Enhanced Vertical Extraction Efficiency From a Thin-Film InGaN–GaN Light-Emitting Diode Using a 2-D Photonic Crystal and an Omnidirectional Reflector

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***Abstract*—An InGaN–GaN thin-film vertical-type light-emitting diode with a two-dimensional photonic crystal (PC) on the emitting surface and a TiO_2–SiO_2 omnidirectional reflector on the bottom was fabricated. The device was investigated by performing a series of experiments and numerical computations. Electroluminescence measurement revealed a strong extraction enhancement in the vertical direction at 433-nm wavelength. The emission spectrum of the light was found to be strongly modified by the PC to have a significantly narrow linewidth of 5 nm. Our experimental results were in accord with those obtained from our numerical findings.**

***Index Terms*—Light-emitting diode (LED), omnidirectional reflector (ODR), photonic crystal (PC).**

I. INTRODUCTION

IMPROVED understanding of the physics of high-brightness GaN-based light-emitting diodes (LEDs) coupled with advances in their processing and fabrication have led to their successful use in flat-panel displays and many other display technologies [1]. To address the next generation of applications of LEDs on projectors and automobile headlights, further improvements of optical power and light extraction efficiency are required. First of all, in the absence of a suitable reflector at the bottom of the LED, a significant fraction of the emitted light would either escape or absorbed at the bottom of the device. In our previous work, we have demonstrated significant enhancement in the extraction efficiency for a vertical flip-chip GaN-based LED incorporated with an omnidirectional reflector (ODR) composed of alternate layers of TiO_2 and SiO_2 [2]. A second source of degradation of extraction efficiency is due to the fact a large portion of the light emitting from InGaN–GaN multiple-quantum-well (MQW) is captured within the GaN and sapphire layers in the form of propagating guided modes. Thus, the light extraction efficiency can be substantially improved by reducing the LED thickness thereby reducing the number of guided modes. For a thin-film LED within the "microcavity" regime, the effective cavity length must be short enough to support just a few modes so that some modes lying within the extraction cone are leaky [3]. The greater the fraction of power emitting into the leaky modes, the larger the light extraction efficiency. Nevertheless, a fraction of the power is still carried away by light guided in the material.

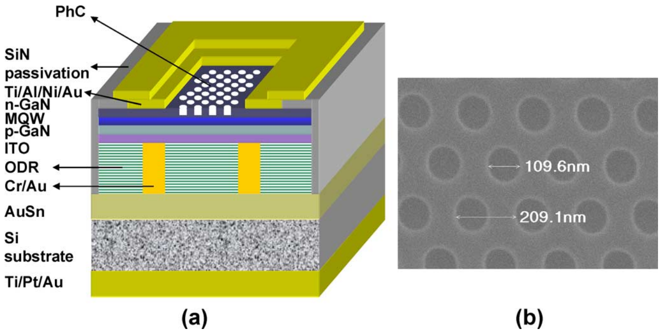

Fig. 1. (a) Schematic diagram of the GaN-based thin-film LED with composite PCs. An ODR was formed on the bottom of microcavity and the 2-D PC was fabricated on the surface of thin-film LED with the etch depth of 170 nm. (b) Top-view SEM image of 2-D PC with the lattice constant $a = 209$ nm and the diameter of air holes $d = 110$ nm.

To further extract the guided light out of the semiconductor material, a properly designed two-dimensional photonic crystal (2-D PC) has been utilized to enhance extraction efficiency of light in the vertical direction from LEDs [4]. Therefore, an LED operating within the microcavity regime and incorporated with 2-D PC on the light-emitting surface and an ODR at the bottom surface is expected to have a significantly improvement on the extraction efficiency compared to without PC. In this letter, we report our fabrication and measurements on such an LED. Numerical modeling is used to aide in the design of the device as well as in the understanding of the experimental findings.

