GaN-Based LEDs With Al-Deposited V-Shaped Sapphire Facet Mirror

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

***Abstract*—A GaN-based light-emitting diodes (LEDs) with V-shaped sapphire facet reflector was fabricated using the double transferred scheme and sapphire chemical wet etching. The {1-102} R-plane V-shaped facet reflector with a 57° against {0001} C-axis has the superior capability for enhancing the light extraction efficiency. The light output power of the V-shaped sapphire facet reflector LED was 1.4 times higher than that of a flat reflector LED at an injection current of 20 mA. The significant improvement is attributable to the geometrical shape of sapphire facet reflector that efficiently redirects the guided light inside the chip toward to the top escape-cone of the LED surface.**

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

I. Introduction

THE III-NITRIDE wide bandgap light-emitting diodes (LEDs) have recently attracted considerable interest due to their various applications, such as traffic signals, backside lighting in liquid crystal displays, and illumination lighting by white light LEDs [1]. Among them, the top emitting LEDs have potential applications such as side-view lighting in the small panel of cell phones, portable projectors, and automobile forward lighting. However, due to the significant difference of the refractive index between the semiconductor epitaxial layer and air, the external quantum efficiency is limited by the total internal reflection. Approximately $1/(4n^2)$ of light from the active region can escape from the top and bottom of the device, where n denotes the refractive index of semiconductor materials [2]. Even though GaN has a lower refractive index ($n \sim 2.5$) than that of other semiconductor materials, only about 4% of the total emitted light can be extracted from one face according to above equation. Therefore, the major issue was then how to get the photons that had been generated inside the active region out into the outside of semiconductor LEDs where they could be used. Many methods have been proposed toward achieving this objective, including chip shaping [3], the top p-type GaN : Mg surface roughening process [4], [5], the n-type GaN : Si surface roughening process that uses a laser-liftoff (LLO) technique [6], [7], and other approaches [8]. Recently, a GaN-based vertical-electrode LED using a wet-etching sapphire technique was proposed by Kim to achieve high performance [9], and Wang *et al.* also using the wet-etching patterned sapphire substrate to investigate the lateral epitaxial overgrowth mechanics for reducing the threading dislocation density [10]. According to the above investigations, the patterned sapphire substrate using wet etching exhibits the V-groove's structure with smooth crystal facets and that is quite suitable for serving as a highly directional reflector after the deposition of metal layer. In this letter, we report the properties and improvement of GaN-based LEDs with high reflectivity V-shaped sapphire facet reflector fabricated using a double transferred scheme and sapphire chemical wet etching technique.

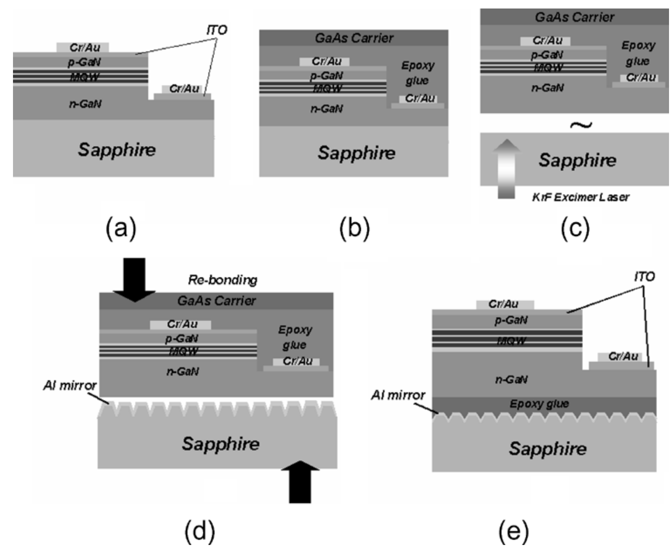

Fig. 1. Schematic of fabrication steps for GaN LEDs with sapphire facet mirror adopting double-transferred technique.

II. Device Fabrication

The GaN-based LEDs used in this study were grown using a low-pressure metal–organic chemical vapor deposition (Aixtron 2600G) system onto the C-face (0001) $2''$-diamerter sapphire substrate. 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 with five periods of InGaN–GaN multiple quantum wells, and a 0.2-μm-thick Mg-doped p-type GaN cladding layer. Fig. 1(a)–(e) shows the fabrication steps of GaN-based LEDs with an Al-deposited V-shaped sapphire facet reflector by double transferred and

Manuscript received November 14, 2005; revised December 19, 2005.

Y. J. Lee is with the Department of Photonic and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 300, Taiwan, R.O.C., and also with the R&D Division, Epistar Co., Ltd., Hsinchu, Taiwan 300, R.O.C. (e-mail: yjlee.eo92g@nctu.edu.tw).

