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Enhanced light output power of GaN-based vertical-injection light-emitting diodes with a 12-fold photonic quasi-crystal by nano-imprint lithography

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Abstract

GaN-based thin-film vertical-injection light-emitting diodes (VLEDs) with a 12-fold photonic quasi-crystal (PQC) by nano-imprint lithography (NIL) are fabricated and presented. At a driving current of 20 mA and with a chip size of 350 μm × 350 μm, the light output power of our thin-film LED with a 12-fold PQC structure reaches 41 mW. This result is an enhancement of 78% when compared with the output power of a VLED without a PQC structure. In addition, the corresponding light radiation pattern shows a narrower beam shape due to the strong guided light extraction effect by the formed PQC structure in the vertical direction.

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

GaN-based materials have attracted considerable interest in many optoelectronic device applications, such as light-emitting diodes (LEDs) and laser diodes (LDs). Recently, high-brightness GaN-based LEDs have penetrated the markets of outdoor displays, traffic signals, LED-backlit liquid crystal displays and direct-view large-area signage [1–3]. To extend the application arm of a GaN-based LED to projectors, an automobile headlight and even general lighting, further improvement on optical power and light extraction efficiency is required. The thin-film LED structure is only recently developed and is already a promising candidate to achieve the above goal. The process to fabricate the thin-film GaN LED structure consists of removing the sapphire using an excimer laser [4–6] and roughening the revealed n-doped GaN [7]. Recently, we reported an increase in the extraction efficiency of GaN-based LEDs by using the surface roughening technique [8, 9]. To improve the light scattering effect or extraction efficiency of a roughened surface, numerous methods of fabricating nanostructures on the GaN surface have been reported, such as GaN nanorods using inductively coupled plasma reactive-ion etching (ICP-RIE) with a nano-mask [10], growth of free dislocation InGaN/GaN MQW nanorod arrays by metal organic-hydride vapor phase epitaxy (MO-HVPE) [11], a nanoporous GaN:Mg structure using photochemical etching (PEC) [12] and InGaN/GaN nanoposts using e-beam lithography [13]. To maximize the light scattering performance of the nanostructure, we utilize a nano-imprint lithography (NIL) technique of fabricating a nano-hole of a photonic quasi-crystal (PQC) structure on

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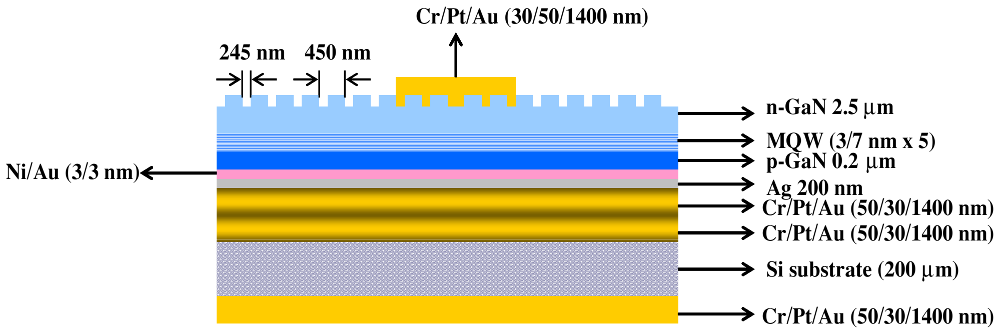


Figure 1. A schematic diagram of a vertical-injection LED structure with a 12-fold PQC structure.

