Extraction Efficiency Improvement of GaN-based Light-emitting Diodes Using Sub-wavelength Nanoimprinted Patterns on Sapphire Substrates

Hao Chen, Chao Wang, and Stephen Y. Chou
Nanostructure Laboratory, Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA
chou@princeton.edu

GaN-based LEDs are important for next-generation solid state lighting. However, conventionally, due to large refractive index difference between the GaN and air, the emitted light is significantly trapped inside GaN, giving poor extraction efficiency and large substrate heating[1]. Currently, micron-sized patterns on sapphire substrates (PSS) have been used to improve the light extraction and have achieved good results[2]. Theoretically sub-wavelength nanopatterned sapphire substrates (NSS) should offer far better light extraction, but they have not been well studied experimentally. Here, we report the fabrication of sub-wavelength features with 200 nm pitch of pillar array on the entire 2" sapphire substrates using nanoimprint lithography (NIL), the light extraction improvements of the GaN LEDs grown on the NSS, and the comparison of them with the GaN LEDs grown on the micron-sized patterned (PSS) and the flat surfaced sapphire substrates that were grown in the same run as the NSS.

Triangle-shaped pillar array patterns of 200 nm pitch (subwavelength) and bar arrays with 1 μm pitch were fabricated on the sapphire surface by NIL, which is an effective nanopatterning with high precision over large area with low cost[3]. The major patterning steps include (Fig. 1): (i) deposit SiO_2 etching mask layer and pattern it by NIL; (ii) wet-etch the sapphire substrate using the mask in a mixture of sulfuric acid and phosphoric acid to achieve 55 nm etching depth; (iii) remove oxide mask. The LED structure with InGaN quantum wells for λ=450 nm emission was grown on the substrates by metal-organic chemical vapor deposition (MOCVD). After the growth, GaN mesas and contacts were fabricated (Fig. 2). The electrons and holes are injected through the contacts, and are recombined at the quantum wells, giving out blue light.

The light from the GaN-LEDs grown on the NSS, the micro-scale PSS and the flat substrates were measured, showing that under different driving currents, the LEDs on the 200 nm-pitch patterned sapphire substrates enhances the light output by 74%~88% than the flat sapphire, while the LEDs on the 1 μm-pitch PSS has an extraction enhancement of 41%~50% (Fig. 3).

Besides of improving the light extraction, our study also found that the NSS reduces the threading dislocation density in GaN due to lateral overgrowth on the nanoscale pattern (Fig. 4), showing the NSS capability of improving the crystal quality of GaN, which in turn improves LEDs' internal quantum efficiency.

In summary, this work present a novel and effective method of patterning subwavelength patterns on LED sapphire substrates, and demonstrated that the nanostructures can not only significantly enhance the light extraction than the flat or micron-sized patterns, but also can improve the GaN crystal quality grown.

[1] T.Fujii, etc., Appl. Phys. Lett. **84(6),** 855-857 (2004).
[2] Seong-Muk Jeong, etc., Journal of Crystal Growth **312** 258–262 (2010).
3 Stephen Y. Chou, etc., Science **272** (5258), 85-87 (1996)

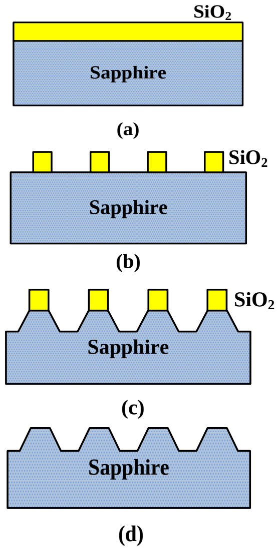

Fig. 1. Scheme of sapphire substrate nano-patterning: (a) oxide mask deposition; (b) NIL and RIE on deposited SiO_2; (c) sapphire anisotropic wet etching; (d) SiO_2 removal.

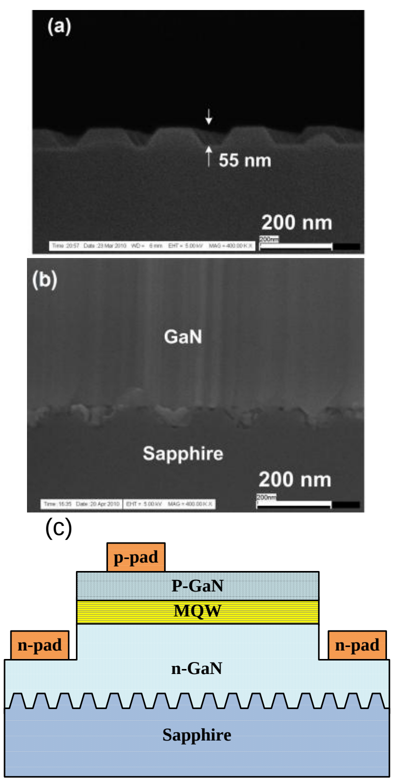

Fig. 2. SEM images of NSS and GaN grown on NSS. (a) 200 nm pitch NPSS (cross-sectional view) before growth; (b) after GaN grown on 200 nm-pitch NSS; and (c) LED device structure with NSS.

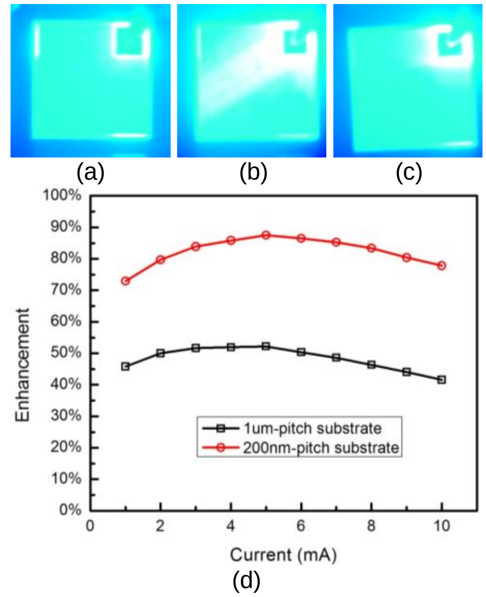

Fig. 3.Optical micrograph of LED devices operating at 1mA injection current with: (a) flat substrate, (b) 200nm-pitch NSS, and (c) 1μm-pitch PSS. (d) Efficiency enhancement compared to LED based on flat substrate under various driving currents.

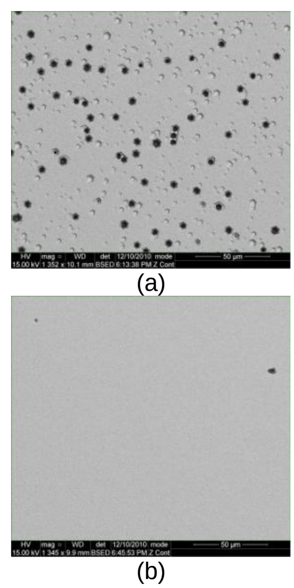

Fig.4 The surface of GaN after phosphoric acid wet-etching for 5 min based on (a) flat substrate and (b) 200nm-pitch NSS. The surface pits are associated with threading dislocations inside GaN. NSS in (b) shows less surface pits, revealing that the GaN quality is better due to the existence of NSS.