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Directional Far-Field Patterns and Light Enhancement Depending on GaN Thickness from GaN Film-Transferred Photonic Crystal Light-Emitting Diodes

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1. Introduction

Recently, high brightness GaN-based LEDs have already been extensively used in projector displays, LCD backlight, and automotive lighting. Exploiting the photonic crystals (PhCs) to improve the light extraction and directional far-field patterns from GaN film-transferred LEDs (FTLEDs) have been addressed [1]. According to Bragg's diffraction theory and free-photon band structure, PhCs can diffract guided light into the air cone from the waveguide structure of FTLEDs that leading to collimated far-field patterns [2]. However, directional far-field patterns depending on GaN thickness from the GaN-based PhC FTLEDs has not been studied in details.

In this paper, experimental observation on the directional far-field and light enhancement depending sensitively on lattice constant and GaN thickness of GaN PhC FTLEDs has been studied. Far-field patterns measurement in the Γ-M and Γ-K directions of GaN PhC FTLEDs were revealed different far-field profiles based on guided mode extraction of Bragg's diffraction and free photon band structures. Additionally, three-dimensional (3D) far-field measurement reveals the PhC diffraction patterns.

2. Experiment

The 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. After the epitaxial wafer bonding was removed the sapphire substrate with the laser lift-off technique [3]. The resulting structure was then thinned down by chemical-mechanical polishing to obtain the different GaN cavity thickness about 1.0, 1.5, and 2.0 μm. Next, 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. According to the free photon band structures have chosen in Γ_1 and Γ_2 points which can lead to collimation far-field patterns [2], as shown in Fig. 1(d). Therefore, the two lattice constant *a* of PhC have been chosen around 380 and 450 nm, respectively. 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 view of the scanning electron microscopy (SEM) image of the PhC was shown in Fig. 1(b) and 1(c). 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. The schematic diagram for the structure of GaN FTLED associated PhC was shown in Fig. 1(a).

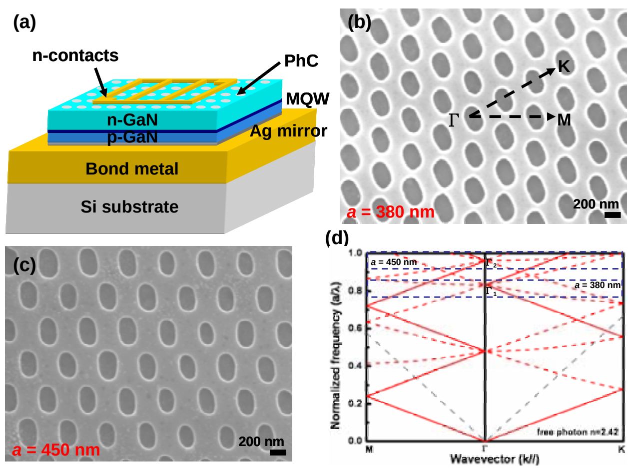

Fig. 1 (a) Schematic diagram of GaN PhC FTLED structures. Top-view SEM image of triangular lattice PhC with the lattice constant (b) *a* = 380 nm and (c) *a* = 450 nm. (d) The complete free photon band structure studied in present work surrounded by the box shown. The thick lines indicate the collinear coupled band. The dash lines indicated the non-collinear coupled bands.

After the sample preparation, we performed electroluminescence (EL) measurement by injecting a continuous current into the devices at room temperature. We first measured the angular distributive far-field patterns from the different lattice constant and GaN thickness of GaN PhC FTLEDs at a driving current of 200 mA, as shown in Fig. 2. The GaN PhC FTLEDs have the different directional far-field patterns, respectively, from the different lattice constant based on numerous guided mode extraction of free photon band structure position in the Γ-M and Γ-K directions. Fig. 2(a), (b) show far fields for GaN thicknesses of 1.0μm and 1.5μm respectively in the same PhC lattice constant a = 380 nm. Fig.2 (a) has a fewer peaks of the far-field pattern according to the thinner GaN thickness which supports a fewer guided modes. Similarly, Fig. 2(c), (d) reveal the same phenomena for the thicknesses of 1.0μm and 2.0μm and PhC lattice constant a = 450 nm. The measured far-field pattern of GaN non-PhC FTLED was nearly Lambertian.

