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M. H. Lo,[1] P. M. Tu,[1] C. H. Wang,[1] C. W. Hung,[1] S. C. Hsu,[2] Y. J. Cheng,[1,2,a)] H. C. Kuo,[1] H. W. Zan,[1] S. C. Wang,[1] C. Y. Chang,[3] and S. C. Huang[4]

[1]*Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, 1001 Ta Hsueh Rd., Hsinchu 300, Taiwan*
[2]*Research Center for Applied Sciences, Academia Sinica, Taipei 11529, Taiwan*
[3]*Institute of Electronics, National Chiao Tung University, 1001 Ta Hsueh Rd., Hsinchu 300, Taiwan*
[4]*Advanced Optoelectronic Technology Inc., Hsinchu 303, Taiwan*

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We report the fabrication and study of high efficiency ultraviolet light emitting diodes with inverted micropyramid structures at GaN-sapphire interface. The micropyramid structures were created by anisotropic chemical wet etching. The pyramid structures have significantly enhanced the light output efficiency and at the same time also improved the crystal quality by partially relieving the strain and reducing the dislocation defects in GaN. The electroluminescent output power at normal direction was enhanced by 120% at 20 mA injection current and the output power integrated over all directions was enhanced by 85% compared to a reference sample. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3190504]

GaN-based light emitting diode (LED) has attracted great attention in past few years due to its importance in solid state lighting applications. Researchers are actively investigating various approaches to improve output efficiency. Among those factors affecting output efficiency, material defect density and light extraction efficiency are two important problems. The GaN-based devices are often epitaxially grown on sapphire. The as grown GaN epitaxial layer has high crystal dislocation density, typically in the range of 10^8–10^{10} cm^{-2}. These crystal defects are detrimental to optoelectronic device performance. The high refractive index of GaN restricts the escape angle of emitting light and results in low light extraction efficiency. There have been great efforts in solving these two problems. While the improvement in defect density has been slow, the light extraction efficiency has experienced rapid progress. Various surface texture,[1–3] photonic crystal structure,[4,5] and patterned substrate[6–8] methods have been investigated and demonstrated significant light extraction enhancement. Recently, patterned sapphire substrate with chemical wet etching in between epitaxial growth steps has provided another way to improve light extraction efficiency.[9,10] A common feature in all these different methods is having large surface variations at the GaN-air or GaN-sapphire interface. The fabrication process often involves microlithography and etching. Here, we report a fabrication process that can significantly improve both the light extraction efficiency and crystal quality without the need of photolithography substrate patterning.

The fabricated UV LEDs have inverted pyramid structures throughout the GaN-sapphire interface. The pyramid structures are created by anisotropic chemical wet etching at GaN-sapphire interface. The chemical etching agent reaches GaN-sapphire interface through channels self-assembled by defect selective etching from top surface. The pyramid structures help to redirect light to the front emitting surface and at the same time also partially relieves the strain in GaN, which in turn reduces dislocation defects.

The material epitaxial growth uses nominal low pressure metalorganic chemical vapor deposition (MOCVD). A 30 nm of low temperature GaN nucleation layer followed by a 2.5 μm GaN buffer layer was grown on (0001) sapphire template. The GaN wafer was immersed in high temperature molten KOH at 280 °C for 12 min. The molten KOH selectively etched defects on wafer surface and etched continuously downward opening up channels to sapphire interface. The molten KOH was led to GaN-sapphire interface through these self-assembled channel openings. The etching process then turned into lateral direction because the defect density was high at interface and etched away a thin layer of GaN along sapphire interface. It is known that KOH etching is typically anisotropic and preferentially etches specific crystallographic planes. A tilted view scanning electron microscopy (SEM) image is shown in Fig. 1(a), where the inverted pyramid structure at GaN-sapphire interface can be seen from a large opening. A large number of hexagonal pits were also formed on the surface. The etch pit density was $\sim 5 \times 10^8$ cm^{-2} from SEM image estimation. Additional GaN was grown on the etched GaN wafer to fill up both the etched openings and surface pits to provide flat top surface for the subsequent LED device growth. The LED device structure was 3.5 μm *n*-doped GaN, ten pairs of $Al_{0.05}Ga_{0.95}N/InGaN$ quantum wells (13/2.5 nm), and 100 nm of *p*-doped GaN cap layer. The designed emission wavelength is at 395 nm. A cross-sectional SEM image of a cleaved sample after regrowth process is shown in Fig. 1(b). The space and the inverted pyramid structures created at the GaN-sapphire interface are still well maintained and distributed throughout the large area, as shown in the zoom out Fig. 1(c). Most of the pyramid tips are still in contact with sapphire. To investigate the performance of the device structure and make fair comparisons, a reference wafer also went through exactly the same fabrication process except for skipping the KOH etching step.

a)Electronic mail: yjcheng@sinica.edu.tw.

