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Enhanced light extraction of InGaN-based green LEDs by nano-imprinted 2D photonic crystal pattern

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Abstract
In this paper, we propose a simple, low cost and mass producible nanoimprint lithography (NIL) method to texture the surface of GaN-based light emitting diodes (LEDs) with a two-dimensional photonic crystal (2DPC). Such a 2DPC structure not only enhanced the light output power but also changed the far-field pattern simultaneously. Also, a TiO_2/SiO_2 omnidirectional reflector (ODR) was deposited on the backside of the LEDs to further increase the light output power. Under 350 mA current injection, it was found that forward voltages were 3.35, 3.34 and 3.75 V while the light output powers of the LEDs were 59.5, 92.5 and 112.1 mW for the conventional LED, the PCLED with 20 nm depth, and the PCLED with 120 nm depth all with chip size of 1 mm × 1 mm, respectively. A 88.4% enhancement in light output power of PCLED with a 120 nm depth and ODR on the backside could be achieved when compared to the conventional LED under the driving current of 350 mA. From the measurement results, it was also found that the NIL process does not degrade the electrical properties of the fabricated LEDs.

(Some figures in this article are in colour only in the electronic version)

Introduction

The GaN-based light emitting diode (LED) has attracted great interest due to its broad applications such as full-color displays, traffic signals, cellphone backlight, exterior automotive lighting, printers, etc [1, 2]. It has many advantages, such as energy saving, long lifetime, environmently friendly and stable. So it has a promising future to become a next generation light source. However, the external quantum efficiency of a GaN-based LED still requires improvement. This comes from the fact that the refractive index of GaN ($n_{\mathrm{GaN}} = 2.45$) differs greatly from that of the air ($n_{\mathrm{air}} = 1$). The critical angle at the GaN–air interface determined by Snell's law is about 24° ($\theta c = \sin^{-1}(n_{\mathrm{air}}/n_{\mathrm{GaN}})$), which limits the light output efficiency to 8.7% (determined by $(1 - \cos\theta c)$) [3]. A large fraction of light generated in the active region of the LED is absorbed by the GaN material and the metal pad at the GaN surface. Some efforts have been made to increase the light extraction efficiency of an LED by making the GaN surface rough [4–7]. These methods improved the opportunities for photons to escape from GaN to the air, thus increasing the light output power by 40–60%.

Because of the enhancement of the light extraction efficiency in LEDs, photonic crystals (PC) have been the subject of a great deal of attention in the LED industry [8–10]. Several groups have used two-dimensional photonic crystal (2DPC) structures on LED surfaces to effectively extract light out of high dielectric LED materials. In those groups' reports, e-beam lithography has been the most popular technology used to fabricate sub-μm structures for 2DPC on LED surfaces. Kim *et al* developed a 2DPC with rectangular arrays of holes on the GaN-based LEDs using a two-step holographic exposure technology to rotate LED samples by 90° [11]. Hsieh *et al* also developed a one-shot laser holographic exposure involving three-beam-interference technology for patterning a triangular-arrayed 2DPC on the InGaN-based LED, and investigated the characteristics of the formed 2DPC green LED [12]. Any kinds of patterns as small as a few tens of nanometers can be formed using e-beam lithography. However, this technique has a very low throughput and cannot be applied for the mass production of LED devices. Compared to e-beam lithography, nanoimprint lithography (NIL) is much simpler and has much higher throughput.

In this work NIL is used because it is one of the most promising technologies for nanosized pattern fabrication due to its high resolution and high throughput patterning capability with extremely low cost. In the NIL process, alignment is very difficult since physical contact between the imprint stamp and substrate is inevitably required. 2DPC patterns comprise a dot array of 100–700 nm but do not require precise alignment. As the result, NIL is a suitable patterning technology for the fabrication of 2DPC patterns in LEDs. Also, depositing an omnidirectional reflector (ODR) structure on the bottom side of the LEDs to reflect the downward light into a useful direction has been proven effective to enhance the light output power [13]. Also, Lin *et al* have shown that the ODR with a TiO_2/SiO_2 stack does have a better performance than a metallic ODR [14]. Therefore, in this research, we used NIL to pattern a 2DPC structure on the top surface of the GaN-based green LEDs with the ODR structure on the bottom side to enhance the light output power. A different depth of the PC structure was fabricated simultaneously for optimizing the enhancement in light output power of the GaN-based green LEDs.

