Enhanced light extraction from GaN-based green light-emitting diode with photonic crystal

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This letter reports the properties of GaN-based green light-emitting diodes (LEDs) having a p-GaN photonic crystal layer with a photonic bandgap (PCWG) and without a photonic bandgap (PCOG). With decreasing the photoluminescence (PL) detection angle from 140° to 60°, the enhancement of PL intensity of LED with PCWG was largely increased from 9 to 25 times, compared to that of LEDs without a patterned structure, while the PL intensity of LED with PCOG was increased from 4.6 to 5.6 times. The electroluminescence output power of green LEDs with a PCWG was enhanced about two times compared to LEDs with a PCOG. These results suggest that the light extraction of green LEDs can be greatly increased by using PCWG instead of PCOG. © 2007 American Institute of Physics. [DOI: 10.1063/1.2804005]

As the brightness of GaN-based light-emitting diodes (LEDs) has increased, GaN LEDs have recently attracted considerable interest for use in displays, traffic signals, and solid-state lighting. 1,2 For the realization of high-brightness LEDs, it is crucial to increase the quantum efficiency of GaN-based LEDs. It has been reported that the internal quantum efficiency (IQE) of blue LEDs reaches more than 80% due to the rapid development of growth methods for high quality materials. The IQE of green LEDs, however, is only 5%–10%, due to the low crystal quality of the InGaN layer with a high In-content and a high piezoelectric field in InGaN/GaN multiple quantum well (MQW) for green emission. 2,3 Furthermore, the external quantum efficiency is much lower than the internal quantum efficiency due to the total internal reflection (TIR) of light in LEDs. 4 Thus, to enhance the light extraction efficiency a few methods, such as surface texturing 5–7 and photonic crystal effect, 6–16 were studied. Surface texturing methods were recently introduced in an attempt to reduce the loss of photons caused by the TIR at the interface of the top layers of GaN and air. LEDs with photonic crystals (PCs), which are materials with a spatially periodic refractive index, could also be designed to efficiently couple light from the dielectric-guided modes into air. They also can be utilized to inhibit emission of guided modes or redirect trapped light into radiated modes. 5–10

Much progress has been made in the fabrication and understanding of photonic crystal LEDs (PC-LED) with emissions from the ultraviolet to the infrared region. 8–18 Fabrication of PC-LEDs was possible by employing an electron-beam lithography, but it is a low-throughput and a small-area processing technique. 12–16 To overcome the limits of electron-beam lithography, both laser holography 17 and nanoimprint lithography 18 (NIL) were used to fabricate PC-LED structures.

Recently, to enhance the light extraction efficiency of LEDs, the effect of two-dimensional (2D) PCs was investigated. However, in most of the studies on the PC effect in the GaN-based LEDs, the light extraction was optimized simply by varying the radius of the hole (r) and the lattice constant (a) of the PC layers without considering the photonic bandgap (PBG). In this study, our group investigated the optical and electrical properties of green LEDs having PC structures with and without a PBG for the green emission.

The PC structures were designed using a simulation program based on the preconditioned conjugate-gradient plane-wave expansion method. 8–11 The PC structures with a periodic hole pattern were formed in the p-GaN layer of a green LED as shown in the schematic diagram in Fig. 1(a). Figures 1(b) and 1(c) show the photonic band diagrams of the GaN slab for a square lattice structure with depths of 100 and

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**FIG. 1.** (Color online) (a) A schematic diagram of a GaN based LED with PC structure with a square lattice hole pattern. (b) Band diagram of GaN slab with a depth of 100 nm at ratio (r/a) of 0.31. (c) Band diagram of a GaN slab with a depth of 65 nm at ratio (r/a) of 0.28.
processes. The LED samples consisted of imprint resists/Cr/H$_2$O$_8$51 indicated by three arrows in Figs.1

tures were investigated in the photonic band diagrams as PCs on the light extraction from green LED, three PC struc-

