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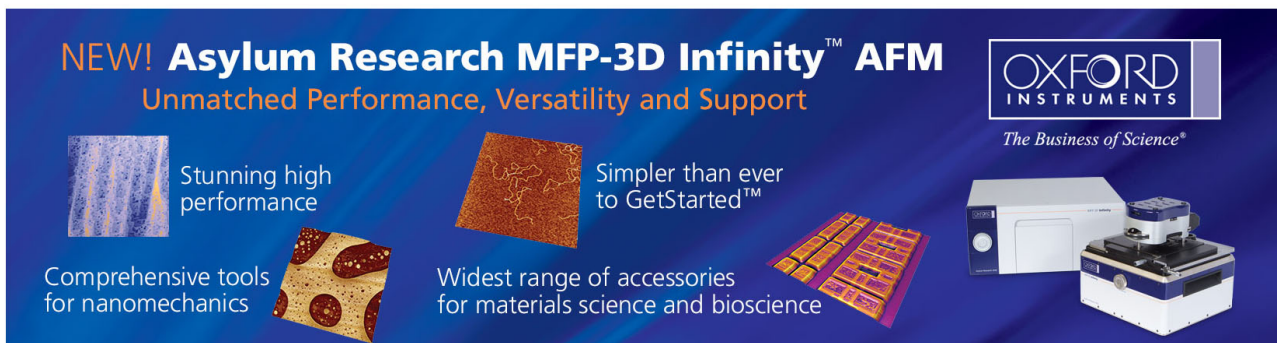
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Highly-directional emission patterns based on near single guided mode extraction from GaN-based ultrathin microcavity light-emitting diodes with photonic crystals

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This study investigates the distribution of highly-directional far-field emission on GaN-based ultrathin microcavity light-emitting diodes (uMCLEDs) with photonic crystals (PhCs). The ultrathin 550 nm cavity, PhC lattice constant of 370 nm, and hole depth of 250 nm in the GaN PhC uMCLED provide near single guided mode extraction and a pattern of high directionality radiation. Angular-spectral-resolved electroluminescence measurements reveal photon-band structure agreement with the fundamental mode effective refractive index dispersion curve. In addition, GaN PhC uMCLED increase the output power extraction efficiency by 145.9% ($\sim 2.46\times$) compared with GaN non-PhC uMCLED, and a directional far-field emission pattern at half intensity of nearly $\pm 15^\circ$. © 2010 American Institute of Physics. [doi:10.1063/1.3459970]

Developing next-generation light-emitting diodes (LEDs) for applications such as projector displays, backlight displays, and automobile headlights requires further improvement in light extraction efficiency (LEE) and directionality of far-field emission distribution.¹ Several schemes have been demonstrated using photonic crystals (PhCs) to control the direction of far-field emissions and enhance LEE from microcavity (thin-film) LEDs (MCLEDs).²⁻⁴ The surface PhC did not closely interact with the lower-order guided modes of GaN PhC MCLEDs, due to the thickness of the GaN. Although many studies have investigated improving LEE in GaN-based MCLEDs with PhC structures, there has been little research into controlling the distribution of directional far-field emission. As yet, no studies have explored the highly-directional far-field emission patterns of blue GaN-based PhC ultrathin MCLEDs (uMCLEDs) with an ultrathin cavity thickness of 550 nm.

This study demonstrated highly-directional light extraction emission, based on near single guided mode from GaN-based PhC uMCLEDs. Angular-spectra-resolved electroluminescence (EL) measurement shed light on the behavior of guided mode extraction from GaN uMCLEDs with and without PhC structures. The photon-band structure correlated with the dispersion curve of the guided mode effective refractive index. This work approached the highly-directional radiation pattern of GaN PhC MCLEDs with ultrathin cavity length and deep PhC.