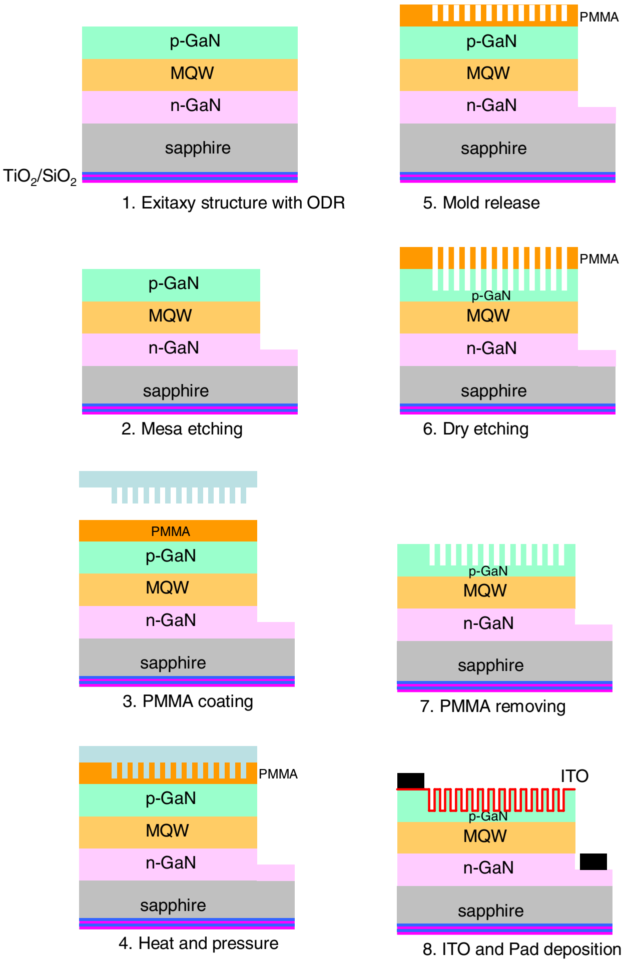
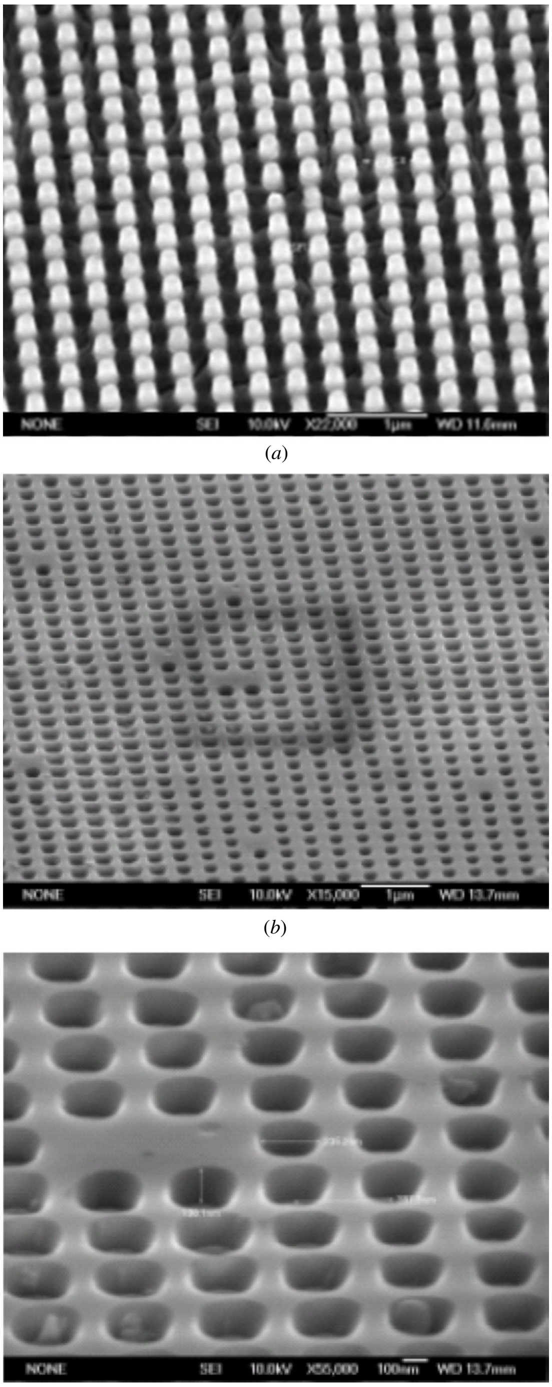


