Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp538-539

Improved Light Output Power of GaN-Based Light Emitting Diodes Using Double Photonic Quasi-Crystal Patterned

J. K. Huang[1], H. W. Huang[1,2], C. H. Lin[2], K. Y. Lee[2], C. C. Yu[2], H.C. Kuo[1], T. C. Lu[1] and S.C. Wang[1]

[1]Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 300, Taiwan, R.O.C.
Phone:+886-3-5712121#56327 E-mail:shodal98.eo96g@nctu.edu.tw
[2]Luxtaltek Corporation, Miaoli 350, Taiwan, R.O.C.
Phone:+886-3-7580792#6212 E-mail:steven.huang @luxtaltek. com

1.Introduction

Impressive recent developments of high brightness Gallium-nitride (GaN)-based light-emitting diodes (LEDs) have made possible their use in large size flat-panel displays [1-2]. There is still a great need to improve the internal as well as external quantum efficiency (EQE) to increase their light output power in order to further drive down the total cost of LED modules. Research into improving the light extraction efficiency and brightness in the LEDs [3]-[7] has been intense. Moreover, high quality GaN-based LEDs have been demonstrated on a micro-scale patterned sapphire substrate (PSS), [6-7] where the micro-scale patterns served as a template for the ELO of GaN and the scattering centers for the guided light. Both the epitaxial crystal quality and the light extraction efficiency were improved by utilizing a micro-scale PSS. Recently, the MOCVD growth of InGaN/GaN LEDs on the PSSs with nano-scale patterns has been reported and compared [8]-[10]. The LEDs grown on the nano-scale PSS showed more enhancements in the EQE than those grown on the without nano-scale PSS.

In this paper, we report a relatively nano-imprinting technique to fabricate a nano-hole patterned sapphire substrate (NHPSS) and photonic quasi-crystal (PQC) on p-GaN surface for mass production. As a result, the light output efficiency of LED with double PQC pattern was significantly higher than that of a conventional LED.

2.Experiments

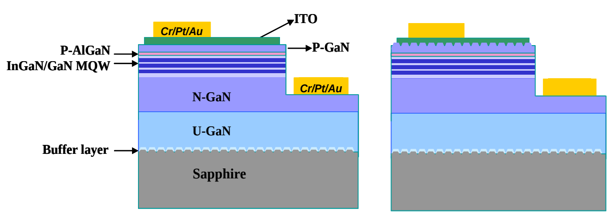

Fig. 1. Schematic diagrams of (a) LED with NHPSS, and (b) LED with double PQC structure.

Figure 1(a) and 1(b) shows the schematic diagrams of LED with NHPSS and LED with double PQC structure pattern. In our study, two types are fabricated in order to investigate the influence of the NHPSS and double PQC structure to the LED output power and beam profile performance. In Fig. 1(a), the LED structure consists of a Cr/Pt/Au p-electrode, ITO transparent layer, LED epitaxial layers, a smooth p-GaN surface, and a Cr/Pt/Au n-electrode on NHPSS. Further, the LED structure of Fig. 1(b) is only different with Fig. 1(a) on p-GaN surface with PQC pattern by NIL process.

This detailed process flow of nano-imprint lithography on sapphire substrate. First, we spin coated a 200 nm polymer layer on the sapphire sample surface. Second, we then placed a patterned mold onto the dried polymer film. By applying a high pressure, we heated the LED samples to above the glass transition temperature of the polymer. Third, The LED samples and the mold were then cooled down to room temperature to release the mold. Finally, we then used a inductively coupled plasma reactive ion etching (ICP-RIE) with BCl_3/Ar plasma to transferred the pattern onto sapphire substrate and remove polymer layer with O_2 plasma etching gas in a reactive ion etching (RIE) system.The Fig. 2(a) SEM image shows the nano-hole dimension and pattern pitch were approximately 240 nm and 450nm, The Fig. 2(b) SEM image shows the etching depth and sidewall angle of NHPSS was approximately 165 nm and 45°.

