Enhancing the Output Power of GaN-Based LEDs Grown on Wet-Etched Patterned Sapphire Substrates

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***Abstract*—GaN-based light-emitting diodes (LEDs) with emitting wavelength of 450 nm were grown on patterned sapphire substrates (PSSs) fabricated by chemical wet etching. The crystallography-etched facet was {1-102} R-plane with a 57° against {0001} C-axis and had superior capability for enhancing light extraction efficiency. The light output power of the PSS LED was 1.15 times higher than that of the conventional LED at an injection current of 20 mA. The output power and external quantum efficiency were estimated to be 9 mW and 16.4%, respectively. The improvement was attributed not only to geometrical shapes of {1-102} crystallography-etched facets that efficiently scatter the guided light to find escape cones, but also to dislocation density reduction by adopting the PSS growth scheme.**

***Index Terms*—GaN, light-emitting diode (LED), sapphire chemical wet etching.**

I. INTRODUCTION

THE GaN-based wide bandgap semiconductors have attracted considerable interest, in terms of applications for optoelectronic devices, which operate in the blue, green, and ultraviolet UV wavelength regions, as well as for electronic devices operating at high-temperature/high-power conditions [1], [2]. However, owing to the large mismatch of lattice constant and thermal expansion between epitaxial GaN films and sapphire substrates, high-density dislocations ranging from $10^8 - 10^{10}$ cm^{-2} degrade the light-emitting diode (LED) performance profoundly. Thus, growth of GaN with low-density dislocations has been a major effort for fabrication of reliable high-efficiency LEDs. By epitaxial lateral overgrowth (ELOG) with SiN_x or SiO_2 mask patterned on as-grown GaN seed crystal, threading dislocations can be significantly eliminated [3]–[5]. Although this overgrowth technique can dramatically improve crystalline quality, the requirement of two-step growth procedure is time-consuming and easily introduced contaminations. Recently, the single-step growth on maskless patterned sapphire substrates (PSSs) has been widely proposed, and a comparable improvement of LED performance was demonstrated compared to the ELOG technique [6]–[10]. Though the single-step growth method cannot reduce the dislocation density to the order of magnitude that the ELOG technique can achieve ($\sim 10^7$ cm^{-2}) [11], the simplified technique shall be feasible for mass fabrication. Besides, geometrical shape of the sapphire patterns can effectively enhance light extraction efficiency by scattering or redirecting the guided-light inside an LED chip to find escaping cones [7], [10], [11]. Nevertheless, PSSs were generally fabricated by dry etching and it is unavoidable to damage the sapphire surface. In this letter, we report GaN-based LEDs grown on the chemical wet etching PSS, hence the sapphire surface damage induced by dry etching can be eliminated. Furthermore, the inclined crystallography-etched facet evolving on sapphire substrates with the etching time facilitates superior light extraction efficiency [13].

II. DEVICE FABRICATION

The GaN-based LEDs used in this study were grown using a low-pressure metal–organic chemical vapor deposition (Aixtron 2600 G) system onto C-face (0001) 2″-diamerter patterned and conventional sapphire substrates. Fabrication of PSSs with inclined crystallography-etched facets was illustrated as follows: The SiO_2 film with hole-patterns of 3-μm diameter and 3-μm spacing was deposited onto the sapphire substrate by plasma-enhanced chemical vapor deposition and defined by standard photolithography to serve as the wet etching mask. The sapphire substrate was then wet etched using an H_3PO_4-based solution at an etching temperature of 300 °C. The sapphire wet-etching rate is about 1 μm/min in this study and can be related to the H_3PO_4 composition and etching temperature [14]. Fig. 1(a) and (b) shows the top and cross section side views scanning electron microscope (SEM) images of the pattern sapphire substrate of the etching time of 90 s. In Fig. 1(a), the crystallography-etched pattern of an (0001)-oriented sapphire substrate has a flat-surface of {0001} C-plane with triangle-shape in the center. Surrounding the triangle-shape C-plane are three facets of {1-102} R-plane with an angle of 57° against [0001] C-axis. This inclined facet with high slope is useful for light extraction in our previous report [13]. It was also found that the sapphire etching rate depends on the crystal orientation and decreases in the order of C-plane $>$ R-plane $>$ M-plane $>$ A-plane [14]. Therefore, the triangle-shape flat-surface of {0001} C-plane in the pattern center finally vanishes as etching time increases. Fig. 1(c) is a simple schematic illustration of the phenomenon mentioned above. According to this figure, the total area of {0001} C-plane decreases as etching time increases due to its

