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Enhanced light output from a nitride-based power chip of green light-emitting diodes with nano-rough surface using nanoimprint lithography

H W Huang[1,2,4], C H Lin[2], C C Yu[2], B D Lee[2], C H Chiu[1], C F Lai[1], H C Kuo[1], K M Leung[3], T C Lu[1] and S C Wang[1]

[1] Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30050, Taiwan, Republic of China
[2] Mesophotonics Limited, Hsinchu 300, Taiwan, Republic of China
[3] Department of Computer and Information Science, Polytechnic University, Six Metrotech Center Brooklyn, NY 11201, USA

E-mail: steven.huang@mesophotonics.com

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Abstract
Enhanced light extraction from a GaN-based power chip (PC) of green light-emitting diodes (LEDs) with a rough p-GaN surface using nanoimprint lithography is presented. At a driving current of 350 mA and with a chip size of 1 mm × 1 mm packaged on transistor outline (TO)-cans, the light output power of the green PC LEDs with nano-rough p-GaN surface is enhanced by 48% when compared with the same device without a rough p-GaN surface. In addition, by examining the radiation patterns, the green PC LED with nano-rough p-GaN surface shows stronger light extraction with a wider view angle. These results offer promising potential to enhance the light output powers of commercial light-emitting devices by using the technique of nanoimprint lithography under suitable nanopattern design.

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

1. Introduction

Recently, the impressive developments of high brightness gallium nitride (GaN)-based light-emitting diodes (LEDs) have made it possible for LEDs to be implanted in large size flat-panel displays [1, 2]. Such incorporated LED backlight modules allow the images to be much sharper and more colorful. To quickly penetrate the consumer display market with LED-based solutions, there is a great need to improve the internal as well as external quantum efficiency in order to increase their light output power and to reduce the total cost of the LED modules. However, the external quantum efficiency of GaN-based LEDs is generally low, because the refractive index difference between the nitride epitaxial material and the air environment is high. Therefore, the resulting critical angle at which light generated in the InGaN/GaN active region can escape is approximately [$\theta_c = \sin^{-1}(n_{\mathrm{air}}/n_{\mathrm{GaN}})$] $\sim 23°$, which limits the external quantum efficiency of conventional GaN-based LEDs to be only a few per cent [3]. The light output power of LEDs can be enhanced either by texturing the top surface or by tilting the sidewalls of the LEDs. Studies on improving the light extraction efficiency (external quantum efficiency) to increase the brightness of the LEDs have been intensely addressed in the past [3–8]. Recently, we reported an impressive increase in the extraction efficiency of GaN-based LEDs by using surface roughening techniques [7, 8]. The photons generated within the LEDs are effectively diffracted out of the surface of the semiconductor materials by the nanoscale roughened surfaces formed, or in other words subwavelength surface textures.

To fabricate a nanoscale surface pattern with good uniformity for manufacturing purposes, various well-known

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[4] Author to whom any correspondence should be addressed.

techniques can be utilized. Electron-beam lithography (EBL) [9, 10] is the most common technique to fabricate very fine structure; however, it is very expensive and time consuming to define a large patterned area. Laser interference lithography (LIL) [11] is a well-developed technique to fabricate nanostructures with high symmetry for a large area; however, the stability of the laser interference system and forming complicated nanostructures without symmetry are still rather challenging. Nanoimprint lithography (NIL) [12, 13], on the other hand, is a promising manufacturing technique after a decade of development. The maturity of imprint materials and working mechanisms allow NIL to possibly be the best candidate to achieve a good nanostructure resolution and high manufacture throughput at a reasonable cost for LED devices [13]. In this study, we investigated the light output performance and the production visibility of a GaN-based LED with a nano-rough p-GaN surface by using nanoimprint lithography. The result showed that the light output efficiency of LED with a nano-rough surface was significantly higher than that of a conventional LED without a nano-rough surface. Additionally, the current–voltage (I–V) measurement demonstrated that the forward voltage of the LED with a nano-rough surface was lower than that of a conventional LED from the same wafer using standard device processes.