II. SAMPLE STRUCTURE

The schematic diagram representation of the structure of thin-film InGaN–GaN LED with a 2-D PC and an ODR is shown in Fig. 1(a). The structure consists of a 50-nm-thick low-temperature GaN buffer layer, a 3-μm-thick GaN undoped

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layer, a 60-nm-thick Al$_{0.15}$Ga$_{0.85}$N etch stop layer [5], a 230-nm-thick Si-doped n-GaN layer, an unintentionally doped InGaN–GaN MQW active layer, and a 230-nm-thick Mg-doped p-GaN contact layer. The MQW active region is composed of five periods of 3-nm/7-nm-thick InGaN–GaN quantum well and barrier layers. A transparent conducting layer composed of a 300-nm-thick indium–tin–oxide (ITO) was first deposited onto the p-GaN surface of the wafer sample by electron beam evaporation for current spreading. Since the ODR is nonconducting, in order for our device to be of the vertical injection type, we need to integrate a couple of conducing channels inside the ODR to make contact with the ITO for vertical current spreading. Our ODR was composed of 14 pairs of TiO$_2$–SiO$_2$ and the refractive indexes of TiO$_2$ and SiO$_2$ are measured to be 2.52 and 1.48, respectively, at 430-nm wavelength. Our numerical modeling yielded thicknesses for the TiO$_2$ and SiO$_2$ that resulted in a complete one-dimensional PC bandgap between 417 and 450 nm. The detailed geometrical parameters as well as our band structure calculation can be found in one of our previous studies [2]. The detail wafer process of thin-film ITO LEDs coated TiO$_2$–SiO$_2$ ODR was fabricated the same as in [2]. To fabricate our 2-D PC on the n-GaN surface, we first deposited a 50-nm-thick layer of SiO$_2$ to serve as a hard mask on the n-GaN by plasma-enhanced chemical vapour deposition. The 2-D PC with a hexagonal array of circular holes was then defined by electron-beam (e-beam) lithography on the top of the hard mask layer. The lattice constant and hole diameter of our 2-D PC were chosen to be 209 and 110 nm, respectively, and a 30 μm$\times$ 30 μm PC region was centered inside a 90-μm square LED mesa area. The 2-D PC pattern was then transferred onto the n-GaN surface by dry etching using the main etch gases of chlorine and methane together with a radio-frequecy power of 125-W inductively coupled plasma (ICP) and 100-W reactive ion etching. The remaining SiO$_2$ was removed by dipping it in 1 : 5 buffered oxide etch solution. The etching depth of the holes was about 170 nm and the top view of the scanning electron microscopy (SEM) image of the 2-D PC is shown in Fig. 1(b). Finally, a bonding pad comprised of Ti–Al–Ni–Au serving as n-electrode and Ti–Pt–Au serving as p-electrode was deposited by an E-beam evaporator.

III. EXPERIMENT RESULTS AND DISCUSSION

We first performed an optical scattering measurement along the vertical axis of our LED. A white light source was directed at the side wall of the device. The light propagated inside the LED structure and was partially reflected by the ODR and scattered out of the LED by the 2-D PC. Fig. 2 shows the scattering spectrum measured at the top of the device in the vertical direction. The spectrum has a sharp peak around the intended wavelength of 430 nm with a very narrow full-width at half-maximum (FWHM) of about 5 nm. The scattering spectrum shows the main peak light extraction wavelength of 430 nm. The electroluminescence characteristics of our device were also performed by using the probe station and a scanning optical microscopy system, which included continuous-wave current source (Keithley 238 CW), a 20 $\times$ microscopy objective with a numerical aperture (NA) of 0.45, and charge-coupled device spectrometer with spectral resolution of 1 Å. Fig. 3 shows a comparison of the emission spectrum of a conventional LED with that of our present LED operating at a current of 5 mA. The emission peak of our device was located at a wavelength of 433 nm with a very narrow FWHM of about 5 nm, which was very close to the width seen in the scattering spectrum in Fig. 2. Therefore, the emission spectrum of thin-film LED without PC exhibits an FWHM of about 40 nm at room temperature. In addition, our result showed a strong light extraction enhancement by a factor of 3.8 near the emission peak compared with the conventional LED. The inset showed the emission image of the present LED operating at an injection current of 5 mA.