Figure 1. Fabrication flowchart of the GaN-based green LED.

Device fabrication

The GaN-based green LED structure, from bottom to top, consisted of a 30 nm thick GaN nucleation layer on a sapphire substrate, a 2 μm thick Si-doped n-GaN buffer layer, an unintentionally doped InGaN/GaN multiple quantum well active region (5 pairs, InGaN/GaN are 3/7 nm in thickness), a 50 nm thick Mg-doped p-AlGaN electron blocking layer, a 0.15 μm thick Mg-doped p-GaN contact layer and a Si-doped n-InGaN/GaN short period superlattice structure. Detailed process steps are shown in figure 1. The ODR of TiO_2/SiO_2 multilayer stake was directly deposited onto the backside of the epitaxy structure we fabricated (i.e., step 1) by an E-gun evaporator. The pairs of the deposited ODR are 14 and the thickness and refractive indexes of the deposited TiO_2/SiO_2 are 56/77 nm and 2.52/1.48, respectively. The details of the ODR structure are described elsewhere in [13].

The LEDs with a size of 1 mm × 1 mm are fabricated using standard photolithography, depositing 1 μm SiN_x as etching mask by plasma enhanced chemical vapor deposition (PECVD) and BCl_3/Cl_2 inductively coupled plasma (ICP) (flow 10/30 sccm, pressure 0.33 Pa, ICP power of 200 W, RF power of 200 W) etching for current isolation purposes. The p-GaN and active layers are partially etched by an ICP etcher to expose an n-GaN layer for electrode formation (i.e., step 2). We then performed NIL process to pattern the p-GaN layer. First, we spin coated a thermosetting polymer layer on top of the p-GaN (i.e., step 3). Secondly, we placed a silicon mold onto the thermosetting polymer film. The silicon mold was fabricated by using e-beam lithography and dry etching. By applying a pressure of 20 atm, we heated the LED samples at 130 °C for 2 min above the transition temperature of the thermosetting polymer (i.e., step 4). Thirdly, the silicon mold was cooled to room temperature to release it from the LED sample wafer (i.e., step 5) [15]. We then used an ICP etcher with short oxygen based plasma to remove the residual PMMA layer and transferred the pattern onto PMMA. Subsequently, we etched the exposed p-GaN by ICP (i.e., step 6) and the etch selectivity of the PMMA with a thickness of 160 nm on the p-GaN was about 10. Finally, we used acetone to remove the PMMA on the patterned p-GaN layer (i.e., step 7). These LED samples were separated into two sets for different etching depths, 20 nm and 120 nm. An indium tin oxide (ITO) of 250 nm in thickness was deposited on the p-GaN layer as the transparent conductive layer by the E-gun evaporator. The samples were then annealed at 500 °C for 10 min in air. The Cr/Pt/Au (50/50/2500 nm) metals were deposited for the p- and n-contact pads (i.e., step 8). We used a simulator (R-soft) to design the PC structure. A photonic bandgap was created at a frequency (a/λ) and a ratio (r/a) of 0.578 and 0.25, respectively, for green light ($\lambda = 510$ nm). According to the simulation result, the diameter and the periodic distance of the PC structure were chosen as 180 and 295 nm, respectively, for higher extraction efficiency [16, 17]. The pattern sizes of Si mold, PMMA and p-GaN are 170 ± 10, 180 ± 20 and 180 ± 20 nm, respectively. The distances of Si mold, PMMA and p-GaN are 275 ± 10, 295 ± 20 and 295 ± 20 nm, respectively. For comparison, conventional LEDs (here meaning LEDs without NIL process) with ODR were also fabricated. Figure 2(*a*) shows a scanning electron microscope (SEM) micrograph of the imprinted patterns on the GaN surface. It can be clearly seen that the pattern was accurately transferred onto the polymer film. It was also found that there are some defects on the surface. We presume that the situation was caused by the mold when it was lifted from the surface. The density of the defects on the surface is approximately 1.67×10^7 cm^{-2} in figure 2(*b*). Figure 2(*c*) shows an enlarged view of figure 2(*b*). It can be seen that the surface of the defect is flat, so it is reasonable to presume that there were some defects on the mold previously.



