discussed in detail elsewhere. Figures 2(a) and 2(b) show the far-field patterns for GaN thicknesses of 1.0 and 1.5 μm, respectively, for the same PhC lattice constant $a = 380$ nm. Figure 2(a) shows fewer peaks of the far-field pattern with decreasing GaN thickness, which supports fewer guided modes. Similarly, Figs. 2(c) and 2(d) show the same phenomena for the GaN thicknesses of 1.0 and 2.0 μm with the PhC lattice constant $a = 450$ nm. Furthermore, the measured far-field pattern of GaN non-PhC FTLED was nearly Lambertian.

The 3D far-field patterns for different lattice constants and GaN thicknesses of GaN PhC FTLED are also been shown in Figs. 3(a)–3(d), which show the PhC diffraction patterns with six fold symmetry due to the triangular lattice.14) The light enhancement for the PhC FTLEDs compared with the non-PhC FTLEDs at a driving current of 200 mA is shown in Fig. 4(a), in which the light enhancement is defined by the ratio of total radiated power of PhC LED to that of non-PhC LED, and the power was measured using an integration sphere with a Si photodiode. The light enhancement strongly depended on the lattice constant and GaN thickness of GaN PhC FTLEDs. For theoretical confirmation, the 3D FDTD method using a perfectly matched layer (PML) is used to calculate the output light extraction efficiency of the LEDs.15) Extraction efficiency is defined as the fraction of emitted flux through the top surfaces of the PhC with respect to the total emitted flux. The isotropic dipole is located at the center of the MQW to fit in with GaN PhC FTLED structure. The light extraction enhancement is then defined as the ratio of the light extraction efficiency of PhC FTLEDs divided by that of non-PhC FTLEDs. The calculated enhancement factor of extraction efficiency is plotted as a function of GaN thicknesses in Fig. 4(b). The extraction efficiencies are relatively large at larger a GaN thicknesses which is

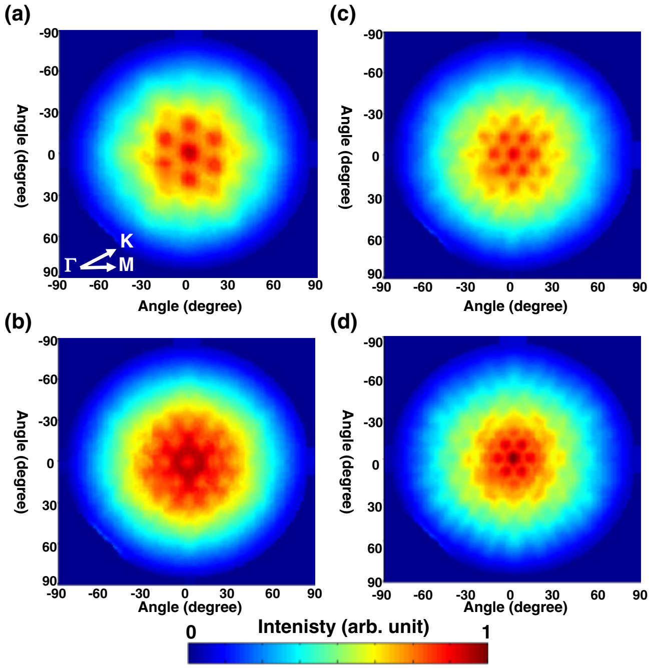

Fig. 3. (Color online) Top-view 3D far-field patterns of the GaN PhC FTLED: GaN thicknesses of (a) 1.0 μm and (b) 1.5 μm with PhC lattice constant $a = 380$ nm; GaN thicknesses of (c) 1.0 μm and (d) 2.0 μm with PhC lattice constant $a = 450$ nm.

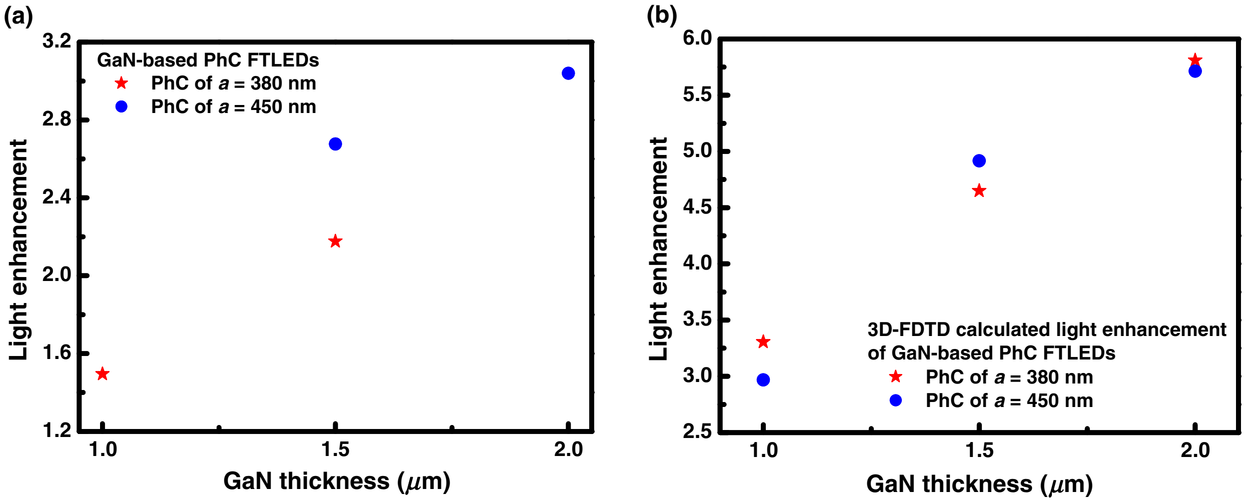

Fig. 4. (Color online) (a) Light enhancement summary for the devices. (b) The 3D FDTD method for calculating the various lattice constants and GaN thicknesses of GaN PhC FTLED for mapping the light extraction enhancement.

consistent with our experimental results. In addition, the light extraction enhancement also depends on the lattice constant of PhCs. Therefore, the lattice constant of PhCs and the GaN thickness of FTLEDs are the predominant factors contributing to light extraction. Nevertheless, when considering collimated far-field patterns, GaN ultrathin PhC FTLEDs will have more collimated far-field patterns.

4. Conclusions

In summary, GaN-based PhC FTLEDs with different lattice constants and GaN thicknesses were fabricated and studied. The obtained radiation far-field patterns showed sensitive dependence on the GaN thickness of GaN PhC FTLEDs. 3D far-field patterns revealed the different diffraction patterns and anisotropic light extraction from the GaN PhC FTLEDs. Furthermore, the light extraction enhancement was dependent on lattice constant and GaN thickness of PhC FTLEDs. Collimated PhC FTLEDs are a promising candidate for étendue-limited applications, such as projection displays.

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