Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp222-223

Nanoscale epitaxial lateral overgrowth of GaN-based light-emitting diodes on a SiO_2 nanorod-array patterned sapphire template

C. H. Chiu[1], C. C. Lin[3], C. H. Wang[1], S. P. Chang[1,2], C. Y. Jang[1], Z. Y. Li[1], H. C. Yang[2], H. C. Kuo[1,*], T. C. Lu[1], S. C. Wang[1]

[1] Department of Photonics & Institute of Electro-Optical Engineering, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu 30010, Taiwan
[2] R&D Division, Epistar Co. Ltd., Science-based Industrial Park, Hsinchu 31040, Taiwan
[3] Institute of Photonic System, College of Photonics, National Chiao-Tung University, No.301, Gaofa 3rd. Road, Guiren Township, Tainan County 71150, Taiwan.
[*]hckuo@faculty.nctu.edu.tw

1. Introduction

The wide band gap GaN-based semiconductors have attracted much attention for practical application, such as short-haul optical communication, traffic and signal lights, backlights for liquid-crystal displays, and daily lightings. Typically, GaN-based light emitting diodes (LEDs) was grown on sapphire and SiC substrate by heteroepitaxial techniques, such as metal-organic chemical vapor deposition (MOCVD) [1]. However, the low thermal conductivity and insulating properties make sapphire less perfect as a substrate for the growth of GaN epilayers. However, the GaN-based epilayers still contain a high threading dislocations density (TDD) (around 10^9-10^{10} cm^{-2}) due to the lack of a suitable substrate, leading to damage on the performance of devices then leaded to the low internal quantum efficiency. On the other hand, the light extraction efficiency of LEDs is limited by critical angle loss is attribution to the refraction index between GaN film and surrounding air have large difference. Therefore, the patterned sapphire substrates (PSS) technique not only decreases the TDD but also improves the light extraction efficiency (LEE). However, experimental and theoretical studies reveal a further reduction TDD method if the lateral overgrowth approach is reduced the nanoscale. In this work, we investigated high efficiency InGaN/GaN LEDs grown on sapphire substrate with different depth SiO_2 nanorod-array (NRA).

2. Experiment and Discussion

The preparation of the sapphire with different depth SiO_2 NRA started with the deposition of 100 nm, 200 nm and 300 nm SiO_2 on the sapphire by plasma-enhanced chemical vapor deposition (PECVD), respectively. Then, 10nm-thick Ni layer was deposited by an e-gun evaporator. The sample was annealed at 850℃ for 60s in nitrogen ambient to form self-assembled Ni nano-cluster on the SiO_2 layer. The Ni nano-clusters acted as etching masks and subsequently, the-reactive ion etching and inductive couple plasma dry etching were performed to form SiO_2 NRA. After etching, the SiO_2 NRA was dipped into hot HNO_3 to remove Ni cluster. The growth of a conventional GaN LED structure, which consists of six periods of InGaN/GaN MQWs and a 100nm-thick p-GaN layer, was deposited by MOCVD. A indium-tin-oxide (ITO) layer was deposited on the surface on the purpose of ohmic contact and current spreading. Lastly, the completely epitaxial structure underwent a standard four-mask LED fabrication process with a chip size 300μm×300μm as shown in Fig. 1. The different depth of the SiO_2 NRA on the surface of sapphire were fabrication by different SiO_2 thickness and RIE time, and could be used to effectively scatter or redirect the guiding light inside the GaN LED to escape. Moreover the epitaxial crystal quality was improved.