(*a*)

(*b*)

(*c*)

Figure 2. (*a*) SEM images of the mold. (*b*) SEM images of imprinted patterns on the GaN surface. (*c*) The SEM image shows an enlarged view of (*b*).

Result and discussion

Figure 3 plots the current-dependent illuminant intensity (*L–I* curve) for both the LED and PCLEDs. Obviously, the *L–I* curve of PCLED moved to the region having larger illuminant intensity. This demonstrates that the light extraction from LED was definitely enhanced via the fabricated 2DPC on the top p-GaN layer. At the driving current of 350 mA, the LED output powers were 59.5, 92.5 and 112.1 mW for the conventional LED, 20 nm PCLED and 120 nm PCLED, respectively. Compared with the conventional LED, the illuminant intensity of PCLED was increased by factors of 1.55 and 1.88 for 20 nm PCLED and 120 nm PCLED, respectively. In other words, we can achieve 88% for 120 nm PCLED by using the simple imprint lithography. In addition, the illuminant intensity of 120 nm PCLED was increased by a factor of 1.21 compared to the emission of 20 nm PCLED. Since the LED and ODR structures of all LEDs were the same, the enhancement of the PCLED was contributed by the 2DPC structure on the surface. Furthermore, such a result suggests that the deeper etch depth can scatter light more efficiency [18].

At a driving current of 350 mA, the working voltages for the conventional LED, 20 nm and 120 nm PCLED were 3.35 V, 3.34 V and 3.75 V, respectively. We presume that the electric characteristic of 20 nm PCLED compared to the conventional LED was not affected by the slight depth. The higher voltage of 120 nm PCLED could be due to the poor ITO step coverage on the sub-micro-pattered p-GaN surface and voids may be formed within the PC structure to increase the operated voltage. However, the working voltage of around 4 V is still acceptable for practical applications and can be improved by tuning the ITO deposit rate and temperature. It is worth noting (figure 4) that the emitting spectrum of PCLED biased with 350 mA shares the same characteristics with the conventional LED which implies that the fabricated 2DPC mainly works to enhance light extraction from the LED. Both emission wavelengths of the conventional LED and PCLED are 510 nm.

We also measured the far-field light output radiation patterns of the conventional LED and 120 nm PCLED to further investigate the optical influence of 2DPC on the light

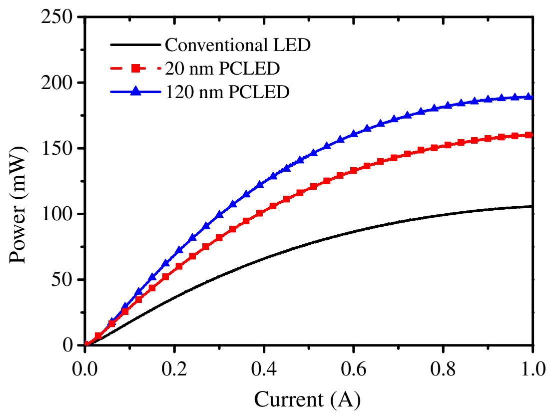


Figure 3. Measured *L–I* characteristics of the fabricated LEDs.