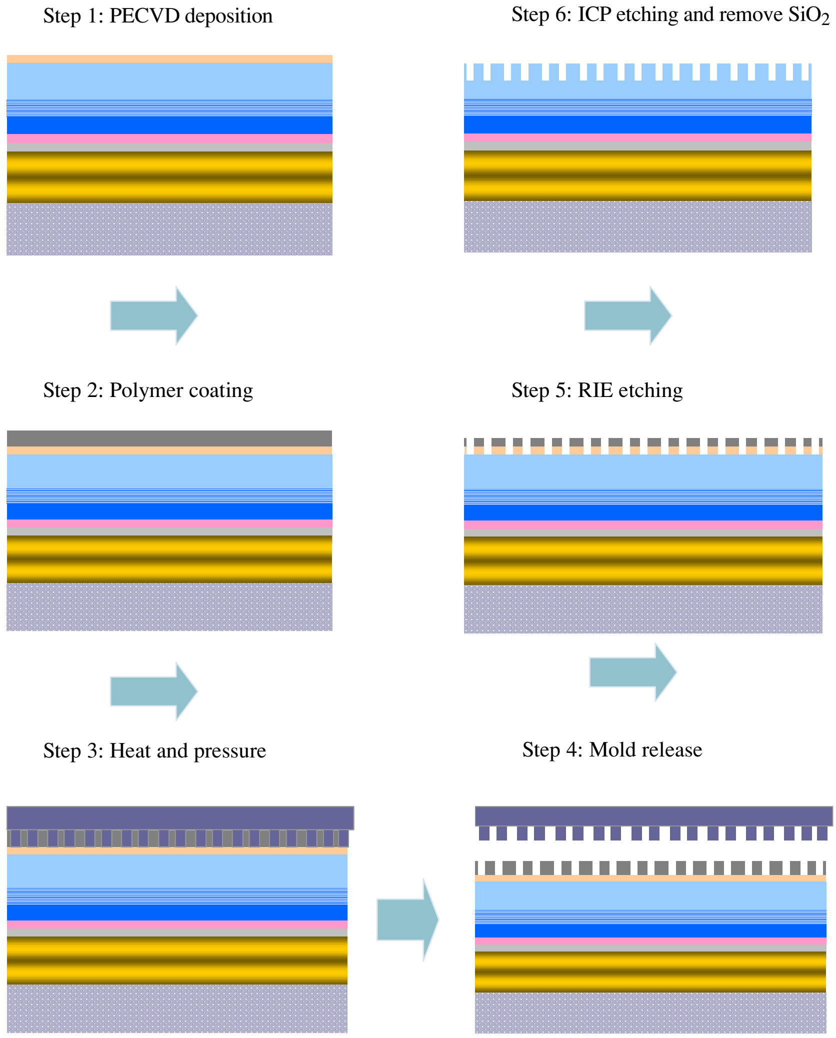


Figure 2. Schematic diagram of process flow for nano-imprint lithography.

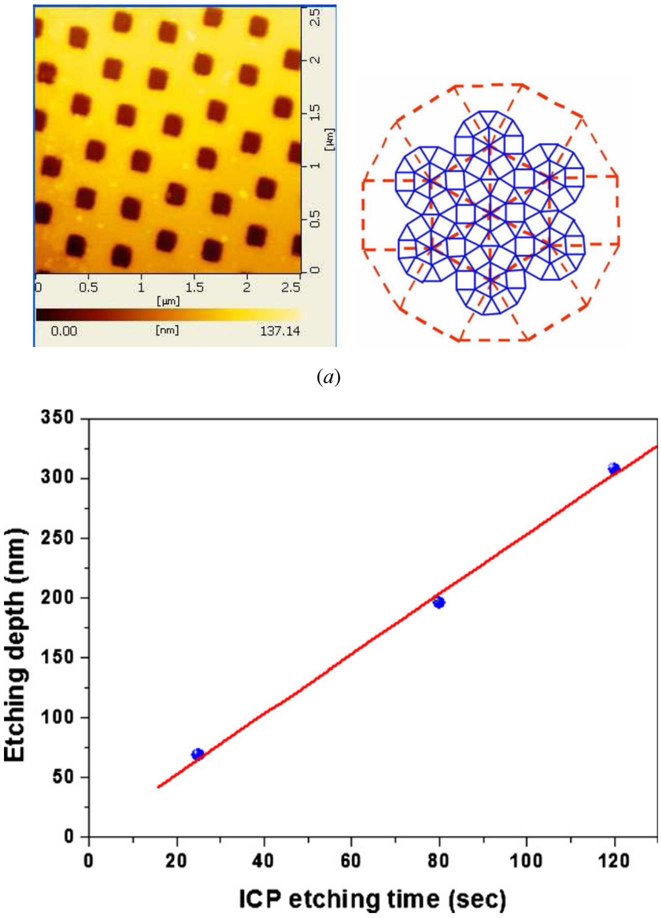
the GaN vertical-injection LEDs (VLEDs) epitaxial film. Furthermore, to demonstrate ultra-high brightness GaN-based LEDs, the electrical and optical characteristics of a thin-film VLED incorporated with a 12-fold PQC structure by NIL are presented.