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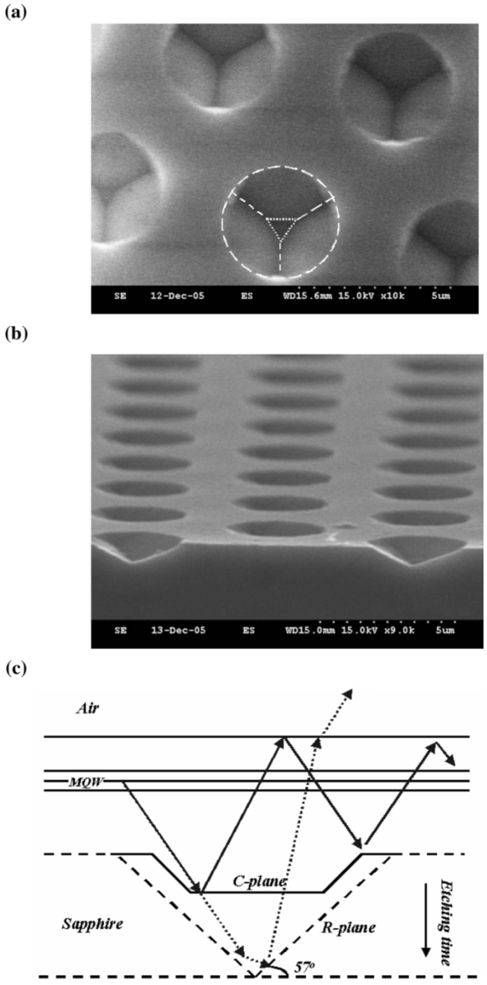


Fig. 1. (a) and (b) Top and cross-sectional side-view SEM images of a PSS of etching time of 90 s. (c) Evolution of sapphire patterns with etching time.

relative fast etching rate. On the other hand, the inclined surface of the {1-102} crystallography-etched facet increases with the etching time, adding the opportunity of the guided light to be extracted outside the LED chip. Nevertheless, the large inclined crystallography-etched surface with longer etching time also indicates deep depth of the sapphire pattern, and it would take more effort for optimizing the epitaxial growth condition to obtain a flat surface of GaN film for the subsequent process. Therefore, we choose the sapphire etching time as short as 30 s, equaling the etching depth of 0.5 μm and providing a flat surface of {0001} triangle-shape C-plane in the pattern center, which is relative suitable and easy for the subsequent epitaxial growth. In this report, the LED layer-structure comprised a 30-nm-thick GaN nucleation layer, a 2-μm-thick undoped GaN layer, a 2-μm-thick Si-doped n-type GaN cladding layer, an unintentionally doped active region of 450-nm emitting wavelength with five periods of InGaN–GaN multiple quantum wells, and a 0.2-μm-thick Mg-doped p-type GaN cladding layer. The grown wafer was patterned with square mesas $350 \times 350\,\mu\text{m}^2$ in size by a standard photolithographic process and was partially etched until the exposure of n-GaN to define the emitting area and n-electrode; a 300-nm-thick ITO was deposited as the transparent conductive layer and Cr–Au were then deposited as n and p electrodes and was alloyed at 200 °C in N_2 atmosphere for 5 min. Fig. 2(a) schematically depicts a cross-sectional image of a GaN-based LED grown on a chemical wet etching PSS. Fig. 2(b) shows a cross-sectional SEM micrograph of the LED full structure. According to Fig. 2(b), the PSS can be buried completely by a GaN epitaxial layer without appearance of void. The typical current–voltage (I–V) measurements were performed using a high current measure unit (KEITHLEY 240). The light output power of LEDs without epoxy resin was measured using an integrated sphere with a calibrated power meter.

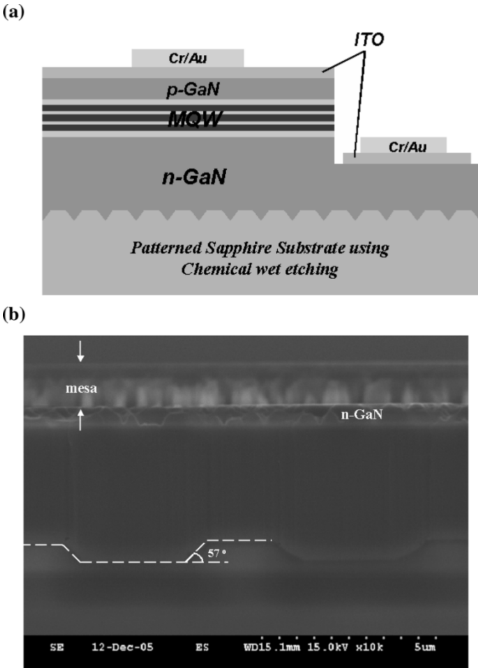
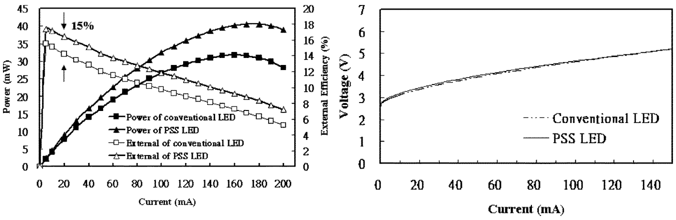


Fig. 2. (a) Schematic drawing of epitaxial layers and device structure with PSS and (b) the cross-sectional SEM micrograph of LED full structure.

