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Optimized Micro-Cavity and Photonic Crystal in GaN-based Thin-Film Light-Emitting Diodes for Highly Directional Beam Profiles

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1. Introduction

Recently, high brightness GaN-based thin-film LEDs (TFLEDs) have been extensively used in projector displays, LCD backlight, and automotive lighting. However, the light extraction efficiency and far-field emission distribution requires further improvement. Exploiting the photonic crystals (PhCs) to improve the light extraction and directional far-field patterns from GaN TFLEDs have been addressed [1-2]. 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 TFLEDs that leading to collimated far-field patterns [2]. However, highly directional far-field emission patterns depending on optimized parameters of GaN PhC ultrathin TFLEDs (uTFLEDs) have not been studied in details.

In this paper, highly directional far-field emission distribution of GaN PhC uTFLED has been experimentally studied. Angular-spectra-resolved electroluminescence (EL) measurement revealed various directional far-field patterns depending on PhC lattice constant based on guided modes extraction of Bragg's diffraction. Furthermore, three-dimensional (3D) far-field measurement reveals the PhC diffraction patterns of GaN PhC uTFLED. The absolute light output power characteristics show the higher directional light extraction enhancement ~3.78x from GaN PhC uTFLEDs compared to GaN non-PhC uTFLEDs.

2. Experiment

The blue LED wafer consists of a 30-nm-thick GaN nucleation layer, a 2-µm-thick un-doped GaN buffer layer, a 2.5-µm-thick Si-doped n-GaN layer, a 120 nm InGaN/GaN multiple quantum well (MQW) active region (dominant wavelength λ_0 = 455 nm), a 20-nm-thick Mg-doped p-AlGaN electron blocking layer, a 125 nm-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 (CMP) to obtain the GaN cavity thickness T about 550 nm (~ 3λ). 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 square lattice of circle holes was then defined by holography lithography on the hard mask. According to the free-photon band structures have chosen in Γ point which can lead to collimation far-field patterns [2]. Therefore, the PhC lattice constant a of PhC have been chosen around 270, 370, and 420 nm, respectively, as shown in Fig. 1. Holes were then etched into the top n-GaN surface using inductively coupled plasma (ICP) dry etching to a depth t = 200 nm. The top view of the scanning electron microscopy (SEM) image of the PhC was shown in Fig. 1. Finally, a patterned Cr/Au (50/5000 nm) electrode were deposited on n-GaN as the n-type contact layer and Cr/Au (5/1000 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 uTFLED associated PhC was shown in Fig. 1.

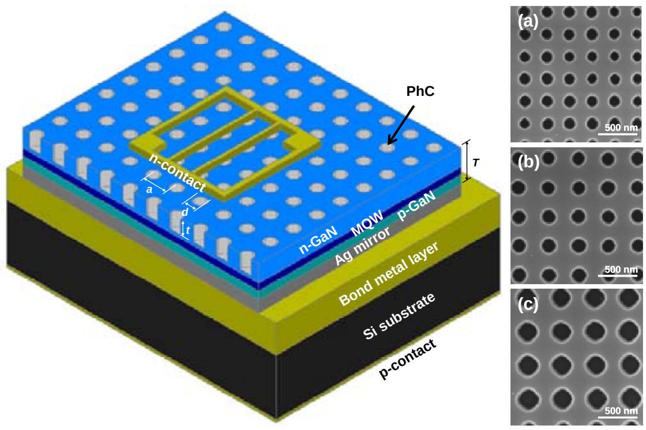

Figure 1. Schematic diagram of GaN PhC uTFLED structures. Top-view SEM image of square PhC lattice with the lattice constant a = (a) 270, (b) 370, and (c) 420 nm, where hole diameter d fixed to the ratio d/a = 0.7.