Our prepared GaN LED wafer consists of a 50 nm thick GaN nucleation layer grown at 550 °C, a 2 μm thick undoped GaN buffer layer grown at 1050 °C, a 3 μm thick Si-doped n-GaN layer grown at 1050 °C, an unintentionally doped InGaN/GaN multiple quantum well (MQW) of the active region grown at 770 °C, a 50 nm thick Mg-doped p-AlGaN electron blocking layer grown at 1050 °C and a 0.2 μm thick Mg-doped p-GaN contact layer grown at 1050 °C. The MQW active region consists of five periods of 3 nm/7 nm thick $In_{0.21}Ga_{0.79}N$/GaN quantum well layers and barrier layers. Figure 1 is a schematic diagram for our GaN VLED with PQC structures. To fabricate the normal VLED, we use the same process as in [14]. Figure 2 is a detailed process flow schematic diagram for our NIL. Step 1: 50 nm SiO_2 is deposited onto the n-GaN surface by using plasma-enhanced chemical vapor deposition (PECVD) for PQC patterning. Step 2: we spin coat a polymer layer on top of SiO_2. Step 3: we then place a patterned mold with 12-fold PQC design onto the dried polymer film. By applying high pressure, we are able to heat the LED samples to above the glass transition temperature of the polymer. Step 4: the LED samples and the mold are then cooled down to room temperature to release the mold. Step 5: we then use RIE with the CF_4 plasma to remove the residual polymer layer and transfer the pattern onto SiO_2. Step 6: we increase the ICP etching depth of n-GaN from 65 to 310 nm by using different etching times to study the performances of our samples. After the n-GaN etch, a buffer oxidation etchant (BOE) is used to remove the residual SiO_2 layer. To examine the etching depth and dimension size of a PQC structure, a scanning electron microscope (SEM) (Hitachi FE-SEM S-5000) and atomic force microscopy (AFM) (Seiko AFM SKII) are used in this paper.

Figure 3(*a*) shows a 2.5 μm × 2.5 μm AFM image of our designed 12-fold PQC based on square–triangular lattice. The lattice constants and hole diameters are 450 nm and 245 nm, respectively. The recursive tiling of offspring dodecagons packed with random ensembles of squares and triangles in dilated parent cells forms the lattice as shown in the right side of figure 3(*a*). Figure 3(*b*) shows the etching depth of the n-GaN layer as a function of etching time of the ICP condition in our experiments. The etching rate of the n-GaN layer is approximately 2.6 nm s^{-1}, and three different etching depths of 65, 210 and 310 nm are fabricated when etching times of 25, 80 and 120 s are applied, respectively.

For comparison, figures 4(*a*), (*b*) show the SEM images of a normal VLED, and figures 4(*c*), (*d*) show the SEM images of a VLED without PQC structure devices. Figure 4(*b*) clearly shows that the surface of the normal VLED is very smooth after our ICP thinner process. The measured root-mean-square (RMS) roughness of the n-GaN surface by AFM is as low as 3.5 nm. This is a better RMS value for the n-GaN surface of the VLED after the ICP process for the u-GaN thinner.

The light outputs of our samples are detected calibrating an integrating sphere with a Si photodiode on a LED wafer device. Figure 5 shows the typical current–voltage (*I*–*V*) characteristics. The measured forward voltages under an injection current of 20 mA at room temperature for the normal VLED, the VLED with a PQC (an etching depth of 65 nm), VLED with a PQC (an etching depth of 210 nm) and VLED with a PQC (an etching depth of 310 nm) are 3.78, 3.79, 3.82 and 3.93 V, respectively. Furthermore, in our experiments, the dynamic resistances ($R = \mathrm{d}V/\mathrm{d}I$) of the VLED with a PQC structure (an etching depth of 65 nm) and VLED with a PQC structure (an etching depth of 210 nm) are 26 Ω and 28 Ω, respectively, which are 7–13% lower than that of the normal VLED (30 Ω). This result indicates that the etching surfaces of PQC structures can facilitate the n-type contact to form an Ohmic contact with a low specific resistance when the etching depth ranges from 65 to 210 nm. However, when the etching depth of a PQC structure exceeds 310 nm, the specific resistance becomes higher (33 Ω). The higher resistance may be due to the surface morphology being too rough to form good contacts on the n-GaN etching surface.