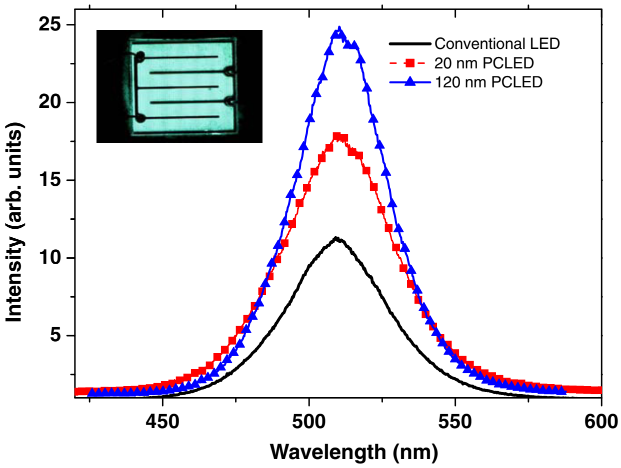


Figure 4. The room temperature EL spectra at a driving current of 350 mA. The inset shows the EL image.

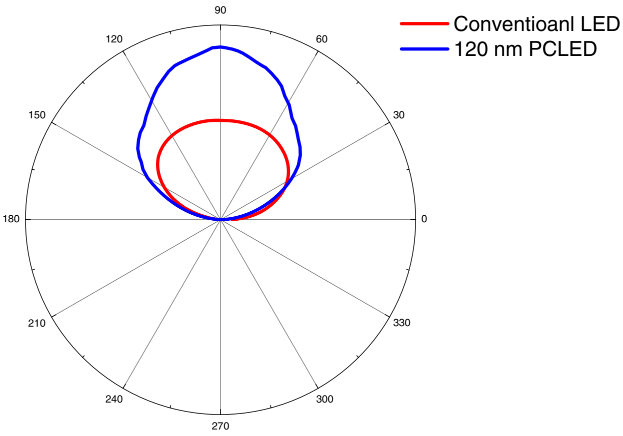


Figure 5. Comparison of the radiation patterns in air between the conventional LED and LEDs with 2DPC.

output of LEDs, at a driving current of 350 mA. As shown in figure 5, the radiation patterns of conventional LED and PCLED are Lambertian type, but a more collimated beam pattern is resulted for PCLED. It is worthnoting that the far-field beam pattern of PCLED is not very highly collimated because the period *d* of the 2DPC is large enough to have many diffraction orders in the green light regime resulting in light leakage along many directions. However, since the leakage bands locating above the light cone have different leakage strengths, more light leaks in the out-of-plane direction. Increased directionality was achieved by the high reflectivity ODR structure [19] since it could reflect most downward light. Also, the fabricated PC structure on the surface could enhance the light output power normal to the surface [20]. The LEDs combined with PCs and ODR were more collimated, and the output power normal to the surface could be enhanced greatly.

Conclusion

GaN-based green LEDs with 2DPC on the top surface by NIL process and ODR on the bottom side were fabricated successfully in this research. A simple, low cost and mass producible NIL method to texture the surface of the GaN-based green LEDs was proposed. At the injection current of 350 mA, it was found that forward voltages were 3.35, 3.34 and 3.75 V while the LED output powers were 59.5, 92.5 and 112.1 mW for the conventional LED, 20 nm PCLED and 120 nm PCLED, respectively. The 88.4% enhancement in LED output power by patterning the nanoimprint 2DPC with depth 120 nm was achieved when compared to the conventional LED. It was also found that the emitting spectrum of PCLED shares the same characteristics with the conventional LED, which implies that the fabricated 2DPC on the surface mainly works to enhance light extraction. The final far-field pattern of PCLED is more collimated compared with that of the conventional LED.

Acknowledgments

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