3. Results and Discussion

After the sample preparation, we performed angular-spectra-resolved EL measurement by injecting a continuous current into the devices at room temperature [4]. In the previous works, the far-field emission distribution has been observed significantly modified by the PhC lattice constant a [2]. Due to the waveguided modes through PhC diffracted light will exhibit anisotropy in the far-field pattern both in the zenith directional and the azimuthal direction [5]. Therefore, the far-field emission pattern in the zenith direction with various PhC lattice constants a of GaN PhC uTFLEDs was measured at a driving current 50 mA for beam shape comparison, normalized with the peak intensity, as shown in Fig. 2. First, Fig. 2(a) shows that the measured far-field pattern at half intensity of the GaN non-PhC uTFLED is 96.24° which is much smaller than that of the typical Lambertian cone 120° due to the strong micro-cavity effect [6]. Next, the PhC lattice constant *a* of 270, 370, and 420 nm of GaN PhC uTFLEDs have highly directional far-field emission patterns at half intensity of 49.11° (36.48°), 30.75° (34.38°), and 34.23° (41.39°) in ΓX (ΓM) orientation, respectively, as shown in Fig. 2(b)-(d). In addition, the photon band structures agreed with fundamental mode effective refractive index dispersion curves. This part will be discussed in elsewhere. Furthermore, the 3D far-field patterns from the different lattice constant *a* of GaN PhC uTFLED were revealed the PhC diffraction patterns with four-fold symmetry due to square PhC lattice [5]. Therefore, highly directional far-field emission distribution on GaN PhC uTFLED was significantly modified by the GaN cavity thickness *T* to collocate the PhC structural parameters.

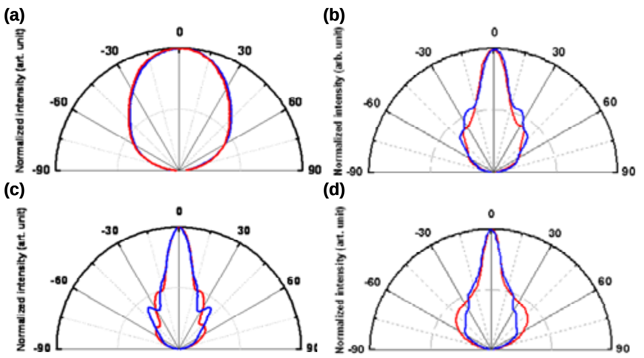

Figure 2. The far-field emission patterns of GaN PhC uTFLED shows the different PhC lattice constant *a* (a) non-PhC, (b) 270, (c) 370, and (d) 420 nm, respectively. Red full line is the ΓX direction and blue full line is the ΓM direction.

Further, the absolute light output power-current -voltage (*L-I-V*) characteristics were also measured using an integration sphere with back-illuminated CCD detector (CAS 140CT - the standard for array spectrometers). The turn on voltage of the devices was about 2.8V. The absolute light output power of the GaN PhC uTFLED at a driving current of 350 mA shown in Fig. 3 that three different PhC lattice constant *a* values, 270, 370, and 420 nm shown output power efficiency (enhancement) by 73.2% (~1.72x), 143.9% (~2.49x) and 278.7% (~3.78x), respectively, compared to the GaN non-PhC uTFLED. In addition, the peak external quantum efficiency (EQE) of GaN uTFLED with the PhC lattice constant *a* values, 270, 370, and 420 nm and without PhC at a driving current of 20 mA (~3.125 A/cm^2) was 17.8 %, 13.0 %, 10.0 %, and 6.3 %, respectively. This forward voltage is higher due to p-ohmic contact (Ni/Ag) agglomerated caused high series resistance. In addition, the measured EQE was lower because the non-optimized chip processes which may suffer current crowding at high current.

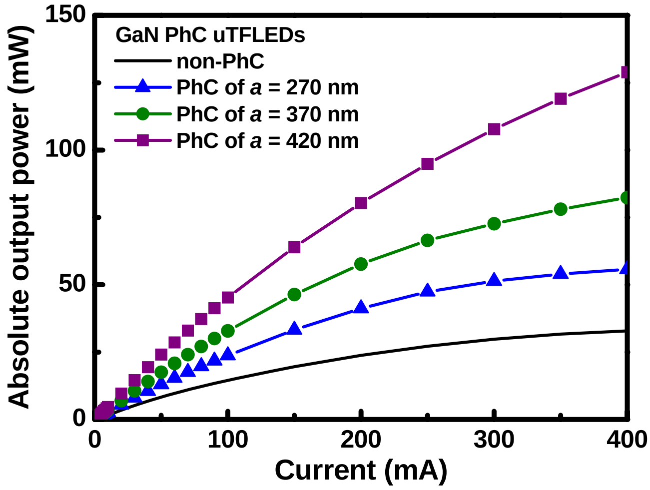

Figure 3. The absolute light output power versus current (*L-I* curves) characteristics of the GaN PhC and non-PhC uTFLEDs.

4. Conclusion

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

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