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Directional light extraction enhancement from GaN-based film-transferred photonic crystal light-emitting diodes

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Experimental investigation of the directionality in the far-field pattern and light extraction enhancement in collected cone were performed in GaN-based film-transferred photonic crystal (PhC) light-emitting diodes (FTLEDs). Angular-resolved measurement revealed directional profile and azimuthal anisotropy in the far-field distribution with guided modes extraction. Good agreement according to Bragg’s diffraction theory and free photon band structure were achieved. The light enhancement in PhC FTLEDs compared to non-PhC FTLEDs within the collection cone angle was obtained according to measured three-dimensional far-field patterns. In a ±20° collection cone, collected light was enhanced by a factor of ~2.4 for the collimated PhC FTLED. © 2009 American Institute of Physics. [DOI: 10.1063/1.3106109]

For next generation applications of light-emitting diodes (LEDs), further improvements of the light extraction efficiency and the directional far-field patterns are required. Directional far-field pattern of the light sources is important for many applications in projector displays, backlight displays, and automobile headlights.1 Approaches based on the photonic crystal (PhC) have attracted much attention to achieve light extraction enhancement, polarization, and directional patterns from GaN LEDs.2–4 Recently, an AlGaN/P film-transferred (FT) resonant cavity LED combined with PhC has been reported for enhancing directional light extraction5 in the red wavelength, as well as GaN PhC FTLEDs in the blue wavelength range for light extraction enhancement.6,7 Nevertheless, a blue GaN PhC FTLEDs with directional light extraction has not been studied in detail.

In this paper, experimental and theoretical studies on the directional light extraction through Bragg diffraction of guided modes in GaN PhC FTLEDs will be addressed. GaN FTLEDs with different PhC lattices based on free photon band structure exhibit the corresponding directional profiles in the far-field patterns. In addition, angular-resolved spectra have been mapped monochromatically to demonstrate the azimuthal evolution of the guided modes’ diffraction behavior. Furthermore, the light enhancement of PhC FTLEDs compared to non-PhC FTLEDs within the collection cone angle was also obtained according to the measured three-dimensional (3D) far-field patterns.

The blue GaN-based LED wafer were grown by metal-organic chemical-vapor deposition onto c-face (0001) 2-in. diameter sapphire substrates. The LED structure consists of a 30-nm-thick GaN nucleation layer, a 4-μm-thick undoped GaN buffer layer, a 3-μm-thick Si-doped n-GaN layer, a 120 nm InGaN/GaN multiple quantum well active region with eight periods (dominant wavelength λ = 475 nm), a 20-nm-thick Mg-doped p-AlGaN electron blocking layer, and a 300-nm-thick Mg-doped p-GaN contact layer. The detailed wafer processing of GaN FTLEDs associated PhC is the same as in Ref. 8, using the laser lift-off technique to remove the sapphire substrate. The resulting structure was then thinned down by chemical-mechanical polishing to obtain the GaN cavity thickness of around 1.5 μm. The square-lattice PhC with circular holes was then defined by holography lithography. PhC holes were etched into the top n-GaN surface to a depth of around 150 nm. The lattice constant a of PhC were 290, 350, and 400 nm and the hole diameter d fixed to ratio d/a = 0.7. A scanning electron microscopy (SEM) image of the square-lattice PhC structure is shown in Fig. 1(a). Finally, a patterned Pt/Cr/Au electrode was deposited on n-GaN as the n-type contact layer. After fabrication, the dies were mounted on transistor outline (TO) package with encapsulant-free.

After sample preparation, angular-resolved measurement under electrical current injection was performed. A continu-

![FIG. 1.](image)

(Color online) (a) The top-view SEM image of PhCs on FTLED with the lattice constant a = 400 nm and the diameter of air holes d = 280 nm fabricated with the holography lithography. Inset: the cross-section TEM image shows the PhC depth t = 150 nm. (b) The optical microscopy showing the blue light distribution across the die operated at low injection current 5 mA. (c) Schematic diagram of the GaN FTLED structure with PhC.

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The agreement between the experiment and calculation are
fit the lowest order mode with the free photon band structure.
As a result, the GaN PhC FTLEDs can be encapsulated to
increase light enhancement, while retaining the directional
patterns.

