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Guided mode emission characteristics of GaN-based ultrathin-film micro-light-emitting diodes with photonic crystals

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1. Introduction

Recently, high-resolution and low-power of next-generation pico-projectors are of great interest for applying in ultra-portable device, such as smart mobile phone, and tablet computer, etc. The projection based on GaN micro-light-emitting diode (μ-LED) arrays of micro-display could achieve direct-projecting optical engine with the highest projection efficiency per volume potentially. Therefore, the microdisplays based on monochromatic GaN μ-LED arrays that are driven in the passive and active mode have been developed [1]. In addition, the GaN μ-LEDs have some advantages of brightness and high efficiency than the conventional size LED that has been obtained [2]. A pico-projector using the μ-LED array as optical engines must be provided with the directional far-field distribution, in order to enhancement the light output efficiency and to avoid the crosstalk. Unfortunately, a common far-field distribution of GaN-based μ-LEDs is the Lambertian emission pattern [3]. In the previous studies, we have developed the photonic crystal (PhC) technique applies on GaN-based ultrathin-film LEDs (uTFLEDs) that obtained the high enhancement and highly directional far-field emission patterns [4]. The concept of deliberate PhC structure has, to our knowledge, not yet been applied to μ-LEDs.

In this study, we report on an investigation into the optical and electric properties of GaN μ-uTFLEDs with PhC nano-structures. The experimental results indicate that GaN PhC μ-uTFLEDs not only improved light output power, but also had directional far-field emission pattern and better thermal dissipation compared to GaN non-PhC μ-uTFLEDs.

2. Experiment

Fig. 1(a) illustrates the individual GaN PhC μ-uTFLEDs consists of a 30-nm GaN nucleation layer, a 2-μm un-doped GaN buffer layer, a 2.5-μm Si-doped n-GaN layer, a 120-nm InGaN/GaN multiple quantum well active region, a 20-nm Mg-doped p-AlGaN electron blocking layer, a 125-nm Mg-doped p-GaN contact layer. After epitaxial wafer bonding, the sapphire substrate was removed with the laser lift-off technique. The resulting structure was then thinned down by chemical-mechanical polishing to obtain a GaN ultrathin-film thickness T of approximately 550 nm (~3λ). The individual circular mesas that diameter were 50, 70, 90, and 140 μm respectively that were etched to the bonding metal interface to isolate single μ-LEDs chips. The SiO_2 was deposited on the n-GaN to form the varying emission aperture sizes of 30, 50, 70, and 120 μm, respectively, and the sidewall as the passivation layer. After fabrication, the lattice constant a of PhC was chosen around 420 nm. Holes d of 180 nm were then etched into the top n-GaN surface using inductively coupled plasma dry etching to a deep depth t of 150 nm. Fig. 1(b) shows the top view of a scanning electron microscopy (SEM) image of the PhC nano-structure. Finally, different emission aperture patterned (5, 30, 50, and 100 μm) Ni/Au (50/2000 nm) electrode was deposited on n-GaN to form an n-type contact layer. The Cr/Au (5/1000 nm) metal was deposited on back of the Si substrate. Inset Fig. 1(b) show the 5 μm PhC emission aperture of GaN PhC μ-uTFLEDs light distribution across the die operated at injection current 1 mA.

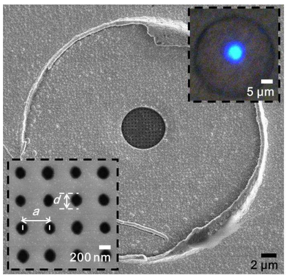

Figure 1. Top-view SEM image of 5 μm PhC emission aperture of GaN PhC μ-uTFLED with lattice constant a = 420 nm, where hole diameter d = 180 nm and hole depth t = 150 nm. The figure inset shows the optical micrograph operated at injection current 1 mA.

3. Results and Discussion

After sample preparation, electroluminescence (EL) measurement was performed by injecting a continuous current into the devices at room temperature. The experiments measured the absolute output power versus current (L-I) characteristics using a 10-in integration sphere of Labsphere with a radiometer and photometer (SC-600). Fig. 2(a) clearly shows that the GaN PhC μ-uTFLEDs had a higher light output power dependence on the PhC emission aperture size. Additionally, heating effects become more prominent as the size of GaN μ-uTFLEDs decreases. For GaN PhC μ-uTFLEDs, the nearly linear optical power output with increasing forward current in the entire measured range will ensure the high brightness. As expected, heat dissipation is well in GaN PhC μ-uTFLEDs with reduced emission aperture sizes. Furthermore, the current-voltage (I-V) characteristics of GaN PhC μ-uTFLEDs of varying PhC emission aperture that the turn-on voltages for 5 μm emission aperture about 4.5 V are larger than that of the 100 μm emission aperture about 3.0 V. Among the different emission aperture sizes of GaN PhC μ-uTFLEDs, the turn-on voltage increases with decreasing GaN PhC μ-uTFLEDs emission aperture sizes. Fig. 2(b) shows the absolute output power enhancement of the GaN μ-uTFLEDs with and without PhC. Varied PhC emission aperture sizes of 5, 30, 50, and 100 μm produced output power enhancement of 90.5%, 124.2%, 151.8 and 249.5% at a driving current of 10 mA, respectively, compared to the same sizes of GaN non-PhC μ-uTFLEDs.