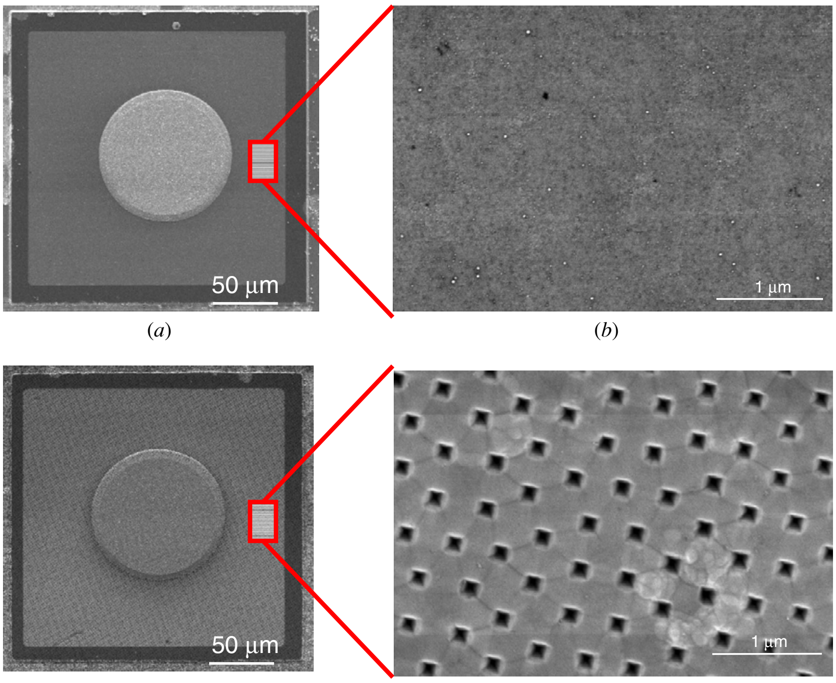


(*a*)

(*b*)

Figure 3. (*a*) AFM image of the n-GaN surface with a PQC structure (left side), a schematic diagram of the 12-fold PQC structure (right side). Panel (*b*) Portrays the etching depth of the n-GaN layer as a function of ICP-RIE etching time.

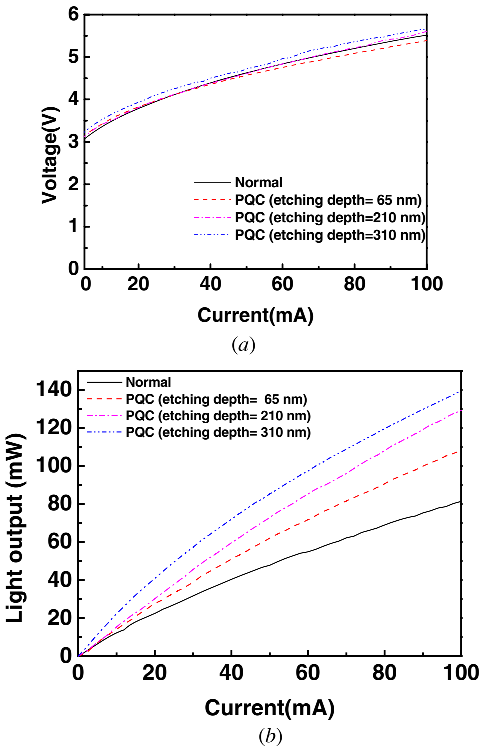
The intensity–current (*L*–*I*) characteristics of our four different types of VLEDs packaged on transistor outline (TO)-cans are shown in figure 5. As expected, the light output powers of VLEDs with a PQC are all higher than that of the normal VLED [15, 16]. At an injection current of 20 mA, the light output powers of the normal VLED, the VLED with a PQC (an etching depth of 65 nm), VLED with a PQC (an etching depth of 210 nm) and VLED with a PQC (an etching depth of 310 nm) are 23, 28, 30 and 41 mW, respectively. Therefore, by sacrificing only 4% on higher voltage, the optimal light output power of the VLED with a PQC structure of an etching depth of 310 nm is enhanced by 78% compared to the normal VLED in this study. Clearly, this enhancement is attributed to the higher light scattering effect by the PQC structure on the n-GaN surface. In addition, the corresponding wall plug efficiencies (WPE) of the normal VLED and the VLEDs with a PQC structure for etching depths from 65 to 310 nm are 31, 37, 39 and 52%, respectively. This is thus addresses a substantial improvement by using the PQC