The blue GaN-based LED wafers used in this study consist of a 30-nm GaN nucleation layer, a 2- μm un-doped GaN buffer layer, a 2- μm Si-doped n-GaN layer, a 120 nm InGaIn/GaN multiple quantum well (MQW) active region with 12 periods (dominant wavelength $\lambda_o=455$ nm), a 20-nm Mg-doped p-AlGaIn electron blocking layer, a 125-nm Mg-doped p-GaN contact layer. After the 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 the GaN effective cavity with thickness 550 nm ($T\sim 3\lambda$). The associated mesas were etched further down to the bonding metal interface to provide single chip isolation. Next, to fabricate PhC on the n-GaN surface, the PhC with a square lattice of circular holes was then defined by holography lithography. PhC holes were etched by inductively coupled plasma into the top n-GaN surface to a depth around $t=100$ (shallow-PhC) and 250 (deep-PhC) nm, respectively. The PhC lattice constant a value is 370 nm and the hole diameter d fixed to the ratio $d/a=0.7$. The schematic of the GaN PhC uMCLED presented in this letter is shown in Fig. 1. Finally, a patterned Cr/Au electrode was deposited on the n-GaN and Si substrate background as the n-type and p-type contact layer. After fabrication, the dies were mounted on transistor outline package with out encapsulation.

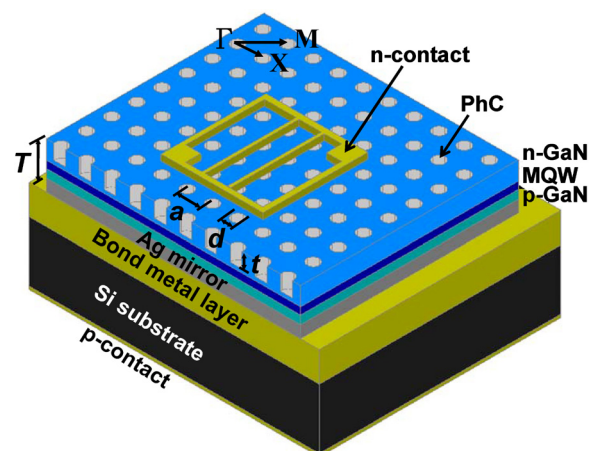


FIG. 1. (Color online) Schematic diagram of the GaN uMCLED with square PhC lattice.

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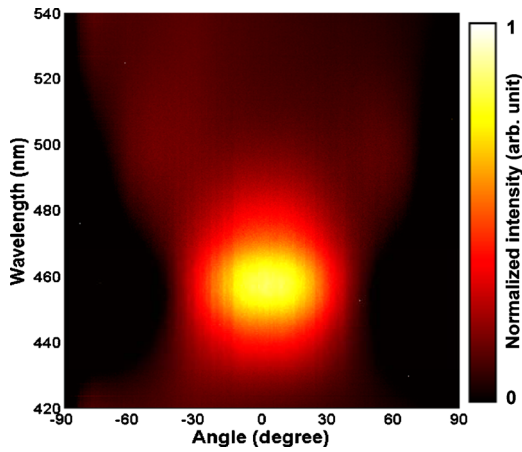


FIG. 2. (Color online) Normalized EL angular spectra of the GaN non-PhC uMCLED for the resonant 550 nm cavity device.

After sample fabrication, we performed angular-spectra-resolved EL measurements to study the guided mode extraction behavior and the distribution of far-field emission.⁵ The angular spectra at various angles from the planar (non-PhC) GaN uMCLED are displayed in Fig. 2 with a plot of “wavelength versus angle.” The angular spectra were normalized by the shape of the MQW line, as in Ref. 6. The 550 nm GaN uMCLED had six resonance modes. Figure 2 reveals only one Fabry–Perot (FP) mode within the extraction cone, and other resonance modes trapped in the GaN waveguide as guided mode. In addition, the FP effect modulates the MQW emission of GaN uMCLED and showed near perfect resonance between the emission wavelength and the cavity length indicated by normal emission.⁶