PBG frequency region below the light line, which is composed of transverse-electric (TE)- and transverse-magnetic (TM)-like guide modes and a PBG. The PBGs can be seen in the region between the first and second TE-like guide modes and between the first and second TM-like guide modes. In this study, we focused our attention on TE-like PBGs, which are characterized by light propagating in parallel to the slab of an LED, since the light extraction efficiency can be enhanced by inhibiting the emission of the guided modes and redirecting trapped light into radiated modes. To study the effect of PCs on the light extraction from green LED, three PC structures were investigated in the photonic band diagrams as indicated by three arrows in Figs. 1(b) and 1(c). The first PC structure, with a frequency of $a/\Lambda=0.60$, is located in the PBG (PCWG), as shown in Fig. 1(b). The second PC structure, with a frequency of $a/\Lambda=1.12$, is located in the high-frequency region (PCHG), as shown in Fig. 1(b). The third PC structure, with a frequency of $a/\Lambda=0.55$, is located in the low-frequency region (PCLG), as shown in Fig. 1(c).

To fabricate the PC-LEDs, the GaN-based green LEDs with a green emission at 525 nm were first grown by metal organic chemical vapor deposition on a $c$-plane sapphire substrate. The green LEDs consisted of the following layers: a 2 $\mu$m thick Si-doped GaN layer, a MQW active layer consisting of undoped InGaN wells and undoped GaN barriers, and a Mg-doped p-GaN with a thickness of 0.12 $\mu$m. A hole concentration of $3 \times 10^{17}$ cm$^{-3}$ was obtained after thermally annealing the p-GaN. The green LEDs with various PC structures were then fabricated by using the NIL process. Figure 2 describes a process flow for the fabrication of PC structures on the p-GaN layer using NIL and dry-etching processes. The LED samples consisted of imprint resists/Cr (10 nm)/p-GaN/MQW layer/n-GaN/sapphire, as shown in Fig. 2(a). The stamp for NIL was prepared using laser holography. A thermal nanoimprint process was performed with a pressure of 50 bar at 145 °C using a nanoimprint machine from Obducat AB, as shown in Fig. 2(b). The thermal imprint resist mrl-8020 (Microresist technology GmbH) was used as a mask for Cr patterning. The NIL mask was formed on the 2 in. green LED wafer. After completing the NIL process, the residual layer was removed by O$_2$ reactive ion etching [Fig. 2(c)]. Then, a p-GaN layer with a Cr mask was etched by inductively coupled plasma (ICP) etching using Cl$_2$/CH$_4$/H$_2$/Ar gases [Fig. 2(d)]. To minimize etching damage in the MQW layer in the green LED, the hole etch depths for PC structures were limited within the thickness of p-GaN. After using the mesa process for electrode formation, an indium tin oxide (ITO) film was deposited as a transparent layer on the p-GaN. Then, a Cr/Au layer was deposited by electron-beam evaporation on the n-GaN and transparent ITO layer as an n- and p-pad electrode, respectively.

Figure 3 shows scanning electron microscopy (SEM) images of p-GaN layers of LEDs with PCWG [Figs. 3(a) and 3(b)], PCLG [Figs. 3(c) and 3(d)], and PCHG [Figs. 3(e) and 3(f)]. The period (a) and hole radius (r) of PCWG were 309±4 and 94.5±6.5 nm, those of PCHG were 607±12.5 and 203±10 nm, and those of PCLG were 295±10 and 83.5±1.5 nm, respectively. The etching depth of p-GaN for PCWG and PCHG was 100 nm and that for PCLG was 65 nm. These results were well agreed with the simulation result in Fig. 1.