The azimuthal anisotropy of the far-field distribution is
measured as a function of the azimuthal angles by using the
angular-resolved setup. Figures 4(a)–4(c) plot the far-field
distributions monochromatically in the azimuthal direction at
a fixed wavelength of $\lambda=475$ nm with $a$ of 290, 350, and
400 nm, respectively. Different guided mode with different
index will trace out an arc with the radius corresponding to
the respective waveguide circle, which are well fitting by
Ewald’s construction of Bragg’s diffraction theory. The
samples with $a$ of 350 nm sample has lobes at around $\pm 17^\circ$ ($\pm 15^\circ$,
$\pm 30^\circ$) in $\Gamma X$ ($\Gamma M$) orientation. Therefore, in GaN PhC
FTLED, the far-field distributions will be significantly modi-
fied by the PhC structure, i.e., lattice constant $a$. With com-
paring to the encapsulant-free PhC FTLED, the encapsulated
PhC FTLED has similar far-field characteristics in our study.
As a result, the GaN PhC FTLEDs can be encapsulated to
increase light enhancement, while retaining the directional
patterns.

The light enhancement in the PhC FTLEDs compared to
non-PhC FTLEDs at a driving current of 50 mA can be charted in Fig. 5 in which the light enhancement is defined as the
ratio of the light output of the PhC FTLED divided by
non-PhC LED, and the power is collected from $\pm 0^\circ$ to
$\pm 90^\circ$. The light enhancements in collection angles strongly
depending on the far-field patterns of GaN PhC FTLEDs are
obtained. The collimated PhC FTLED in a $\pm 20^\circ$ collection
V, respectively. The high forward voltages could attribute to
high series resistance in such thin PhC device. Furthermore,
due to the discrete nature of the guided modes, this diffra-
ction light will exhibit anisotropy in the far-field pattern both
in the zenith directional and the azimuthal direction. The
far-field patterns in the zenith direction were measured at a
driving current of 50 mA, normalized with the peak intensity,
as shown in Figs. 3(b) and 3(c). The samples with $a$ of 290
and 400 nm have collimated far-field patterns that both are
peaked near normal to the FTLED surface and have small
far-field angle at half intensity of $\pm 31.7^\circ$ ($\pm 41.05^\circ$) and
$\pm 42.45^\circ$ ($\pm 49.7^\circ$) in $\Gamma X$ ($\Gamma M$) orientation of PhC lattice,
respectively, which are much smaller than that of a typical
Lambertian cone, $\pm 60^\circ$. The measured far-field pattern of
the GaN non-PhC FTLED is nearly Lambertian. In addition,
the $a$ of 350 nm sample has lobes at around $\pm 17^\circ$ ($\pm 15^\circ$, $\pm 30^\circ$) in $\Gamma X$ ($\Gamma M$) orientation. Therefore, in GaN PhC
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cone achieves the light enhancement of \( \sim 2.4 \). For collimated patterns, the light enhancement increases with collection angle shrinking. The divergent profile of PhC with \( a = 350 \) nm reveals little light enhancement in a small collection angle. Therefore, the collimation profile of far-field pattern could contribute to the stronger directional light enhancement in many applications, especially for etendue limited applications. Additionally, the extraction enhancement is not only a function of the PhC parameters, but also on other variables such as the GaN thickness and QW placement, as shown in Ref. 7.

In conclusion, the far-field directionality and light extraction enhancement in collected cone in GaN-based PhC FTLEDs with three different square PhC lattice have been experimentally investigated. Angular-resolved measurements revealed directional profile and azimuthal anisotropy in the far-field distribution with guided modes extraction based on the Bragg’s diffraction. The extracted guided mode corresponds with the high symmetry point along the \( \Gamma_1 \) and \( \Gamma_2 \) that shows the light collimation profile. The light enhancement in PhC FTLEDs compared to non-PhC FTLEDs within the collection cone angle was also obtained according to measured 3D far-field patterns. In a \( \pm 20^\circ \) collection cone, collected light was enhanced by a factor of \( \sim 2.4 \) for the collimated PhC FTLED. The collimated PhC FTLED is a promising candidate for etendue limited applications, such as projecting display.