J. M. Hwang, T. C. Hsu, M. H. Hsieh, M. J. Jou, and B. J. Lee are with the R&D Division, Epistar Co., Ltd., Hsinchu, Taiwan 300, R.O.C.

T. C. Lu, H. C. Kuo, and S. C. Wang are with the Department of Photonic and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 300, Taiwan, R.O.C.

Digital Object Identifier 10.1109/LPT.2006.871136

LLO techniques. The grown wafer was patterned with square mesas 350×350 μm^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. 1(a)]. The processed wafer was then brought into contact with a GaAs carrier using a commercially available epoxy glue (index of refraction ∼1.6 at 470 nm) at an operating temperature of 80 °C [Fig. 1(b)]. The bonded structure was then subjected to the LLO process [Fig. 1(c)]. A KrF excimer laser at a wavelength of 248 nm with a pulsewidth of 25 ns was used to remove the sapphire substrate. The laser with a beam size of 1.2×1.2 mm^2 was incident from the backside of the sapphire substrate onto the sapphire–GaN interface to decompose GaN into Ga and N_2. In this process, the beam size of KrF laser was larger than that of the size of the LEDs. Therefore, the laser irradiation on the interface of sapphire and GaN was uniform. The GaN thin-film was again brought into contact with the Al-deposited V-shaped sapphire facet reflector using epoxy glue at an operating temperature of 80 °C [Fig. 1(d)]. The fabrication of the Al-deposited V-shaped sapphire facet reflector was illustrated as follows: The SiO_2 film with hole-patterns of a diameter of 3 μm 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 with an etching time of 180 s and etching temperature of 250 °C. The sapphire wet-etching rate is about 0.8 μm/min in this study and can be related to the H_3PO_4 composition and etching temperature [9]. A sapphire substrate with V-shaped facet patterns was formed after the chemical wet etching process. A 200-nm-thick Al metal with a reflectivity of about 90% was then deposited on the top of the V-shaped sapphire substrate by e-beam evaporation. After the rebonding process, the GaAs carrier was removed using a NH_4OH-based solution [Fig. 1(e)]. Thus, GaN-based LEDs with high reflectivity V-shaped sapphire facet reflectors could be realized by adopting what we called the double-transferred technique since the LED epitaxy was first transferred into a sacrifice GaAs substrate, and after the LLO process, retransferred into a host sapphire substrate with Al-deposited V-shaped reflectors. It should also be noted that although the thermal conductivity of epoxy glue (∼0.32 W/mK) we used for the attaching material is lower than that of the sapphire substrate (∼23 W/mK), we have reduced the thickness of the epoxy to as thin as 0.2 μm during the bonding process to minimize the impact of relatively low thermal conductivity of the epoxy on the overall device heat dissipation. A reference LED sample with the same fabrication procedure, except without the wet etching sapphire substrate process, was also prepared for comparison.

III. Results and Discussion

Fig. 2 shows scanning electron micrograph (SEM) images of the wet etched sapphire substrate. According to Fig. 2, the etched V-shaped facet of an (0001)-oriented sapphire substrate

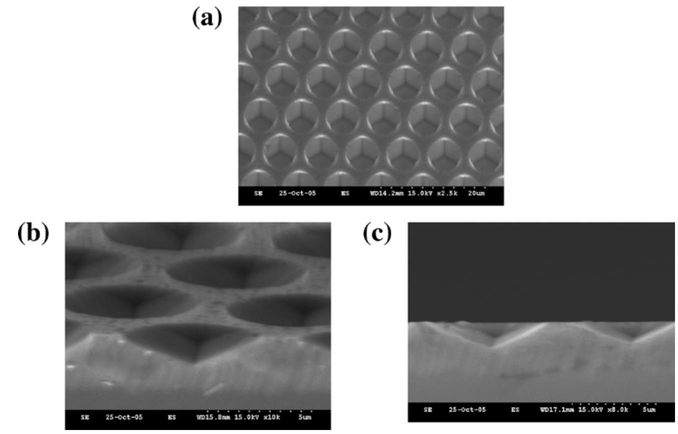

Fig. 2. SEM images of the wet etching sapphire substrate with R-plane of {1-102}. (a) Top view, (b) and (c) cross section side view images.