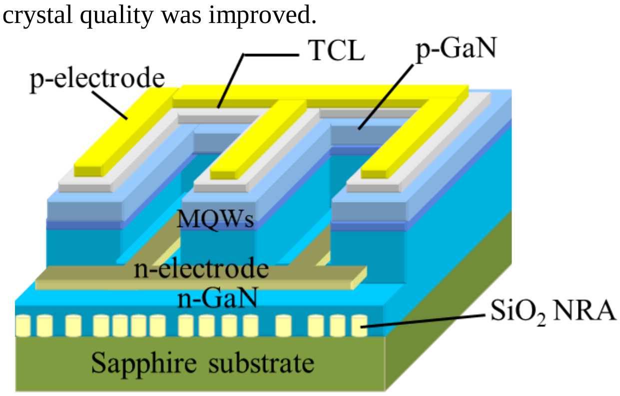


Fig. 1 The schematic of InGaN/GaN LED structure

Fig. 2(a) shows image indicating that the SiO_2 nanorods were approximately 180nm~200nm in diameter. The spacing between nanorods was about 130nm~150nm. Fig. 2(a) also shows that the exposed sapphire surface was flat enough for epitaxy. As the deposition process began, localized and hexagonal islandlike GaN nuclei were first form the sapphire surface to initiate GaN overgrowth, as shown in fig. 2(b). Fig. 2 (c)(d)(e) shows the cross-section SEM image of GaN epitaxial layer, where air voids were observed between the SiO_2 nanorods. The existing of the voids between nanorods observed from the micrographs suggested that not all the exposed surface enjoyed the same growth rate. Hence, only the regions with the higher growth rates, which might be originate from larger exposed surface, could play the role of a seed layer, facilitating the lateral coalescence of GaN.

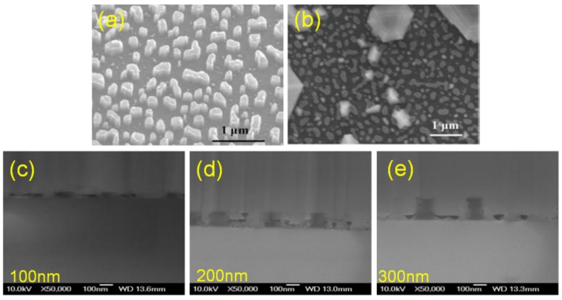


Fig. 2 SEM image of (a) the fabrication SiO_2 NRA (b) GaN nuclei on the sapphire with SiO_2 NRA as growth seeds (c) the GaN epilayer on the sapphire with 100nm SiO_2 NRA (d) 200nm SiO_2 NRA (e) 300nm SiO_2 NRA

Fig. 3 (a) shows XRD full-width at half- maximums (FWHMs) of the GaN films grown on flat sapphire and sapphire with 100nm, 200nm, 300nm SiO2 NRA. The FWHMs of the ω scan rocking curve for (102) planes infer the densities of edge dislocations [2]. The FWHMs of (102) planes were 360, 323, 275 and 327 arcsec for GaN films grown on flat sapphire and sapphire with 100nm, 200nm, 300nm SiO_2 NRA, respectively. The room temperature photoluminescence spectrum was also used to analyze GaN crystal quality. The peak intensity of GaN divided by peak intensity of yellow band (GaN peak/yellow peak), as shown in the Fig. 3 (b). The intensity of yellow band is related to defect density. The ratios of the GaN films grown on flat sapphire and sapphire with 100nm, 200nm, 300nm SiO_2 NRA were 85, 91, 183 and 113, respectively. The significant decreases in XRD FWHM and increases in GaN peak/yellow peak indicate a reduction in threading dislocation density. The improvement in crystal quality is attributed to the strain relaxation of the partially relieved GaN layer in combination with the subsequent regrowth. When the initial GaN epitaxial layer was grown on sapphire, a compressive strain was built up inside the material due the mismatched lattice constants and thermal expansion coefficients between GaN and sapphire. These mismatched factors introduced threading dislocations. The nanoscale epitaxial lateral overgrowth (ELOG) process relaxed the compressive strain. It acted as a buffer layer to partially filter out the problems of mismatched lattice constant and thermal expansion coefficient for MOCVD growth and resulted in improved crystalline quality.

