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A Fast Sapphire Substrate Surface Roughening Technology Using CO_2 Laser for Enhancing Light Extraction of GaN-Based Flip-Chip Light-Emitting Diodes

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1. Introduction

Continuous efforts have been made to promote GaN-based LEDs as a boost to white-light LEDs in the applications of flashlight, backlight source of liquid crystal display television, and even solid-state lighting [1], [2]. Among these, GaN-based flip-chip LED (FC-LEDs) is very attractive for high brightness (HB) applications because of better thermal management and the relatively large critical angle for light extraction up to 33.8^o as compared with those top-emitting structures on sapphire substrates (***i.e.,*** light emitted from the GaN/air interface) [3]. Recently, attempts to further improve the light extraction efficiency of FC-LEDs by means of chemical wet etching, focus ion beam (FIB), and inductively coupled plasma (ICP) dry etching techniques to roughen sapphire substrates and increase surface scattering have been reported and significant advancements have been demonstrated [4]-[5]. Nevertheless, these techniques were time-consuming (***e.g.*** 20–30 min using ICP and ~10 hrs using chemical wet etching [4]-[5]) or not cost-effective [6]. In this work, we reported a fast surface roughening technology using CO_2 laser irradiation on sapphire substrate for light extraction enhancement of FC-LEDs. Through the control of the irradiation power and scanning speed, the surface of sapphire substrate could be uniformly roughened within 5 min for a 2" wafer. Advantages include simplicity and fast fabrication, and cost effectiveness were demonstrated. Superior electrical and optical characteristics of the fabricated laser-roughening LEDs (LR-LEDs) were reported and investigated as well.

2. Sample preparation

The GaN wafer used in this work were epitaxially grown on 2 inch c-plane 400-μm-thick sapphire substrates by metal–organic chemical vapor deposition (MOCVD). For the detailed epitaxial structures, please refer to ref.7. A schematic drawing illustrating the fabrication processes of the proposed surface roughening technology using CO_2 laser is shown in Fig. 1. The p-GaN was partially etched until the n-type GaN layer as exposed using an inductively coupled plasma (ICP) etching system. Subsequently, the deposition/oxidization of Ni/Au layer structure and deposition of indium zinc oxide (IZO) film as the transparent conductive layer were carried out in sequence onto the p-GaN layer, and bonding pads were formed on the TCL and n-type GaN. In this stage, 300 ×300 μm^2 regular top-emitting GaN-LEDs were fabricated (Fig. 1(a)). Afterwards, CO_2 laser (Universal Laser system Inc./M300) with wavelength of 10.5 μm was used to roughen the surface of sapphire substrate [Fig. 1(b)]. The laser was focused on the surface of sapphire, and the irradiation power and scanning speed used in this work were 30% and 50% respectively [8]. During the process, most CO_2 laser would induce thermal decomposition of Al_2O_3 on sapphire surface, and this would give rise to surface roughening [9]. After a surface clean in ultrasonic acetone bath, the fabrication for the LR-LEDs was completed (Fig. 1(c)). It's worth mentioning here, in present work, roughening a 2" wafer was done within 5 min. Note that, top-emitting GaN-LEDs (namely regular LEDs) were also fabricated on the same wafer simultaneously for comparisons.

3. Results and discussion

The SEM images of the surface morphology of the samples at some specific processing stages were shown in Fig. 2. Figure 2(a) shows the surface of the sapphire substrate before roughening with CO_2 laser irradiation. A flat and even surface was obtained. Figure 2(b) shows the surface of the sapphire substrate after roughened and Fig. 2(c) shows the magnification of Fig. 2(b). As is evident from the figure, popcorn-like nano-posts formed on the sapphire surface. Figure 2(d) shows the cross-sectional view of sapphire substrate. It is noted that a few micro-cracks appeared on the surface of the sapphire substrate. The average penetration depth of these micro-cracks from the surface of sapphire substrate is about 10 μm. The comparisons of the typical current-voltage (I-V) characteristics of LR-LEDs and regular LEDs were shown in Fig. 3. At 20 mA, the forward voltages (V_F) of LR-LEDs and regular LEDs have the same value of 3.2 V. The inset shows the reverse I-V characteristics. No noticeable difference in V_F and comparably good reverse characteristics reveal that the proposed surface roughening technology using CO_2 laser irradiation did not affect electrical performance of devices. Figure 4 shows the comparison of typical light output power-current (Lop-I) characteristics of LR-LEDs and regular LEDs. At 20 mA, it is seen that a considerable improvement in Lop by 40.2% (***i.e.***, ΔLop/Lop) was obtained from LR-LEDs. This could be mainly attributed the essential improvement provided by flip-chip configuration (22% in present work) and a remarkable enhancement from the popcorn-like nano-posts induced by the CO_2 laser roughening technology. Taking these advantages, the power conversion efficiency of LR-LEDs was about 41% higher than that of regular LEDs. It should be noted here that the improvement on Lop could be further enhanced through optimizing the thickness of the sapphire substrate, output power of the CO_2 laser, and its scanning speed. The inset shows the measured electroluminescence (EL) characteristics of LR-LEDs and regular LEDs. No obvious difference was observed, suggesting that the optoelectrical properties of the multi-quantum-wells (MQWs) of the GaN-based epiwafer were not affected by the proposed technology.