has the R-plane {1-102} facet, and the angle against the {0001} C-axis is about 57°. This large etching slope is useful for providing appropriate slant surfaces, which are helpful to the light extraction, according to the calculated results based on the Monte Carlo ray tracing simulation [11]. In addition, this high slope facet using chemical wet etching is difficult to achieve by using other methods, such as the ICP dry etching, and the smooth crystal facet of R-plane is quite suitable for the subsequent deposition of the metal layer serving as a reflector. Thus, a high slope and reflectivity V-shaped sapphire reflector for increasing the light extraction efficiency of LEDs can be realized by adopting the sapphire wet etching process. Fig. 3 shows the (a) output power (L–I curve) and (b) current–voltage (I–V curve) characteristics of flat and V-shaped Al-deposited sapphire reflector LEDs as a function of forward driving current. The L–I–V characteristics were measured with an on-wafer testing configuration, consisting of the Si detector mounted directly above the LED and the driving current being applied through the probes. It means that the power measurement is a relative axial output from the top surface of the chip. As can be seen in Fig. 3(a), the light output power of both structures increased continuously as the driving current was increased from 0 to 100 mA. The L–I of the V-shaped sapphire facet reflector LEDs has higher output power of about 40% compared to the flat Al-deposited sapphire reflector LEDs at an injection current of 20 mA, i.e., a significant improvement attributed to the V-shaped sapphire facet reflector to effectively reflect the emission light toward to the chip surface. In Fig. 3(b), about 3.3 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 were observed under the measurement condition of the driving current up to 100 mA, indicating that a feasible process for high brightness GaN-based LEDs was achieved without electrical damage. In order to realize the enhancement mechanism of output power by adopting the V-shaped sapphire facet reflector, the top view light-emission of LEDs were observed by charge-coupled device and the obtained images are shown in Fig. 4. The photograph of the GaN-based V-shaped Al-deposited sapphire reflector LED without current driving is shown in Fig. 4(a). According to this figure, a V-shaped sapphire facet reflector is successfully attached to the LED

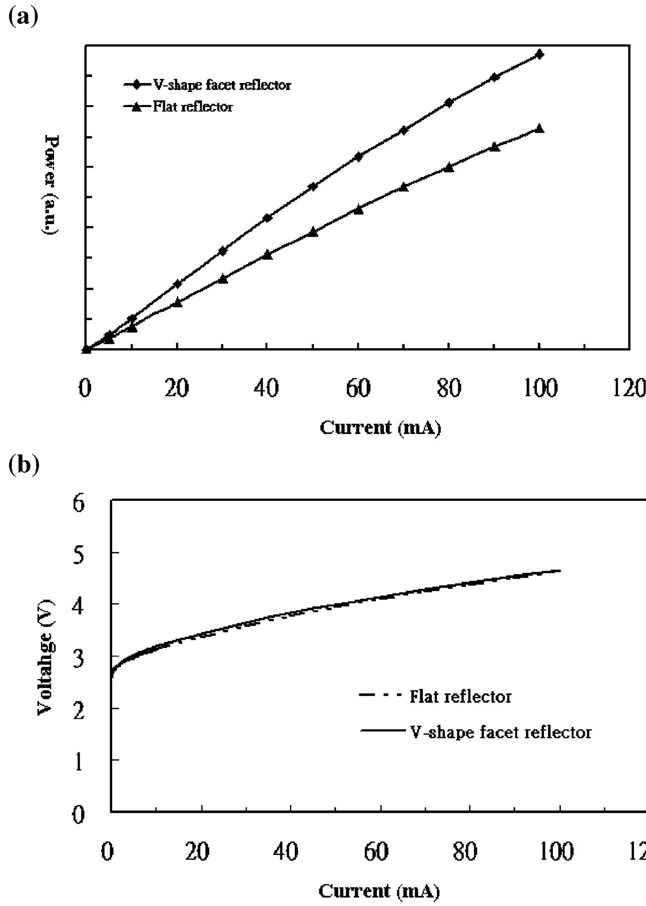

Fig. 3. (a) L–I curve and (b) I–V curve characteristics of flat and V-shaped Al-deposited sapphire reflector LEDs as a function of forward driving current.

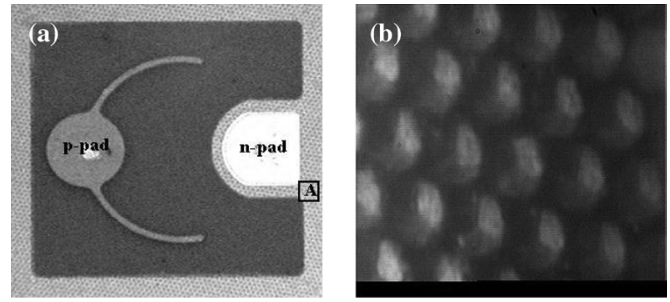

Fig. 4. Top view light-emission images. (a) Plane-view photograph of the GaN-based V-shaped Al-deposited sapphire reflector LED. (b) The light-emission image of the enlarged photograph of area A in Fig. 4(a) under a driving current of 20 mA.