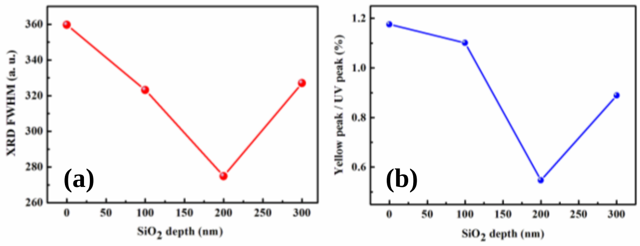
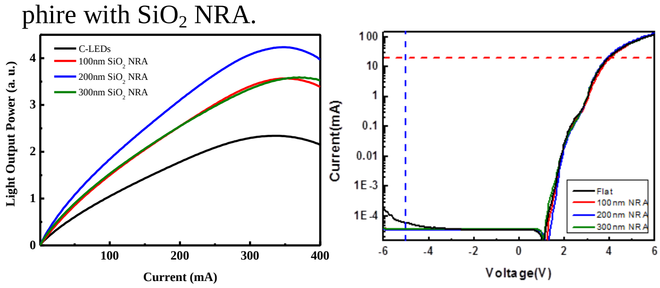


Fig. 3(a) XRD full-width at half- maximums (FWHMs) ; (b) The peak intensity of GaN divided by peak intensity of yellow band of the GaN films grown as a function of the SiO_2 NRA depth

Fig.4 (a) shows the measured L-I curve for LED grown on sapphire with and without SiO_2 NRA. The enhancement in light output power of LED grown on sapphire with 100nm, 200nm and 300nm SiO_2 NRA at injection current of 20mA were 49.6%, 77.6%, and 54.3% , respectively, as compare to the LED grown on sapphire without SiO_2 NRA. We believe the enhancement in light output power is due to the improvement of IQE and the enhanced extraction efficiency. The NRA-assisted NELO effectively suppress the threading dislocation density of GaN LED, which increased the IQE. Moreover the SiO_2 NRA in GaN epilayers contributed to light extraction due to light scattering at the interface of different refractive indices. Ueda *et al* [3] reported that the output power linearly increased with the surface coverage ratio of nanosilica spheres. Therefore, the extraction efficiency was enhanced by the SiO_2 NRA. To examine the leakage current of GaN LED devices under reverse bias voltage, as shown in the Fig.4 (b). The leakage current of GaN grown on sapphire with SiO_2 NRA and that grown on planar sapphire were 40nA and 120nA at reverse bias voltage of -6V, respectively. The much smaller leakage current might indicate the better crystalline quality for GaN-based LED regrowth on sapphire with SiO_2 NRA.



(a) **(b)**

Fig. 4 (a) L-I curves ;(b) I-V of GaN-based LED grown on sapphire with and without SiO_2 NRA

3. Conclusions

In summary, the SiO_2 nanorod array was fabricated by self-assembled Ni cluster, followed by ICP-RIE ion etching. The work introduced the SiO_2 nanorod-array assisted NELO method suitable for the MOCVD growth of the high-brightness blue LEDs. The LED grown on sapphire with SiO_2 nanorod-array demonstrated an enhanced IQE and light extraction efficiency when compared to a conventional LED grown on flat sapphire. The TDD reduction in GaN-based epilayers was realized by the SiO_2 nanorod-array assisted NELO method, where three potential TD reduction mechanisms were identified.

Acknowledgements

The authors would like to thank Dr. T. C. Hsu and M. H.Shieh of Epistar Corporation for their technical support. This work was founded by the National Science Council NSC 98-3114-E-009-002-CC2 in Taiwan, R.O.C.

References

[1] S. Nakamura, S. Pearton, and G. Fasol, *The Blue Laser Diode: GaN Based Light Emitters and Lasers*, 2nd ed. _Springer, New York, 2000_, pp. 1–9.

[2] H. Heinke, V. Kirchner, S. Einfeldt, and D. Hommel, Appl. Phys. Lett. 77, 2145 (2000)

[3] K. Ueda, Y. Tsuchida, N. Hagura, F. Iskandar, K. Okuyama, and Y. Endo, Applied Physics Letter 92, 101101 (2008).