To increase the LEE and obtain a directional far-field emission pattern from a non-optimized cavity length of 550 nm GaN uMCLED, we used the GaN uMCLED incorporated with a PhC lattice to enhance the LEE. Angular-spectra-resolved EL measurement indicated GaN PhC uMCLED with a square PhC lattice constant of $a=370$ nm, and two different PhC hole depths, where the shallow and deep etching of the PhC hole depth were about 100 and 250 nm. This is clearly shown in Figs. 3(a) and 3(b) with light collected along the ΓX (left) and ΓM (right). The shape of MQW line normalized these angular spectra of GaN PhC uMCLED. The light traveling through the waveguide in the GaN PhC uMCLEDs was diffracted by reciprocal wave vectors associated with the PhC. The sharp lines could be attributed to extracted wave guided modes propagating in the GaN waveguides formed with the GaN ultrathin cavity between the Ag reflector mirror and the air. Observations of the GaN shallow-PhC uMCLEDs revealed only two lower-order guided mode extractions, as shown in Fig. 3(a). In contrast, Fig. 3(b) illustrated the GaN deep-PhC uMCLEDs in nearly single guided mode extraction. To study these modes more clearly, this study transformed the spectra shown in Fig. 3(b) to the guided mode dispersion curves shown in Fig. 3(c). The image shows the normalized dispersion curves for each mode line in the ΓX (left) and ΓM (right) directions, which were sections of the band of PhC. They can be quantitatively analyzed using the Ewald construction of the Bragg diffraction theory in reciprocal space.⁸ When the in-plane component of the resultant wave vector after coupling to a reciprocal lattice vector fell within the circle of air, the diffracted