epitaxy using the double-transferred technique. Fig. 4(b) shows the light-emission image of the enlarged photograph of area A in Fig. 4(a) under a driving current of 20 mA. In this figure, the emitting light from the LED mesa edge is redirected toward to the axial direction by the V-shaped sapphire facet reflector, thus higher intensity was observed on the individual V-shaped pattern than that on other regions, indicating that employing the V-shaped sapphire facet reflector has the superior benefit for improving the light extraction efficiency by effectively redirecting the guided light inside the LED chip toward to the top escape cone.

IV. Conclusion

High light-extraction-efficiency GaN-based LEDs employing an Al-deposited R-plane of {1-102} with 57° against the C-axis and V-shaped sapphire facet reflector were successfully fabricated. The output power is increased by approximately 40% on this novel structure compared with the standard one with a flat reflector at an injection current of 20 mA, and with a normal forward voltage of about 3.3 V. The improvement is attributable to the geometrical shape of the sapphire facet reflector that enhances the light extraction efficiency by redirecting the guided light toward to the top exit cone of the LED surface.

References

[1] M. Koike, N. Shibata, H. Kato, and Y. Takahashi, "Development of high efficiency GaN-based multiquantum-well light-emitting diodes and their applications," *IEEE J. Sel. Topics Quantum Electron.*, vol. 8, no. 2, pp. 271–277, Mar./Apr. 2002.

[2] M. Broditsky and E. Yablonovitch, "Light-emitting-diode extraction efficiency," *Proc. SPIE*, vol. 3002, pp. 119–122, 1997.

[3] M. R. Krames, M. Ochiai-Holcomb, G. E. Höfler, C. Carter-Coman, E. I. Chen, I.-H. Tan, P. Grillot, N. F. Gardner, H. F. Gardner, H. C. Chui, J.-W. Huang, S. A. Stockman, F. A. Kish, and M. G. Craford, "High-power truncated-inverted-pyramid $(Al_xGa_{1-x})_{0.5}In_{0.5}P$/GaP light-emitting diodes exhibiting >50 external quantum efficiency," *Appl. Phys. Lett.*, vol. 75, pp. 2365–2367, 1999.

[4] C. Huh, K.-S. Lee, E.-J. Kang, and S.-J. Park, "Improved light-outputand electrical performance of InGaN-based light-emitting diode by microroughening of the p-GaN surface," *J. Appl. Phys.*, vol. 93, pp. 9383–9385, 2003.

[5] S. J. Chang, L. W. Wu, Y. K. Su, Y. P. Hsu, W. C. Lai, J. M. Tsai, J. K. Sheu, and C. T. Lee, "Nitride-based LEDs with 800 °C grown p-AlInGaN-GaN double-cap layers," *IEEE Photon. Technol. Lett.*, vol. 16, no. 6, pp. 1447–1449, Jun. 2004.

[6] Y. Gao, T. Fujii, R. Sharma, K. Fujito, S. P. Denbaars, S. Nakamura, and E. L. Hu, "Roughening hexagonal surface morphology on laser lift-off (LLO) N-face GaN with simple photo-enhanced chemical wet etching," *Jpn. J. Appl. Phys.*, vol. 43, pp. L637–L639, 2004.

[7] T. Fujii, Y. Gao, R. Sharma, E. L. Hu, S. P. DenBaars, and S. Nakamura, "Increase in the extraction efficiency of GaN-based light-emitting diodes via surface roughening," *Appl. Phys. Lett.*, vol. 84, pp. 855–857, 2004.

[8] T. N. Oder, K. H. Kim, J. Y. Lin, and H. X. Jiang, "III-nitride blue and ultraviolet photonic crystal light emitting diodes," *Appl. Phys. Lett.*, vol. 84, pp. 466–468, 2004.

[9] 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.

[10] J. Wang, L. W. Guo, H. Q. Jia, Z. G. Xing, Y. Wang, H. Chen, and J. M. Zhou, "Origin of selective growth of GaN on maskless V-grooved sapphire substrate by metalorganic chemical vapor deposition," *Jpn. J. Appl. Phys.*, vol. 44, pp. L982–L984, 2005.

[11] C. C. Sun, C. Y. Lin, T. X. Lee, and T. H. Yang, "Enhancement of light extraction of GaN-based light-emitting diodes with a microstructure array," *Opt. Eng.*, vol. 43, pp. 1700–1701, 2004.