(*a*) (*b*)

(*c*) (*d*)

Figure 4. SEM images of the n-GaN surface: (*a*), (*b*) normal VLED and (*c*), (*d*) VLED with a 12-fold PQC structure.



(*b*)

Figure 5. (*a*) Current–voltage (*I*–*V*) and (*b*) intensity–current (*L*–*I*) for the VLED with and without a PQC structure.

structures. For a good comparison, the samples we chose are geographically close to each other, and the emission peaks of the typical room-temperature electroluminescence (EL) spectrum are all located at 460 nm at a driving current of 20 mA.

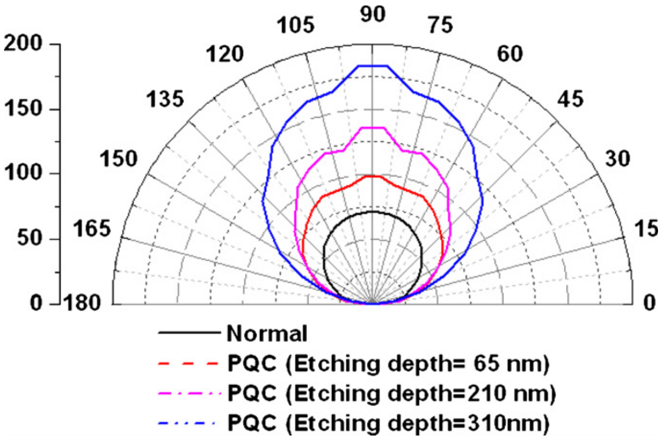


Figure 6. Far-field pattern of the VLED with and without a PQC structure at a driving current of 20 mA.

To further study the influence of the PQC structure on the devices, we also measured the light output radiation patterns of the compared VLEDs packaged on TO-cans at a driving current of 20 mA, as shown in figure 6. It can be seen that the VLED with a PQC structure possesses a much higher extraction efficiency with a narrower view angle of 115° compared to a view angle of 130° for the normal VLED. Additionally, the enhancement percentages of EL intensities in the vertical direction for the VLED with a PQC (an etching depth of 65 nm), VLED with a PQC (an etching depth of 210 nm) and VLED with a PQC (an etching depth of 310 nm) are 38%, 90% and 158%, respectively, compared to that of the normal VLED. This enhancement is attributed to the strong light beam shaping effect in the vertical direction by the PQC structure using the NIL process. With the higher fold symmetry (12-fold) of our designed PQC, the beam shaping capability of the PQC performs better than that of the normal photonic crystal (PC) structure along the azimuth angle [17]. Both the PC and the PQC structures improve total emission and the amount of light channeled. The PC structure can have considerable intensity variation in the illumination profile—parameters could be re-optimized to improve the profile, but this would be at the expense of extraction efficiency. Further, the PQC structure actually improves illumination homogeneity and overall emission simultaneously. In terms of brightness close to the vertical axis, EL intensity is increased compared to that of a normal VLED [17].

In summary, GaN-based VLEDs with a PQC structure that incorporates NIL is fabricated. At a driving current of 20 mA and with a chip size of 350 μm × 350 μm, the optimal light output power can reach 41 mW, and the WPE of the VLEDs with a specific PQC structure (etching depth of 310 nm) can achieve 52%. The results show an increase of 78% and 67%, respectively, when compared with the results of the normal VLED. The corresponding light radiation pattern shows a narrower beam shape due to the strong light beam shaping effect by our 12-fold PQC structures.

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