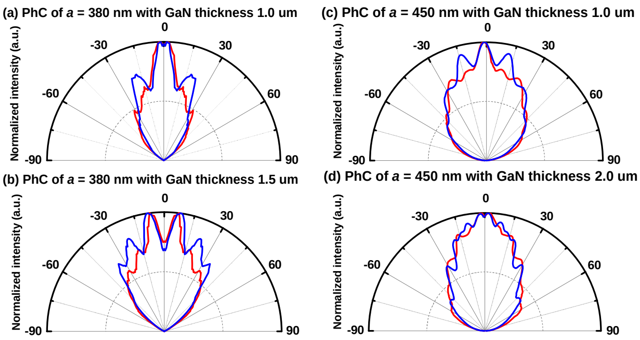

Fig. 2 Far-field patterns of the GaN PhC FTLED: GaN thickness of (a) 1.0 um and (b) 1.5 um with the same PhC lattice constant a = 380 nm of PhC, respectively; GaN thickness of (c) 1.0 um and (d) 2.0 um with PhC lattice constant a = 450 nm, respectively. Red line stands for the ΓM direction and blue line is for the ΓK direction.

In addition, the 3D far-field pattern from the different lattice constant and GaN thickness of GaN PhC FTLED were also been shown in Fig. 3 which reveals the PhC diffraction patterns with six-fold symmetry due to triangular lattice [4]. The light enhancement for the PhC FTLEDs compared to non-PhC FTLEDs at a driving current of 200 mA can be charted in Fig. 4 in which the light enhancement is defined by the ratio of total radiated power of PhC LED to non-PhC LED, and the power was

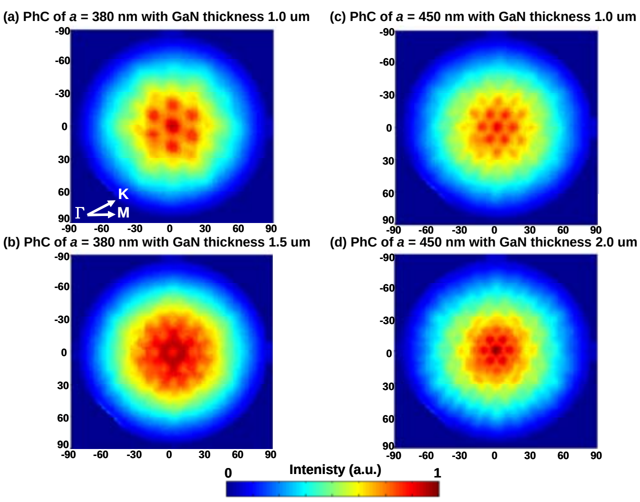

Fig. 3 Top-view 3D far-field patterns of the GaN PhC FTLED: GaN thickness of (a) 1.0 um and (b) 1.5 um with PhC lattice constant a = 380 nm, respectively; GaN thickness of (c) 1.0 um and (d) 2.0 um with PhC lattice constant a = 450 nm, respectively.

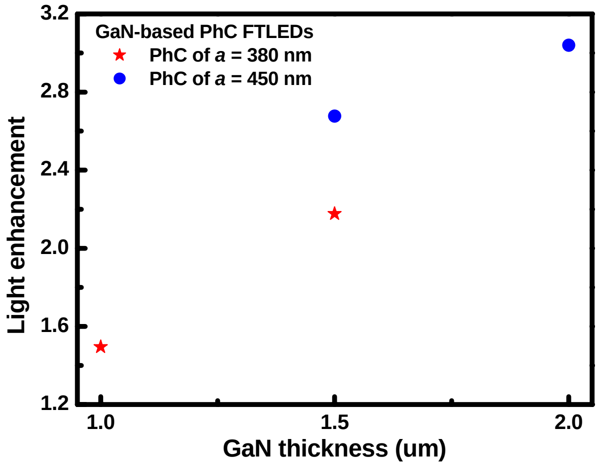

Fig. 4 Light enhancement summary for the devices

measured by using an integration sphere with Si photodiode. The light enhancement strongly depending on the lattice constant and GaN thickness of GaN PhC FTLEDs were obtained. In this case, the measured output power was low in thinner GaN thickness due to the non-optimized chip designs including pad design which may suffer current crowding at high current, chip surface treatment which may cause high series resistance. Therefore, when consideration the chip and pad design, we believe the ultra-thin GaN PhC FTLEDs which will have high extraction efficiency and more collimation far-field pattern.

3. Conclusions

In summary, GaN-based PhC FTLEDs with different lattice constant and GaN thickness were fabricated and studied. Radiation far-field patterns revealed sensitive dependent on the different GaN thickness of GaN PhC FTLEDs. 3D far-field patterns revealed the different diffraction pattern and anisotropy light extraction from the GaN PhC FTLEDs. Further, the light enhancement was dependent on lattice constant and GaN thickness of PhC FTLEDs. The collimated PhC FTLEDs is a promising candidate for etendue-limited applications, such as projecting display.

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