2. Experimental details

Our GaN-based green LED sample wafers were grown by using metal–organic chemical vapor deposition (MOCVD) with a rotating-disk reactor (Emcore D75™) on a c-axis sapphire (0001) substrate at the growth pressure of 200 mbar. The LED structure consisted of a 50 nm thick GaN nucleation layer grown at 500 °C, then a 2 μm undoped GaN buffer layer at 1050 °C, a 3 μm thick Si-doped GaN layer grown at 1050 °C, an unintentionally doped InGaN/GaN multiple quantum well (MQW) active region grown at 770 °C, a 50 nm thick Mg-doped p-AlGaN electron blocking layer grown at 1050 °C, and a 0.1 μm thick Mg-doped p-GaN contact layer grown at 1050 °C. The MQW active region consisted of five periods of 3 nm/7 nm thick $In_{0.3}Ga_{0.7}N$/GaN quantum well layers and barrier layers. The prepared green LED sample wafer then underwent surface texturing by NIL. Figure 1 is a detailed process flow schematic diagram for our NIL process. First, the 50 nm SiO_2 layer was deposited onto the sample surface by plasma enhanced chemical vapor deposition (PECVD) serving as a hard mask. Second, we spin-coated a thermosetting polymer layer on top of the SiO_2. Third, we placed a silicon mold which was fabricated by using e-beam lithography onto the thermosetting polymer film. 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. Fourth, the silicon mold was cooled to room temperature to release it from the LED sample wafer. Finally, a procedure of reactive ion etching (RIE) with 3 min etching time was applied to remove the residual polymer layer and to transfer the defined pattern on the silicon mold onto SiO_2 layer under a gas condition of $CF_4 = 10$ standard cubic centimeters per minute (sccm) with the RF bias power set at 70 W and a chamber pressure of 30 mTorr.

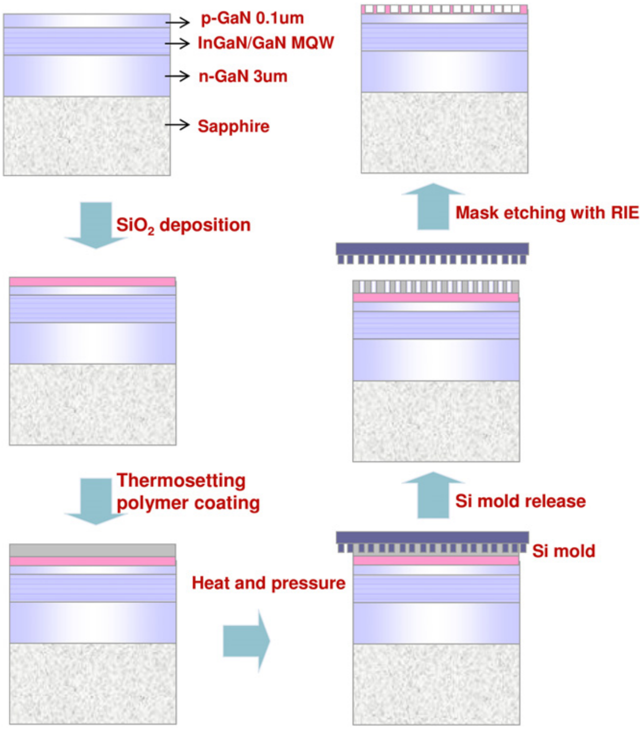
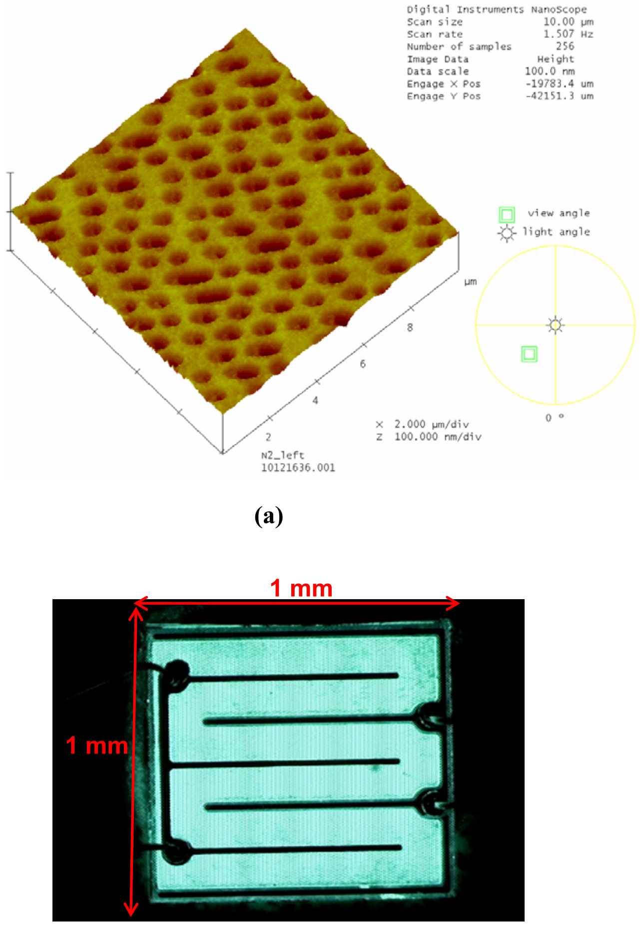