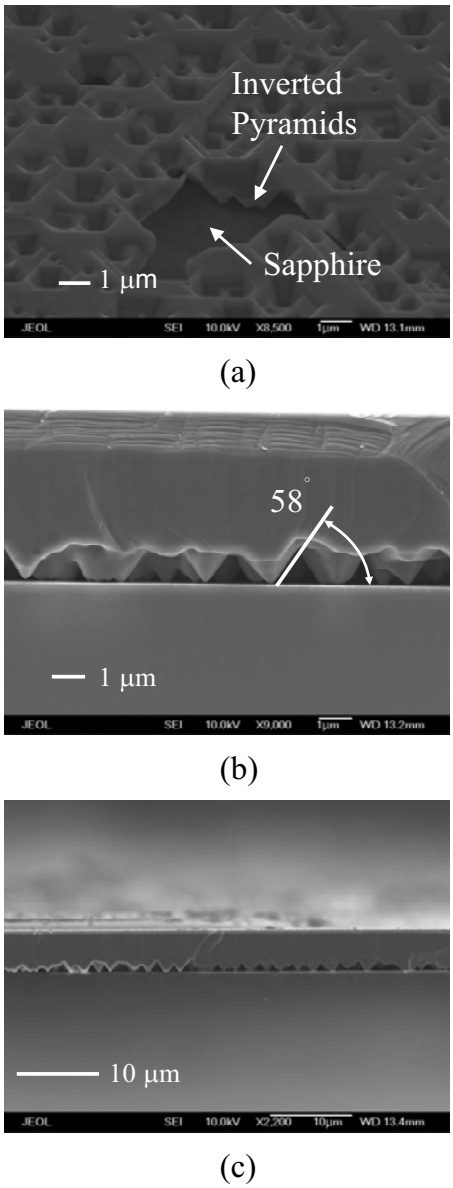

FIG. 1. (a) SEM image of the etched GaN surface. (b) SEM cross-sectional image of the regrown sample. (c) A zoom out view of the inverted pyramid structures.

The x-ray diffraction (XRD) rocking curves of these two samples are shown in Fig. 2. The linewidth for (102) planes was reduced from 552 to 472 arc sec. The linewidth for (002) planes was only reduced from 338 to 335 arc sec.

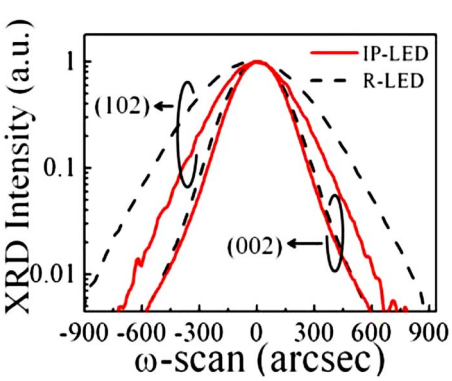

FIG. 2. (Color online) XRD rocking curves for IP-LED and R-LED samples.

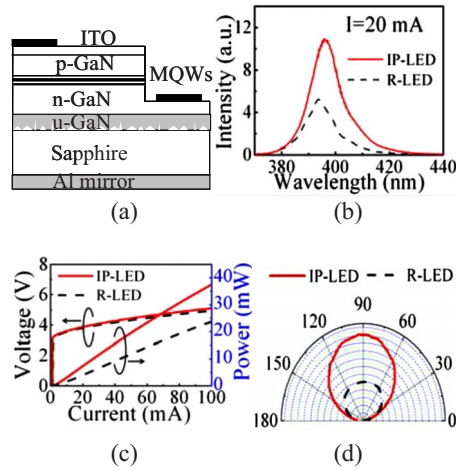

FIG. 3. (Color online) (a) Schematic of IP-LED structure. (b) EL spectra of IP-LED and R-LED in normal direction. (c) *L-I-V* curves of IP-LED and R-LED. (d) Far field patterns of IP-LED and R-LED.

The XRD linewidths for (102) and (002) planes are related to edge and screw threading dislocation densities, respectively.[11] The decrease in XRD linewidth indicates improved material quality. The improvement is attributed to the strain relaxation of the partially relieved GaN layer by interfacial etching and the subsequent regrowth. When GaN epitaxial layer was first grown on sapphire, a compressive strain was built up in the material due to the mismatched lattice constants and thermal expansion coefficients between GaN and sapphire. The KOH interfacial etching partially relieved GaN from sapphire interface and relaxed the compressive strain. This partially relieved layer served as a buffer layer to reduce the problems of mismatched lattice constants and thermal expansion coefficients during MOCVD regrowth and led to improved crystal quality.