Figure 4 shows the dependency of the photoluminescence (PL) detection angle on the PL spectra of the green LEDs with PCWG, PCLG, and PCHG. The detection angle was changed by adjusting the distance between PL detector and LED samples. Figure 4(a) shows that the integrated PL intensity of the PL peak measured at a large detection angle of 140° was increased by ninefold for PCWG, 4.6-fold for PCHG, and fourfold for PCLG, compared to an LED without a patterned structure. This result shows that the PL emission intensity of PCWG is about two times stronger than either PCHG or PCLG, while the PL emission intensities of PCHG and PCLG are almost the same. This indicates that using a PCWG structure with a PBG for green light is very important to realize the high efficiency green LED. When the detection angle for PL measurement was decreased from 140° to 60°, as shown in an inset in Fig. 4(b), the integrated PL intensity was increased by 25-fold for PCWG, 5.6-fold for

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**FIG. 2.** (Color online) A schematic of the fabrication flow of PC-LEDs using the nanoimprint lithography and the ICP etching process; (a) sample preparation, (b) the nanoimprint lithography process, (c) residual layer removal and Cr patterning, and (d) the p-GaN ICP etch process.

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**FIG. 3.** (Color online) SEM images of p-GaN for a green LED with (a) and (b) PCWG, with (c) and (d) PCLG, and with (e) and (f) PCHG on p-GaN, respectively.

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**FIG. 4.** (Color online) Photoluminescence (PL) spectra of green LEDs with PCWG, PCLG, PCHG, and no patterning structure at a collection angle of (a) 140° and (b) 60°.

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PCHG, and sixfold for PCLG, compared to an LED without a patterned structure. Figures 4(a) and 4(b) show that the PL intensity of LEDs with a PCWG was increased by twofold by decreasing the detection angle from 140° to 60°, but the PL intensities of LEDs with PCLG and PCHG were not. These results show that the intensity and the direction of PL emission of LEDs with PCWG are more intense and vertical, compared to those of LEDs with PCLG and PCHG. This is due to the redirect effect of light from a laterally guided mode to a vertically radiated mode in LEDs with PCWG. The small increase of PL intensity in LEDs with PCLG and PCHG, as shown in Figs. 4(a) and 4(b), is attributed to the surface-texturing effect rather than the PC effect in patterned structures because two structures do not have PBG for green emission. The blueshift of PL peak of LEDs with PCWG, PCLG, and PCHG compared to LEDs without a patterned structure, as shown in Fig. 4, can be attributed to a band-filling effect by the increased carrier concentration in the quantum well due to the easy access of laser beam through the air holes to the quantum well in order of no patterned structure, PCLG, PCHG, and PCWG.

To study the electroluminescence (EL) emission from green LEDs having nanopatterned PC structures with and without PBG for green emission, the current-voltage, and light output–current (L–I) characteristics of green LEDs with PCWG and PCHG were measured. The forward voltages of LEDs with PCWG, PCHG, and no patterned structure were 4.2, 3.6, and 3.5 V at an input current of 20 mA, respectively. The series resistances of LEDs with PCWG, PCHG, and without a patterned structure were 20.16, 17.23, and 17.19 Ω, respectively. By increasing the hole density and surface area of holes in the p-GaN layer from PCWG to PCHG, the electrical characteristics were significantly degraded, which was attributed to the ICP plasma-etch damage in the p-GaN layer.19 Figure 5 shows L–I characteristics of LEDs with PCWG and PCHG. The optical output power of the green LEDs was measured using a 2 cm diameter calibrated Si photodiode connected to an optical power meter on top of a LED sample at an EL detection angle of 110°, as shown in the inset in Fig. 5. The optical output power of green LEDs with PCWG increased by twofold, compared to that of green LEDs with PCHG, even though the electrical characteristic was significantly degraded.

In summary, a green LED having a PC structure with PBG (PCWG) was fabricated by the NIL process and was compared with green LEDs with PC structures without PBG (PCLG and PCHG). The integrated PL intensity of LEDs with PCWG increased by 3.8 times at a small detection angle of 60° and increased by two times at a large detection angle of 140°, compared to those of LEDs with PCLG and PCHG, respectively. The collection-angle dependent PL intensity indicated that the PL enhancement from PCWG is due to the PC effect, but those of PCLG and PCHG are due to the surface-texturing effect. The light output power of LEDs with PCWG was increased by two times, compared to those with PCHG, even though the electrical property of LEDs with PCWG was significantly degraded due to the ICP etch damage produced during the formation of air holes in the p-GaN layer.

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