Figure 1. Process flow schematic diagram for nanoimprint lithography.

The p-GaN layer of the LED sample wafer was then etched by inductively coupled plasma reactive ion etching (ICP-RIE) using a gas mixture of Cl_2/Ar. The etching gases, Cl_2 and Ar, were introduced into the reactor chamber through independent electronic mass flow controllers (MFCs) that can control the flow rate of each gas with an accuracy of about 1 sccm. An automatic pressure controller (APC) was placed near the exhaust end of the chamber to control the chamber pressure. The etching rate was about 50 Å min^{-1} under a gas mixture condition of $Cl_2/Ar = 10/25$ sccm with the ICP/bias power set at 200/200 W and a chamber pressure of 2.5 mTorr. The etching depth of p-GaN reached 75 nm after an etching time of 15 s. Finally, we used a buffer oxidation etchant (BOE) to remove the residual SiO_2 layer.

Both the conventional LED and the LED with nano-rough p-GaN surface using NIL were fabricated by the following standard processes with a mesa area of 950 × 950 μm^2. A SiO_2 layer with thickness of 520 nm was deposited onto the LED sample surface by using plasma enhanced chemical vapor deposition (PECVD). Photolithography was used to define the mesa pattern after wet etching of SiO_2 by a BOE solution. The mesa etching was then performed with Cl_2/Ar etching gas in an ICP-RIE system which transferred the mesa pattern onto an n-GaN layer. An ITO layer with thickness of 300 nm was subsequently evaporated onto the p-GaN surface, serving as a transparent conducting layer. The metal pads, composed of Cr/Pt/Au (20/30/1000 nm), were patterned by a lift-off procedure and deposited onto the samples by electron beam evaporation.



(a)

(b)

Figure 2. (a) AFM image and (b) plain view photomicrograph of a LED with nano-rough surface using nanoimprint lithography.

For comparison purposes, PC LEDs with and without a nano-rough p-GaN surface were chosen from the same wafer location possessing the same internal quantum efficiency and the same emitting wavelength.

3. Results and discussion

Figure 2(a) shows the atomic force microscopy (AFM) pattern image of a PC LED with a nano-rough surface using NIL before RIE etching. The image indicated that the nanohole dimension and density on the PC LED's mesa surface were 200–500 nm and 1×10^8 cm^{-2}, respectively, with the polymer layer height of 150 nm. The various nanohole dimensions distributed in our nanopattern design allowed the light emitted inside the nitride epitaxial materials to be diffracted out of the p-GaN surface more effectively when the full width at half maximum (FWHM) of the emitting spectrum as wide (i.e., green LEDs). The operation image of a 1 mm × 1 mm green PC LED with nano-rough p-GaN surface using NIL at a driving current of 350 mA is shown in figure 2(b).