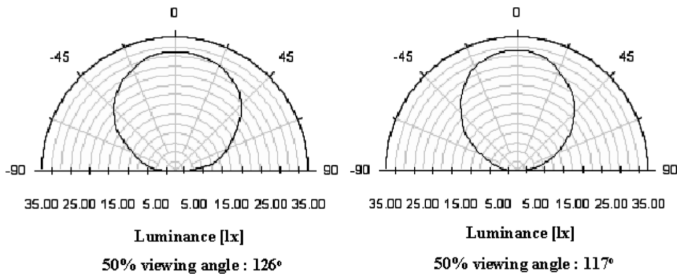


(a) (b)

Fig. 3. (a) Measurement results of room temperature output power (L–I curve) and external quantum efficiency and (b) the I–V curve characteristics of conventional and PSS LEDs.

III. RESULTS AND DISCUSSION

Fig. 3(a) shows measurement results of room temperature output power (L–I curve) and external quantum efficiency of conventional and PSS LEDs as a function of the forward-bias current. The data were obtained from the same fabrication process with and without crystallography-etched patterns on the sapphire substrate, explaining why any factor causing this difference except the patterned sapphire would be neglected. The light output powers at 20 mA of the conventional and PSS LEDs without epoxy resin are 7.8 and 9 mW, respectively, i.e., an improvement factor of approximate to 1.15 was achieved by adopting the sapphire substrate with crystallography-etched



(a) (b)

Fig. 4. Far-field patterns of (a) conventional and (b) PSS LEDs at an injection current of 20 mA.

facet patterns. The current dependent external quantum efficiency is similar in conventional and PSS LEDs and the external quantum efficiency of the PSS LED is 1.15 times higher than that of the conventional LED under all our measurement condition. According to this figure, the external quantum efficiency at 20 mA are 14.2% and 16.4% for conventional and PSS LEDs, respectively. We know the external quantum efficiency is equal to the product of internal quantum efficiency and light extraction efficiency; and it is also well accepted that the GaN-based LED grown on the pattern sapphire substrate gets a considerable improvement on both of them [8]–[12]. Therefore, improvement of the external quantum efficiency of a PSS LED is contributed not only to enhancement of light extraction efficiency via the crystallography-etched facets that efficiently redirect guided light to find escape cones, but also to dislocation density reduction by adopting the PSS growth scheme. Fig. 3(b) shows the I–V curve characteristic of the conventional and PSS LEDs as a function of forward driving current. In Fig. 3(b), about 3.4 V of forward voltages was measured on both devices at the injection current of 20 mA and no significant difference of the I–V curves was observed under the measurement condition of the driving current up to 150 mA, indicating that no damage occurred on the epitaxial film of PSS LEDs fabricated by chemical wet etching. To confirm that the crystallography-etched facet of {1-102} R-plane possesses superior capability for redirecting or scattering guided light to find escape cones, the light output pattern of the PSS and conventional LED was measured at 20 mA and the results are shown in Fig. 4, where the chips were not encapsulated into epoxy resin. In Fig. 4, the view angle (half-center brightness or 50% of the full luminosity) of the PSS LED is smaller than that of the conventional LED. For the conventional LED structure, the emitting light from active region with incidence larger than the critical angle would be trapped inside the LED chip; however, after the multireflection, some of trapped light could be extracted on the edge of the LED chip or of the sapphire substrate. For the PSS LED, the light that is supposed to be trapped as in the case of a conventional LED, would be effectively directed to the top escape-cone of the LED surface because of the inclined crystallography-etched facets. Thus, the smaller fraction of trapped light on the PSS LED will be extracted on the chip edge, i.e., a smaller view angle was observed on the PSS LED.

IV. CONCLUSION

High light-extraction-efficiency GaN-based LEDs were successfully grown on PSSs fabricated by chemical wet etching. The output power is increased by approximately 15% on the PSS LED compared with the conventional one at an injection current of 20 mA. The improvement was attributed not only to the geometrical shape of {1-102} crystallography-etched facets that efficiently redirects the trapped light to find escape cones, but also to dislocation density reduction by adopting the PSS growth scheme.