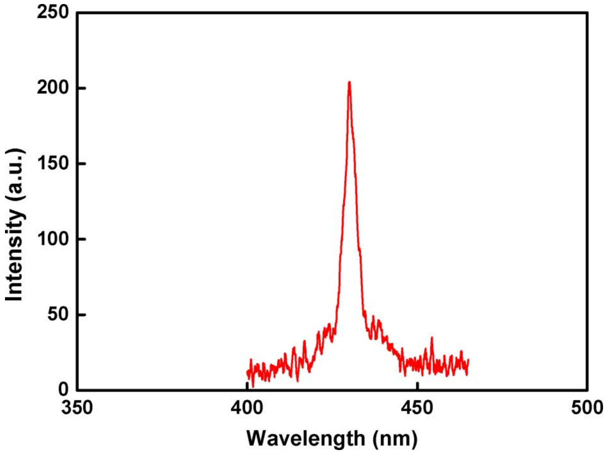

Fig. 2. Optical scattering spectrum of the thin-film LED with composite PCs by a white light source from the sidewall of the device.

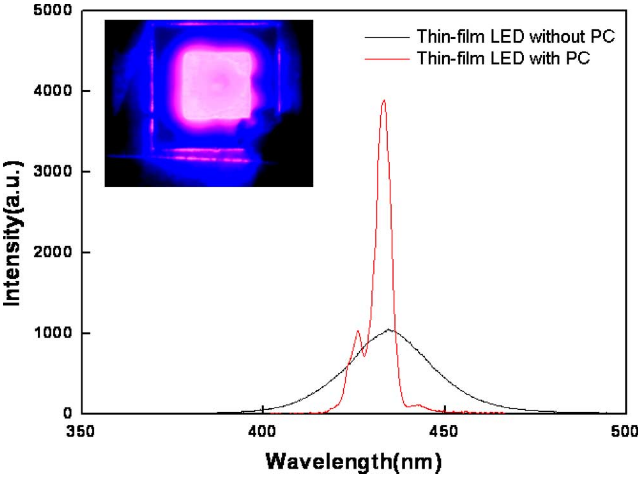

Fig. 3. Emission spectra of the thin-film LED with composite PCs at current 5 mA. Inset shows the top view image of the device with an emission at current of 5 mA.

To realize the 2-D PC effect shown in the narrow linewidth on the emission spectrum of our LED, we compare the experimental results to numerical simulations. To calculate the band diagram of the triangular PC patterns in our structure, we employ the plane-wave expansion method in 2-D with an effective index approach that took into account the effects of partial modal overlap of electromagnetic fields with the PC structures [6], [7]. As a starting point, the ratio of light confined within the 2-D PC structure to light extended in the entire device Γ_g and the effective refractive index of the entire device n_{eff} were first estimated by the transfer matrix method to be 0.194 and

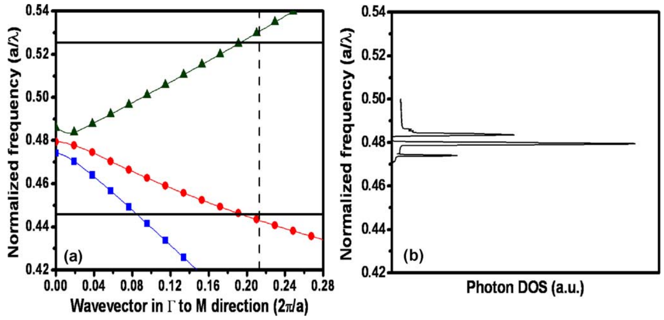

Fig. 4. (a) Leakage band structure in Γ to M direction of 2-D PC structure. The dashed line is the accepted air cone. The solid lines are the spectrum range. (b) Photon DOS for 2-D PC structure.