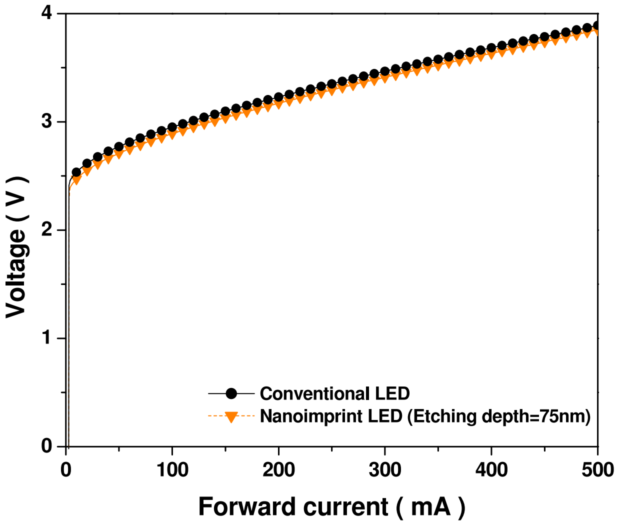


Figure 3. Current–voltage (I–V) characteristics of green PC LEDs with nano-rough surface using nanoimprint lithography and conventional LEDs, respectively.

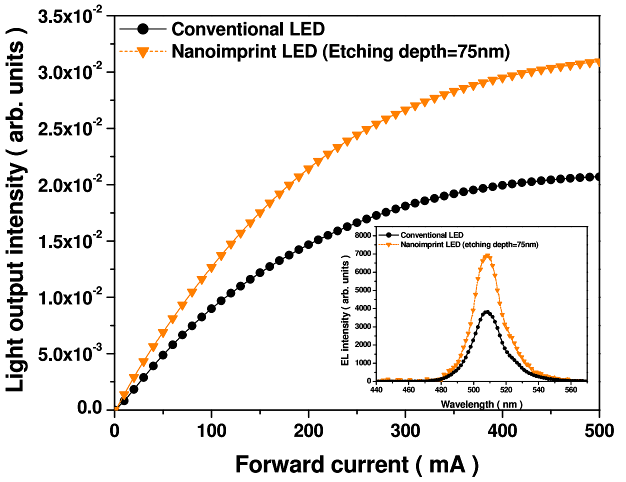


Figure 4. Intensity–current (L–I) characteristics of green PC LEDs with nano-rough surface using nanoimprint lithography and conventional LEDs, respectively. The inset shows the room-temperature EL spectra at a driving current of 350 mA.

The light outputs of our fabricated LEDs packaged on TO-cans were detected by calibrating an integrating sphere with a Si photodiode. Figure 3 shows the typical current–voltage (I–V) characteristics. Under an injection current of 350 mA at room temperature, the measured forward voltages for the green PC LEDs with and without nano-rough surface were 3.51 V and 3.58 V, respectively. Our I–V result indicated that the nano-rough surface formed facilitated p-type ohmic contact, resulting in a lower forward voltage. It is worth noting that the forward voltage of our device met the standard specification of commercial PC LEDs.

Figure 4 shows the intensity–current (L–I) characteristics of our fabricated LEDs packaged on TO-cans. At an injection current of 350 mA, the light output power of the PC LED with nano-rough surface was enhanced by 48% compared to that of the PC LED without nano-rough surface. The inset of figure 4 shows the typical room-temperature electroluminescence (EL) spectra of the compared LEDs obtained by injecting a continuous current of 350 mA. Clearly, both devices possessed the same MQW emission peak of 510 nm.

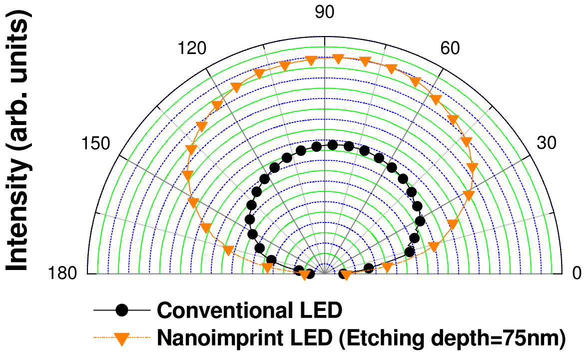


Figure 5. Radiation patterns of PC LEDs with nano-rough surface using nanoimprint lithography and conventional LEDs, respectively.