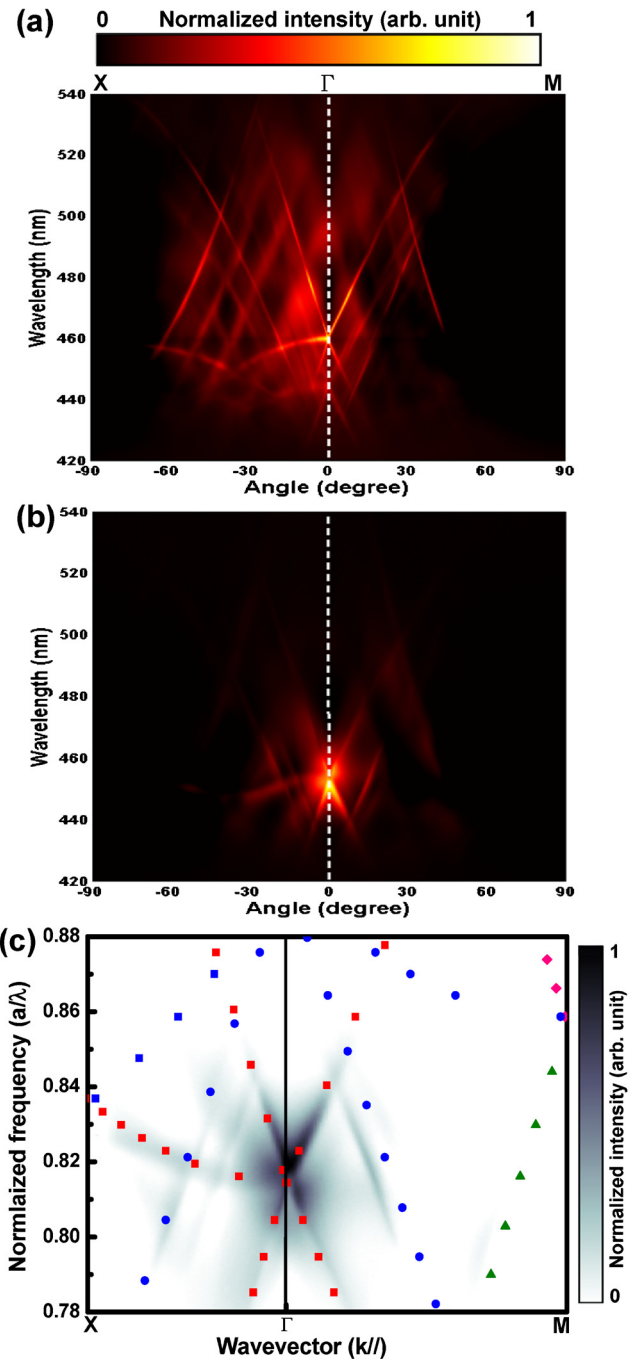


FIG. 3. (Color online) Un-polarized angular-spectra-resolved measurements of the GaN PhC uMCLED with PhC hole depths (a) shallow $t=100$ nm and (b) deep $t=250$ nm of the PhC lattice constant $a=370$ nm, where ΓX is (left) and ΓM is the (right) direction. (c) shows the guided mode dispersion curves determined from the data shown in (b) and compared with the fundamental mode effective refractive index dispersion curves for the transverse electric (TE) modes.

light escaped into the air. To study the observed lines of guided mode, the dispersion of the effective refractive index $n_{m,\text{eff}}(\lambda)$ of fundamental mode ($m=0$) was calculated by a slab waveguide with the GaN material dispersion formula as a Sellmer equation.⁷ The effective refractive index dispersion curves of the fundamental mode were calculated by a Bragg diffraction equation as $|k_{0,\text{eff}} \pm xG| < k_0$, where $k_{0,\text{eff}} = 2n_{0,\text{eff}}(\lambda)\pi/\lambda$ is a wave vector of the fundamental mode effective refractive index dispersion; $k_0 = 2\pi/\lambda_0$ is a wave vector of the air circle; $x=1, 2, \dots$ is an integer of diffraction

order; $2G_{\Gamma X}$ (square, \blacksquare), G_{XIM} (circle, \bullet), $G_{\Gamma M}$ (triangular, \blacktriangle), and $2G_{\Gamma M}$ (rhombus, \blacklozenge) of four reciprocal diffraction vector interactions with ΓX and ΓM direction of the square PhC lattice,⁸ as shown in Fig. 3(c). These dispersion curves were used to match the observing guided mode lines in Fig. 3(c). The fundamental guided mode was clearly visible and could be matched to the corresponding fundamental mode effective refractive index dispersion curves. This indicated that the measured guided mode was accurate. In addition, this study proved the guided mode dispersion of Fig. 3(a) agreed with the first ($m=0$) and second ($m=1$) lower-order guided mode effective refractive index dispersion curves. The above results revealed the near single guided mode extraction of Fig. 3(c), because $2G_{\Gamma X}$ had interacted with the second-order guided mode appearing in Fig. 3(c) [observed from Fig. 3(a)]. Results for guided mode dispersion were different from previous work with shallow PhC etching of GaN PhC MCLEDs, where the dispersion was simply that of folded free-photon bands.^{2,3} In addition, the other higher-order modes are not extracted. The reason for the mismatch between samples is due to the tilting during the lapping and polishing or reabsorption in the MQW as well as absorption in doped or metallic layers influenced the extracted modes.⁴