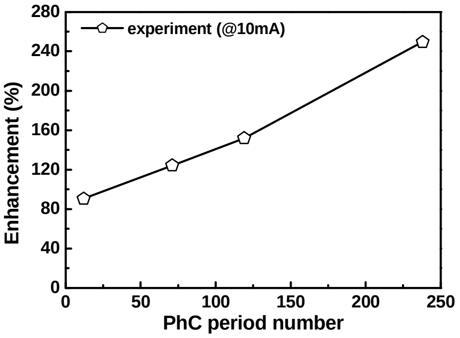

Figure 2. Light extraction enhancement of experiment results versus varied PhC period numbers.

For these applications in pico-projector, the directional far-field emission pattern is one of the crucial parameters. Therefore, varying PhC emission aperture sizes of GaN PhC μ-uTFLEDs have been measured by angular-spectra-resolved EL at injected current 10 mA. Fig. 3 shows the normalized guided mode curves for each mode line in the ΓX (left) and ΓM (right) directions. To study the observed lines of guided mode, the guided mode of the effective refractive index $n_{m,eff}(\lambda)$ of fundamental mode (m=0) was calculated by a slab waveguide with the GaN material dispersion formula. The dispersion curves of the fundamental mode were evaluated by a Bragg diffraction equation as $|k_{0,eff} \pm xG| < k_0$, where $k_{0,eff} = 2n_{0,eff}(\lambda)\pi/\lambda_0$ was a wavevector of the fundamental mode, $k_0 = 2\pi/\lambda_0$ was a wavevector of the air circle, $2G_{\Gamma X}$ (square, □), G_{X1M} (circle, ○), $G_{\Gamma M}$ (triangular, ▽), and $2G_{\Gamma M}$ (diamond, △) of four diffraction vectors in ΓX and ΓM directions, respectively, of the square PhC lattice, as shown in Fig. 3(d). The fundamental guided mode was clearly visible and could be matched to the corresponding dispersion curves of fundamental mode. Several important observations can be obtained from Fig. 3. The 5 and 30 μm PhC emission aperture of GaN PhC μ-uTFLEDs observed the guided mode curves only $2G_{\Gamma X}$ and G_{X1M} diffraction vector, as shown in Fig. 3(a)-3(b). The PhC emission aperture sizes larger over 50 μm that caused the total diffraction vector can be observed, as shown in Fig. 3(c)-3(d). Therefore, the larger PhC emission aperture size created higher output power due to increased guided mode coupling extraction. These experimental results indicated the guided mode emission characteristics dependence on the PhC period number of GaN PhC μ-uTFLEDs.

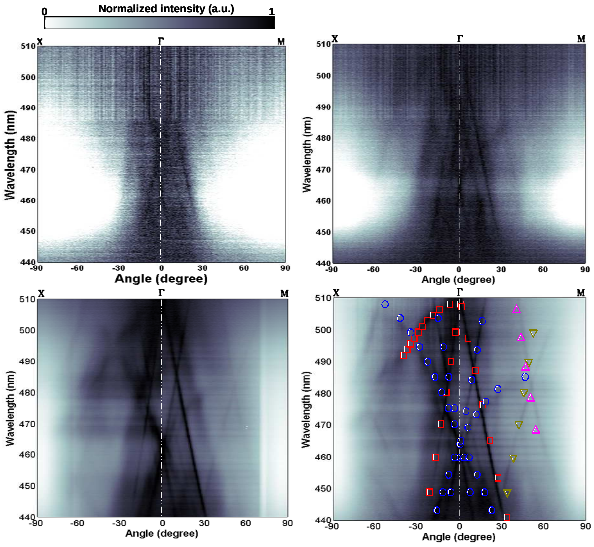

Figure 3. Un-polarized angular-spectra-resolved EL measurements of the GaN PhC μ-uTFLED measured the different PhC emission aperture size (a) 5, (b) 30, (c) 50, and (d) 100 μm under the driven current of 10 mA.

4. Conclusion

In summary, the PhC period number of GaN PhC μ-uTFLEDs effects on the light extraction characteristics has been fabricated and studied. It was found that the guided mode extraction behavior of GaN PhC μ-uTFLEDs is dependent on PhC emission aperture sizes. The proposed GaN PhC μ-uTFLEDs with 5 μm emission aperture exhibited the absolute output enhancement 91% under driven current 10 mA compared to GaN non-PhC μ-uTFLEDs. The present study clearly demonstrated, that GaN PhC μ-uTFLEDs have directional light extraction enhancement, are a favorable competing technology for ultra-portable products such as next-generation pico-projectors.

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