We also measured the light output radiation patterns of the compared PC LEDs packaged on TO-cans at a driving current of 350 mA, as shown in figure 5. It can be seen that the PC LED with nano-rough surface using NIL possessed higher extraction efficiency with a wider view angle of 155° compared to the PC conventional LEDs with a view angle of 144°. This enhancement was attributed to the strong light-scattering effect by the nano-rough p-GaN surface defined by NIL on our PC LEDs.

4. Conclusion

In conclusion, GaN-based green PC LEDs with nano-rough surface using NIL were demonstrated and fabricated. At a driving current of 350 mA and with a chip size of 1 mm × 1 mm, the light output power of the green PC LED with nano-rough surface using NIL was enhanced by 48% when compared with that of a conventional LED. Furthermore, the strong light-scattering effect of the nano-rough surface defined by NIL resulted in a stronger light extraction with a wider view angle when examining the radiation patterns of fabricated PC LEDs.

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References

[1] Schubert E F 2003 *Light-Emitting Diodes* (Cambridge: Cambridge University Press)

[2] Koike M, Shibata N, Kato H and Takahashi Y 2002 Development of high efficiency GaN-based multi-quantum-well LEDs and their applications *IEEE J. Sel. Top. Quantum Electron.* **8** 271

[3] Huh C, Lee K S, Kang E J and Park S J 2003 Improved light-output and electrical performance of InGaN-based light-emitting diode by microroughening of the p-GaN surface *J. Appl. Phys.* **93** 9383

[4] Fujii T, Gao Y, Sharma R, Hu E L, DenBaars S P and Nakamura S 2004 Increase in the extraction efficiency of GaN-based light-emitting diodes via surface roughening *Appl. Phys. Lett.* **84** 855

[5] Oder T N, Shakya J, Lin J Y and Jiang H X 2003 III-nitride photonic crystals *Appl. Phys. Lett.* **83** 1231

[6] Oder T N, Kim K H, Lin J Y and Jiang H X 2004 III-nitride blue and ultraviolet photonic crystal light emitting diodes *Appl. Phys. Lett.* **84** 466

[7] Huang H W, Chu J T, Kao C C, Hsueh T H, Yu C C, Kuo H C and Wang S C 2005 Enhanced light output of an InGaN/GaN light emitting diode with a nano-roughened p-GaN surface *Nanotechnology* **16** 1844

[8] Huang H W, Kuo H C, Chu J T, Lai C F, Kao C C, Lu T C, Wang S C, Tsai R J, Yu C C and Lin C F 2006 Nitride-based LEDs with nano-scale textured sidewalls using natural lithography *Nanotechnology* **17** 2998

[9] David A, Fujii T, Moran B, Nakamura S, DenBaars S P, Weisbush C and Benisty H 2006 Photonic crystal laser lift-off GaN light-emitting diodes *Appl. Phys. Lett.* **88** 133514

[10] Lai C F, Kuo H C, Chao C H, Hsueh H T, Wang J F T, Yeh W Y and Chi J Y 2007 Anisotropy of light extraction from two-dimensional photonic crystal light-emitting diodes *Appl. Phys. Lett.* **91** 123117

[11] Divliansky I B, Shishido A, Khoo I C, Mayera T S, Pena D, Nishimura S, Keating C D and Mallouk T E 2001 Fabrication of two-dimensional photonic crystals using interference lithography and electrodeposition of CdSe *Appl. Phys. Lett.* **79** 3392

[12] Byeon K J, Hwang S Y and Lee H 2007 Fabrication of two-dimensional photonic crystal patterns on GaN-based light-emitting diodes using thermally curable monomer-based nanoimprint lithography *Appl. Phys. Lett.* **91** 091106

[13] Chang S J, Shen C F, Chen W S, Kuo C T, Ko T K, Shei S C and Sheu J K 2007 Nitride-based light emitting diodes with indium tin oxide electrode patterned by imprint lithography *Appl. Phys. Lett.* **91** 013504