To investigate how the depth of the PhC hole t influenced the distribution of far-field emission distribution of GaN PhC uMCLED, this study measured the 3D far-field radiation pattern of GaN uMCLED, with and without the PhC structure, by means of imaging spheres (Radiant imaging IS-LI) under the same current (50 mA) for beam shape comparison, normalized with peak intensity, as shown in Figs. 4(a) and 4(b). The measured far-field pattern at half intensity of the GaN non-PhC uMCLED was 104.17° that is much lower than that of the typical Lambertian cone 120° due to strong influence of the microcavity.⁶ The shallow (~ 100 nm) and deep (~ 250 nm) PhC hole depth t of the GaN PhC uMCLEDs caused differing far-field emission patterns, as shown in Figs. 4(a) and 4(b). The patterns peaked near normal on the surface of the device with far-field angle (at half intensity) of 120.54° (84.88°) and 30.75° (34.38°) in ΓX and (ΓM), respectively. The GaN deep-PhC uMCLEDs based on near single lower-order guided modes and the strong influence of microcavity caused a highly-directional far-field emission pattern. Therefore, the depth of the PhC hole t and GaN cavity thickness T that affected the guided modes extraction behavior, had significantly modified the distribution of the directional far-field emission on GaN PhC uMCLED.

We measured the characteristics of the absolute light output power-current-voltage ($L-I-V$) using an integration sphere with a back-illuminated charge coupled device (CCD) detector (CAS 140CT—the standard for array spectrometers). The turn-on voltage of the devices was 2.8 V. The forward voltage of GaN uMCLED with and without PhC was 4.62 V and 4.4 V, respectively, under the current 350 mA, as shown in Fig. 4(c). The absolute light output power of the GaN deep-PhC uMCLED under the driven current of 350 mA shows efficiency of the output power enhanced by 145.9% ($\sim 2.46\times$), compared with the GaN non-PhC uMCLED as shown in Fig. 4(c). GaN deep-PhC uMCLED exhibited a highly-directional light enhancement, compared

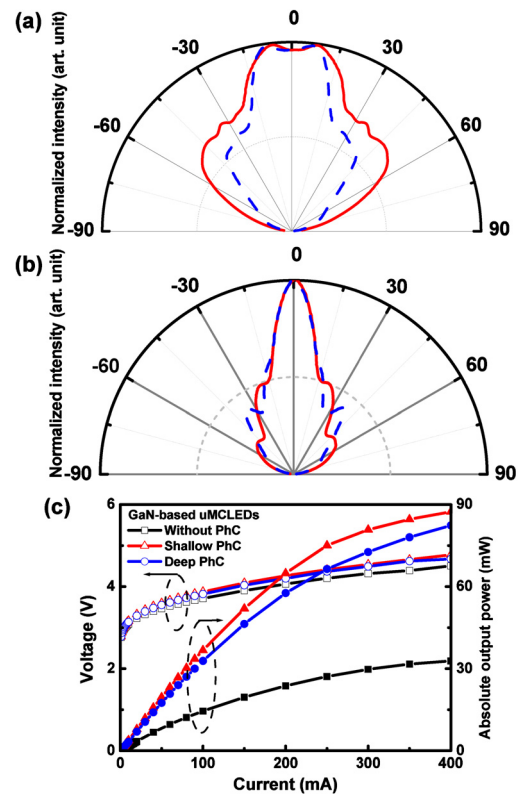


FIG. 4. (Color online) The far-field emission pattern shows the PhC lattice constant $a=370$ with different hole depth (a) shallow $t=100$ nm and (b) deep $t=250$ nm of GaN PhC uMCLED, where the solid line indicates the direction of the ΓX and the dash line indicates the direction of ΓM . (c) The characteristics of absolute light output power-current-voltage ($L-I-V$ curves) of the GaN uMCLEDs with and without PhC.

with the GaN non-PhC uMCLED with the same cavity thickness.

In conclusion, this study conducted experiments and a theoretical investigation into directional far-field emission patterns based on the influence of microcavity and near single guided mode extraction of GaN PhC uMCLEDs. Angular-spectra-resolved EL measurements showed a correlation between photon-band structure and guided mode effective refractive index dispersion curves. The GaN deep-PhC uMCLED showed highly-directional far-field emission patterns at half intensity near $\pm 15^\circ$. The results indicated that highly-directional far-field light extraction efficiency could contribute to the development of many applications, especially for limited etendue applications such as pico-projectors.

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