460-nm InGaN-Based LEDs Grown on Fully Inclined Hemisphere-Shape-Patterned Sapphire Substrate With Submicrometer Spacing

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***Abstract*—This letter investigates 460-nm InGaN-based light-emitting diodes (LEDs) grown on a hemisphere-shape-patterned sapphire substrate (HPSS) with submicrometer spacing. The full-width at half-maximum of the (102) plane rocking curves for GaN layer grown on a conventional sapphire substrate (CSS) and HPSS are 480 and 262 arcsec, respectively. Such improvement is due to the reduction of the pure edge threading dislocations. At the forward current of 20 mA, the light output power of the LEDs grown on CSS and HPSS were 4.05 and 5.86 mW, respectively. This improvement of 44% light–output power can be attributed to the improved quality of the material and the increase of the light extraction by the fully inclined facets of the HPSS.**

***Index Terms*—Edge threading dislocations, light-emitting diodes (LEDs), patterned sapphire, submicrometer.**

I. Introduction

CONSIDERABLE interests have been paid to development of the GaN-based semiconductor due to its potential for optoelectronic application. Investigations on these GaN devices reveal that the quality of epitaxial material is the predominating factor for the device performances. These devices are generally grown on sapphire substrate; however, a high threading dislocation density with the order of $10^9 - 10^{10}$ cm^{-2} is induced due to the large lattice mismatch between GaN-based film and sapphire substrate [1], [2]. The approach using patterned sapphire substrate (PSS) to solve this problem has been typically reported [3], [4]. Light-emitting diodes (LEDs) performance can be enhanced by PSS technique due to the reduction of dislocation density by the lateral growth mechanism. Additionally, it was found that inclined facets of PSS are another important factor for the enhancement of performance due to the increase of light extraction by such facets [5]. Furthermore, smaller spacing between each pattern is also found to help enhance the LEDs performance [6].

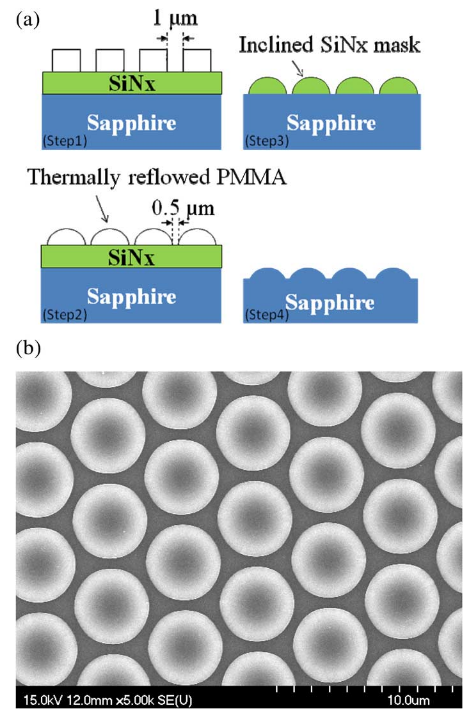

Fig. 1. (a) Process flow of the HPSS with submicrometer spacing. (b) Top-view SEM image of the HPSS. The diameter and the closest spacing between each hemisphere are 4.3 and 0.5 μm, respectively.

In this letter, a thermally reflowed photoresist technique was used to fabricate inclined PSS via dry etching and to increase the pattern density by reducing the spacing to submicrometer scale. To the author's acknowledgement, such submicrometer scale spacing is the smallest ever reported for PSS. The improvement of the GaN film quality and the GaN LEDs grown on such substrates are described.

II. Experiment

Fabrication of the PSS in this work was accomplished by process steps as shown in Fig. 1(a). A SiN_x film was first deposited on a 2-in sapphire substrate by the plasma-enhanced chemical vapor deposition (PECVD) method as the etching

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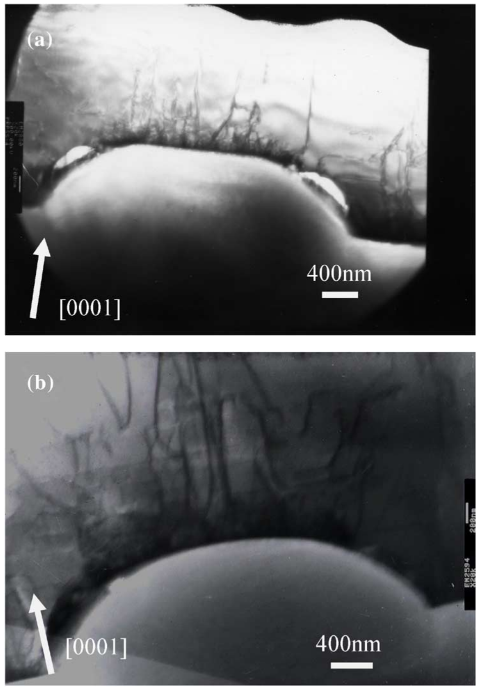