REFERENCES

[1] S. Nakamura and G. Fasol, *The Blue Laser Diode*. New York: Springer, 1997.

[2] H. Morkoc, S. Strite, G. B. Gao, M. E. Lin, B. Sverdlov, and M. Burns, “Large-band-gap SIC, III-V nitride, and II-VI ZnSe-based semiconductor device technologies,” *J. Appl. Phys.*, vol. 76, pp. 1363–1398, 1994.

[3] A. Sakai, H. Sunakawa, and A. Usui, “Defect structure in selectively grown GaN films with low threading dislocation density,” *Appl. Phys. Lett.*, vol. 71, pp. 2259–2261, 1997.

[4] T. S. Zheleva, O. H. Nam, M. D. Bremser, and R. F. Davis, “Dislocation density reduction via lateral epitaxy in selectively grown GaN structures,” *Appl. Phys. Lett.*, vol. 71, pp. 2472–2474, 1997.

[5] K. Hiramatsu, K. Nishiyama, M. Onishi, H. Mizutani, M. Narukawa, A. Motogaito, H. Miyake, Y. Iyechika, and T. Maeda, “Fabrication and characterization of low defect density GaN using facet-controlled epitaxial lateral overgrowth (FACELO),” *J. Cryst. Growth*, vol. 221, pp. 316–326, 2000.

[6] K. Tadatomo, H. Okagawa, Y. Ohuchi, T. Tsunekawa, Y. Imada, M. Kato, and T. Taguchi, “High output power InGaN ultraviolet light emitting diodes fabricated on patterned substrates using metalorganic vapor phase epitaxy,” *Jpn. J. Appl. Phys.*, vol. 40, pp. L583–L585, 2001.

[7] M. Yamada, T. Mitani, Y. Narukawa, S. Shioji, I. Niki, S. Sonobe, K. Deguchi, M. Sano, and T. Mukai, “InGaN-based near-ultraviolet and blue-light-emitting diodes with high external quantum efficiency using a patterned sapphire substrate and a mesh electrode,” *Jpn. J. Appl. Phys.*, vol. 41, pp. L1431–L1433, 2002.

[8] D. S. Wuu, W. K. Wang, W. C. Shih, R. H. Horng, C. E. Lee, W. Y. Lin, and J. S. Fang, “Enhanced output power of near-ultraviolet InGaN-GaN LEDs grown on patterned sapphire substrates,” *IEEE Photon. Technol. Lett.*, vol. 17, no. 2, pp. 288–290, Feb. 2005.

[9] Z. H. Feng and K. M. Lau, “Enhanced luminescence from GaN-based blue LEDs grown on grooved sapphire substrates,” *IEEE Photon. Technol. Lett.*, vol. 17, no. 9, pp. 1812–1814, Sep. 2005.

[10] Y. J. Lee, T. C. Hsu, H. C. Kuo, S. C. Wang, Y. L. Yang, S. N. Yen, Y. T. Chu, Y. J. Shen, M. H. Hsieh, M. J. Jou, and B. J. Lee, “Improvement in light-output efficiency of near-ultraviolet InGaN-GaN LEDs fabricated on stripe patterned sapphire substrates,” *Mater. Sci. Eng., B*, vol. 122, pp. 184–187, 2005.

[11] K. Tadatomo, H. Okagawaa, Y. Ohuchia, T. Tsunekawaa, H. Kudoa, Y. Sudoa, M. Katob, and T, Taguchic, “High output power near-ultraviolet and violet light-emitting diodes fabricated on patterned sapphire substrates using metalorganic vapor phase epitaxy,” *Proc. SPIE*, vol. 5187, pp. 243–249, 2004.

[12] S. Watanabe, N. Yamada, M. Nagashima, Y. Ueki, C. Sasaki, Y. Yamada, T. Taguchi, K. Tadatomo, H. Okagawa, and H. Kudo, “Internal quantum efficiency of highly-efficient $In_xGa_{1-x}N$-based near-ultraviolet light-emitting diodes,” *Appl. Phys. Lett.*, vol. 83, pp. 4906–4908, 2003.

[13] Y. J. Lee, J. M. Hwang, T. C. Hsu, M. H. Hsieh, M. J. Jou, B. J. Lee, T. C. Lu, H. C. Kuo, and S. C. Wang, “GaN-based LEDs with Al-deposited V-shape sapphire facet mirror,” *IEEE Photon. Technol. Lett*, vol. 18, no. 5, pp. 724–726, Mar. 1, 2006.

[14] S. J. Kim, “Vertical electrode GaN-based light-emitting diode fabricated by selective wet etching technique,” *Jpn. J. Appl. Phys.*, vol. 44, pp. 2921–2924, 2005.