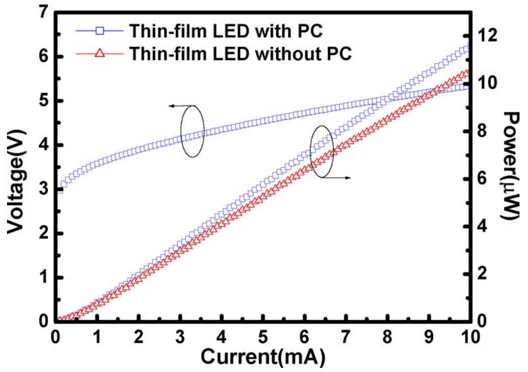

Fig. 5. Forward current versus voltage and light output power of the thin-film LED with composite PCs and without PCs.

2.41, respectively. Then, we determine the effective dielectric constants of the two materials in the unit cell, ε_a and ε_b, using $n_{\text{eff}}^2 = f\varepsilon_a + (1-f)\varepsilon_b$ and $\Delta\varepsilon = \varepsilon_b - \varepsilon_a = \Gamma_g(\varepsilon_{\text{mat}} - \varepsilon_{\text{air}})$, where the $f = 2\pi r^2/\sqrt{3}a^2$ is a filling factor and ε_{mat} and ε_{air} are dielectric constants of GaN ($= 2.5^2$) and air ($= 1^2$), respectively. The values of $\varepsilon_a = 5.04$ and $\varepsilon_b = 6.06$ thus obtained were then put into the calculation of the band diagram for the 2-D hexagonal-lattice structure with $r/a = 0.26$. Fig. 4(a) shows the calculated band diagram of the 2-D triangular lattice structure for transverse-electric mode. The x axis represents the wavevector $k_{//}$ varying from Γ to M in the first Brillion zone. In addition, the microscopy objective with NA of 0.45 is both the accepted angle $\sim 26^\circ$ and the wavevector $k_{//} \sim 0.214\ (2\pi/a)$, shown in Fig. 4(a) with a dashed line. We see the three different bands in the $k_{//} \sim 0.214\ (2\pi/a)$ air cone angle to fall behind in the spectrum range $400 \sim 470$ nm (which corresponds to frequency $0.523 \sim 0.445\ (a/\lambda)$). Therefore, density of state (DOS) was calculated within the vicinity of Γ point [8], as shown in Fig. 4(b). It can be expected that the resonance mode at Γ points such as at Brillouin-zone boundary near the band edges, because the DOS is higher in these points [8]. The light extraction from the Γ point in the vertical direction is due to the PCs resonance mode. Furthermore, DOS calculation shows that vertical coupling via PC Bloch modes near the light emission wavelength. Our computed results, therefore, agree well with the narrow linewidth, strong light extraction, and multipeak emission observed in the emission spectra.

Fig. 5 shows the current versus voltage and the light output power of the thin-film LED both with PCs and without PCs at room temperature. The turn-on voltage and resistance of the present LEDs were similarly about 2.97 V and 160 Ω, respectively. The high resistance of the device may be due to lateral current crowding in the thin n-type GaN layer, which further limits device operation at higher current density. The light output power of the device was measured by an integrating sphere with Si photodiode at room temperature. At an injection current of 10 mA, the thin-film LED with PCs shows output power enhancement by 10% when compared to the thin-film LED without PCs. As the current increased beyond 10 mA, the thermal roll-over began and the output power started to saturate because of the high serial resistance of the device.

IV. CONCLUSION

In summary, a GaN-based thin-film vertical-type LED incorporated with a 2-D PC on the emitting surface and an ODR on the bottom was fabricated and studied. Our device showed a significant extraction enhancement around the emission peak wavelength of 433 nm with a very narrow FWHM of 5 nm. Our theoretical calculation showed the presence of a set of flat dominant leaky resonant modes near the wavelength of 430 nm. These leaky modes are responsible for coupling the guided modes out of the device. Thus, our LED has superior performance in terms of the extraction efficiency and a narrow linewidth, has advantages for white light generation by both of RGB and phosphor conversion packages.

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