Fig. 2. Cross-section bright-field TEM image of GaN buffer layer grown on (a) MPSS and (b) HPSS. The images were taken on $\langle 11-20 \rangle$ zone axis.

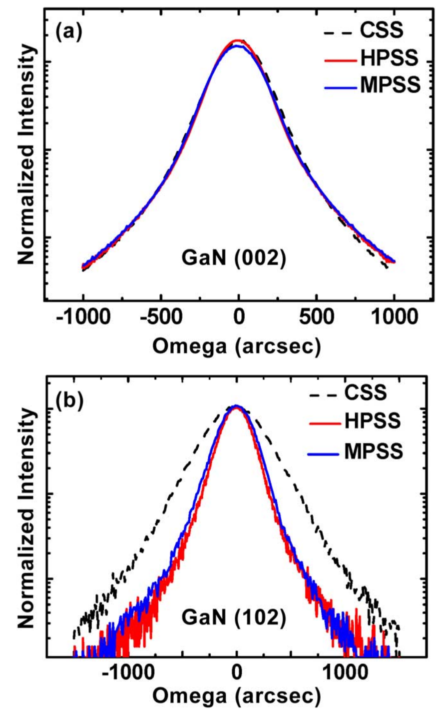

Fig. 3. Rocking curves of the GaN films grown on CSS, MPSS, and HPSS. (a) (002) plane, (b) (102) plane.

mask and was patterned using polymethyl methacrylate (PMMA) by contact aligner with a deep ultraviolet lamp. Then, the spacing of the developed structure was reduced using a thermal reflow technique. After the hemisphere-like profile was transferred to SiN_x by a reactive ion etcher, the sapphire substrate was then etched utilizing an inductively coupled plasma etcher with BCl_3 plasma. Fig. 1(b) shows the top-view scanning electron microscope [(SEM) Hitachi S4700] image of the PSS. The diameter and the closest spacing of the hemisphere were 4.3 and 0.5 μm, respectively. By altering the thickness ratio between PMMA and SiN_x, a mesa-shape and a hemisphere-shape-patterned sapphire substrate (MPSS and HPSS) were obtained, as shown in Fig. 2. The height of each PSS was 1 μm.

The GaN-based LEDs in this work were grown on c-plane 2-in-diameter PSS and conventional sapphire substrate (CSS) using metal–organic chemical vapor deposition (MOCVD). The epitaxial structure consisted of an undoped GaN buffer layer, a Si-doped n-type GaN layer, an active region with five periods of InGaN–GaN multiple quantum wells, an undoped $Al_{0.05}Ga_{0.95}N$ layer, and an Mg-doped p-type GaN layer. The epitaxial wafers were fabricated by the conventional LEDs process flow as described below. The p-GaN layer was partially etched to the n-GaN layer to define the device size of 350×350 μm^2. The 300-nm-thick indium–tin–oxide (ITO) layer was deposited and then patterned on the p-GaN layer. Finally, a metal stack of Ti–Al–Au was evaporated onto both p-GaN and n-GaN layers as contact electrodes.

III. Results and Discussion

Fig. 2 compares the cross-section transmission electron microscopy (TEM) (JEOL 2100) bright field images of the GaN buffer layer grown on MPSS and HPSS, respectively. As shown in Fig. 2(a), there are two voids observed clearly near the mesa-shape edge for MPSS. These voids were thought to be the evidence of free standing laterally growth GaN which helps reduce the threading dislocation density [7]. For HPSS, however, no void was observed but 90° bending dislocations appear above the dot shape region. It suggests HPSS prevent dislocation propagation in c-axis direction and reduce the threading dislocation density. The founding is similar to the GaN grown on cone-shape PSS reported by Lee, *et al.* [6].