4. Conclusion

In summary, through the use of CO_2 laser irradiation, a fast surface roughening technology was proposed to enhance the light extraction of GaN-based flip-chip LEDs. The processing time to roughen a 2" wafer was within 5 min. As compared with conventional top-emitting regular LEDs, LR-LEDs exhibited a 40.2% enhancement in Lop and comparably good I-V characteristics. These provided a 41% improvement in power conversion efficiency. Furthermore, no obvious changes were observed in I-V and EL characteristics, which suggests that the proposed technology does not affect the optoelectrical properties of MQWs of the epiwafer. It is expected that the proposed CO_2 laser roughening technology would provide a fast and cost-effective tool for further improving the light extraction of GaN-based FC-LEDs.

Acknowledgements

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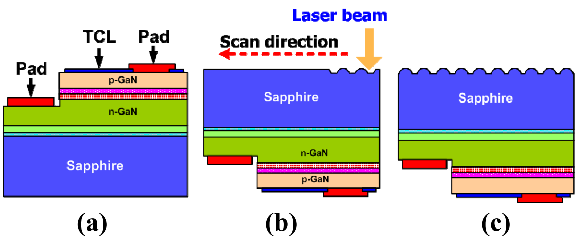

Fig. 1 Schematic drawing for the key fabrication processes of the proposed surface roughening technology. (a) After the fabrication of a top-emitting GaN-LED (regular LED). (b) CO_2 laser roughening process. (c) After the fabrication of an LR-LED.

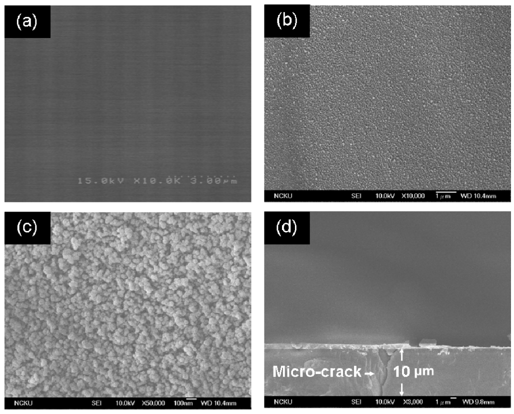

Fig. 2 SEM images of the sapphire surface: (a) top-view of the sapphire substrate before CO_2 laser treatment, (b) top-view of the sapphire substrate after CO_2 laser roughening, (c) magnification of (b), and (d) cross-sectional image of sapphire substrates after CO_2 laser roughening.

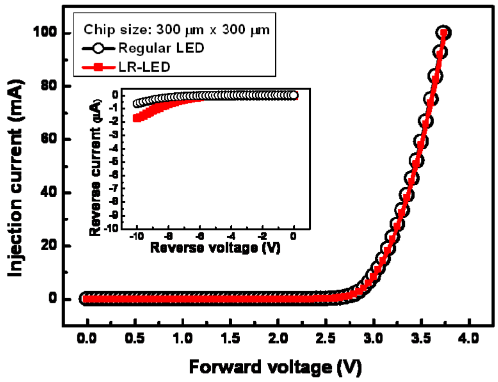

Fig. 3 Comparisons of the typical I-V characteristics of LR-LEDs and regular LEDs. The inset shows the reverse I-V characteristics.

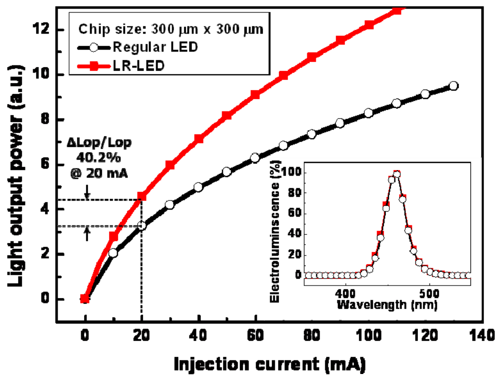

Fig. 4 Comparisons of the typical Lop-I characteristics of LR-LEDs and regular LEDs. The inset shows the EL characteristics at 20 mA.

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