These two samples were made into LED chips. Indium tin oxide was used as a current spreading layer and Ni/Au as a *p*-type electrode contact. Ti/Al/Ni/Au was deposited on the exposed *n*-GaN to serve as an *n*-type electrode contact. The sapphire substrates of both samples were lapped down and a 240 nm Al metal reflector coating was deposited on the sapphire back surface. The use of back reflector is common in finished LED package. Therefore, it was also included. They were finally scribed into 350×350 μm^2 LED chips. The schematic of the LED with inverted micropyramid structures (IP-LED) is shown in Fig. 3(a). The reference LED (R-LED) has similar structure except for a flat GaN-sapphire interface. The electroluminescence (EL) spectra of both LEDs collected in the normal to the front surface direction are shown in Fig. 3(b). The peak intensity of IP-LED is enhanced by 112% compared to that of R-LED. The EL spectrum of R-LED shows slight Fabry–Pérot mode ripples. The Fabry–Pérot mode spacing is about 5 nm, which is consistent with the overall GaN thickness of 6 μm and refractive index of ~2.55 at 394 nm. The EL spectrum of IP-LED on the other hand does not have the same Fabry–Pérot mode ripples. This is because the randomly distributed micropyramid structures suppress the standing wave formation between the top and bottom interfaces. The peak wavelength of IP-LED is redshifted by ~2 nm compared to that of R-LED, indicating the relaxation of compressive strain in IP-LED.[12]

The light-current (*L-I*) and voltage-current (*V-I*) characteristics are shown in Fig. 3(c). The forward voltages of IP-

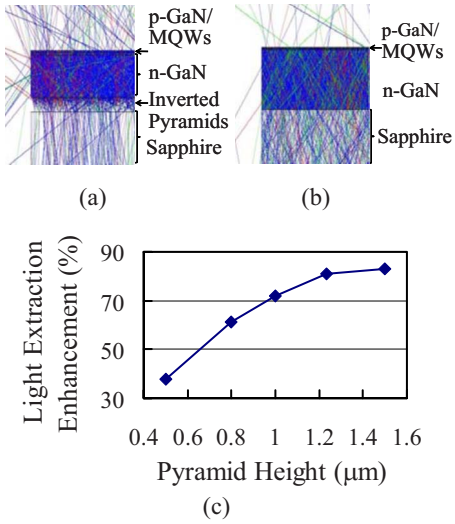

FIG. 4. (Color online) Monte Carlo ray tracing simulations. (a) and (b) are zoom in views at GaN-sapphire interface for IP-LED and R-LED. (c) Light extraction enhancements vs different pyramid heights.

LED and R-LED are 3.86 and 3.80 V, respectively, at 20 mA and increase to 5.09 and 4.93 V at 100 mA. The electric characteristic of IP-LED is still reasonably well maintained. The optical power of IP-LED and R-LED collected by an integrating sphere are 7.31 and 3.95 mW at 20 mA and 37.5 and 23.7 mW at 100 mA, respectively. The IP-LED output power exhibits 85% and 58% enhancement at 20 and 100 mA, respectively. The decrease of output power enhancement is likely due to the lower thermal conductance from the smaller GaN-sapphire contacts. The small interface contacts on the other hand are crucial for relieving the compressive strain and reducing material defects as described previously, which in turn reduces heat generation. The low thermal conductance problem is therefore not as serious as it would be. We also measured the far field pattern at 20 mA injection current as shown in Fig. 3(d). The IP-LED emission in normal direction is much more enhanced. The emission intensity is enhanced by 120% in normal direction and 62% in 45° direction. The divergent angles of IP-LED and R-LED are 108° and 128°, respectively.

To obtain a better physical understanding of output power improvement, ray tracing simulations based on Monte Carlo method are carried out for both LEDs. There is a slight distribution of pyramid heights. The pyramid facet angle is however fairly well defined as can be seen from Fig. 1(b). To simplify the calculation, an averaged pyramid height of 1 μm and 58° facet angle were used. This model is not exact but is believed to be close enough to provide reasonable estimates. Figures 4(a) and 4(b) are the ray tracing results for both LEDs. The inverted pyramid structures indeed effectively increase light output in the front surface direction. The light extraction efficiencies versus various pyramid heights are also calculated, as shown in Fig. 4(c). The calculated 72% enhancement at 1 μm pyramid height accounts for the major part of the observed 85% total power enhancement. The other 13% enhancement can be attributed to internal quantum efficiency improvement from better crystal quality. The simulation also shows that light extraction enhancement for 1 μm pyramid height is close to the optimum enhancement value.

In conclusion, we have demonstrated a high efficiency UV LED with inverted micropyramid structures at GaN-sapphire interface. The micropyramid structures were created by interfacial anisotropic chemical wet etching without the use of photolithography patterning. The LED was fabricated by growth interrupt, chemical etching, and regrowth processes. The device electrical performance is well maintained after these steps. The overall optical output power has shown significant 85% enhancement at nominal operating current 20 mA, which is attributed to both improved crystal quality and better light extraction efficiency.

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