To compare the dislocations density of the GaN buffer layer grown on CSS, MPSS, and HPSS, rocking curve of high-resolution X-ray diffractions (Bede D1) were performed with an accuracy of ± 7 arcsec and the results are shown in Fig. 3. In Fig. 3(a), the full-width at half-maximum (FWHM) of the (002) plane rocking curves of the GaN films grown on each substrate were 274, 277, and 256 arcsec, respectively. These similar results could be due to that the rocking curves of the symmetric planes, such as (002) plane, is insensitive to the edge threading dislocations which are the predominant component for the threading dislocations in GaN films grown on sapphire [8]. It has been reported that the pure edge threading dislocations distort the asymmetric planes so that the rocking curves of asymmetric planes are required to analyze the pure edge threading dislocations of the GaN films [9]. Fig. 3(b) compares the asymmetric (102) plane rocking curves of GaN grown on CSS and PSS. In comparison with GaN grown on CSS, the FWHM of GaN decreases from 480 arcsec to 293 arcsec and 262 arcsec for MPSS and HPSS, respectively. It indicates that the quality of the GaN film grown on PSS was improved and GaN on HPSS was slightly better than that on MPSS.

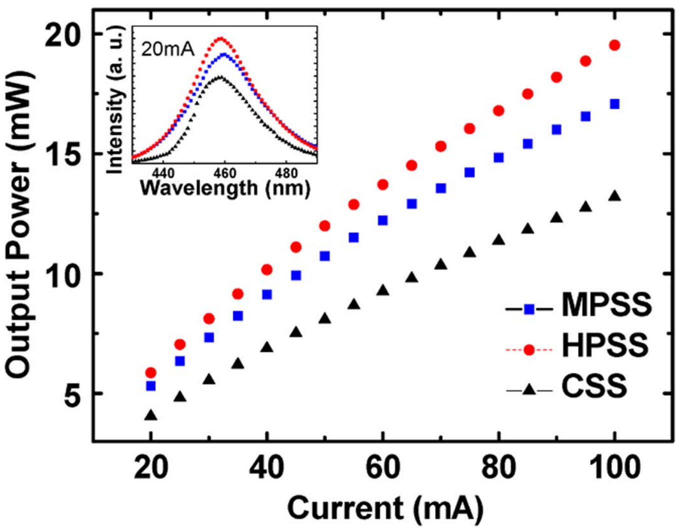

Fig. 4. Light–output power characteristics of 460-nm InGaN-based LEDs grown on CSS, MPSS, and HPSS. The inserted figure shows the EL spectra of the three type LEDs, where the injection current was 20 mA.

Fig. 4 plots the light–output power as a function of the injection current for nonencapsulated 460-nm LEDs grown on CSS and PSS, where the output power was measured using an integrated sphere detector. The output powers were 4.05, 5.32, and 5.86 mW for CSS, MPSS, and HPSS, respectively, under the typical driving current of 20 mA. As compared with LEDs on CSS, the output power of LEDs on MPSS and HPSS were enhanced by 31% and 44%, respectively. It has been reported that the inclined facets of the PSS can redirect photons back to the device surfaces so that the efficiency of the light extraction can be increased [10]. Therefore, enhancement of brightness in this work resulted not only from the improvement of the epitaxial layer quality of the GaN films by PSS technique but also from the increase of the light extraction by the inclined facets of the PSS. It is worth noticing that LEDs on HPSS exhibited higher output power than those on MPSS. In addition to slightly better quality of GaN grown on HPSS, the HPSS could also redirect more photons due to its fully inclined geometry. As a result, there is an additional 13% increase in the output power for the LEDs grown on the MPSS compared to those grown on HPSS.

IV. Conclusion

The performances of 460-nm InGaN-based LEDs grown on MPSS and HPSS were reported. From rocking curve measurements of GaN asymmetric (102) plane, the FWHM decreases from 480 arcsec to 293 arcsec and 262 arcsec for GaN grown on MPSS and HPSS, respectively. It indicates that lower threading dislocation density can be achieved through such PSSs technique. For light–output power performance, although GaN materials grown on MPSS and HPSS demonstrated similar dislocation density, a 44% improvement of light–output power for the LEDs grown on HPSS was observed, which is higher than a 31% improvement for the LEDs grown on MPSS. This result can be contributed not only to better quality of LEDs grown on HPSS but also to HPSS's fully inclined facets which increases light redirecting and thus increases the LED light extraction efficiency. In addition to the LED applications, PSSs presented in this letter can also be used for laser diode applications due to their contributions to the improvement of GaN film quality which is very important for high quality laser diode.

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