All LED samples are grown by metal-organic chemical vapor deposition (MOCVD) with a rotating-disk reactor (Veeco) on a c-axis sapphire (0001) substrate at the growth pressure of 200 mbar. The LEDs structure consists of a 50 nm-thick GaN nucleation layer grown at 500 ℃, a 2 μm un-doped GaN buffer, a 2 μm-thick Si-doped GaN buffer layer grown at 1050 ℃, an unintentionally doped InGaN/GaN multiple quantum well (MQW) active region grown at 770 ℃, a 50 nm-thick Mg-doped p-AlGaN electron blocking layer grown at 1050 ℃, and a 120 nm-thick Mg-doped p-GaN contact layer grown at 1050 ℃, The MQW active region consists of five periods of 3 nm/20 nm-thick $In_{0.18}Ga_{0.82}N$/GaN quantum well layers and barrier layers.

At first, the LED samples with NHPSS are fabricated using the NIL process on p-GaN surface for LED with double PQC structure (in Fig. 1(b)). Fig. 2(c)-(d) shows top-view and cross-section SEM images of the 12-fold photonic quasi-crystal pattern based on square-triangular lattice (inset in Fig. 2(c) right side model). The lattice constant and hole diameters are 450 nm, and 275 nm, respectively. The recursive tiling of offspring dodecagons packed with random ensembles of squares and triangles in dilated parent cells forms the lattice. Fig. 2(d) shows the PQC etching depth of the p-GaN layer is approximately 80 nm.

voltages under injection current 20 mA at room temperature for conventional LED, LED with NHPSS, and LED with double PQC structure were 3.11, 3.08

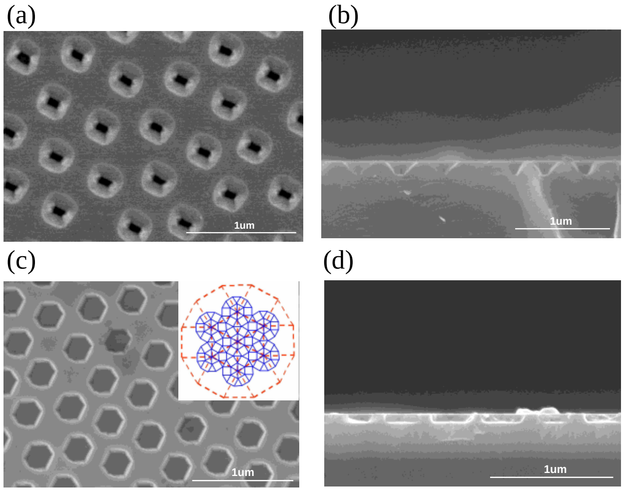

Fig. 2. SEM images of (a) top-view of sapphire surface with NHPSS, (b) cross-section of sapphire surface with NHPSS, (c) top-view of p-GaN surface with PQC (The inset shows that the 12-fold PQC structure model), and (d) cross-section of p-GaN surface with PQC.

and 3.12 V, respectively. In addition, the dynamic resistance of conventional LED, LED with NHPSS, and LED with double PQC structure are about 16.0, 16.1, and 16.3 Ω, respectively. Therefore, in terms of dynamic resistance, there is no influence on this type of devices by incorporating NHPSS and PQC structure by NIL process.

The light output is detected by calibrating an integrating sphere with Si photodiode on the package device, so that light emitted in all directions from the LED can be collected. The intensity-current (*L-I*) characteristics of conventional LED, LED with NHPSS, and LED with double PQC structure are shown in Fig. 3(b). At an injection current of 20 mA and peak wavelength of 455 nm for TO-can package, the light output powers of conventional LED, LED with NHPSS, and LED with double PQC structure on TO-can are given by 14.0 mW, 18.7 mW, and 22.5 mW, respectively. Hence, the enhancement percentages of LED with NHPSS, and LED with double PQC structure are 34%, and 61%, respectively, compared to that of conventional LED. The higher enhancement on standard LED type addresses the effect of the NHPSS which allow the reflect light from sapphire substrate onto the top direction, higher scattering effect using 12-fold PQC pattern and higher epitaxial crystal quality [8]-[10] to increase more light output power. In addition, the corresponding wall plug efficiencies (WPE) of conventional LED, LED with NHPSS, and LED with double PQC structure were 23%, 30%,and 36%, respectively, which addresses a substantially improvement by the PQC structures as well.

4.Conclusion

GaN-based LEDs with double 12-fold PQC structure are fabricated and demonstrated. At a driving current of 20 mA on TO-can package, the light output power of LEDs with double PQC structure is enhanced by a factor of 1.61. The higher output power of the LED with double PQC is contributed to higher reflectance on NHPSS and higher scattering effect on p-GaN surface using12-fold PQC pattern. This work offers promising potential to increase output powers of commercial light emitting devices.

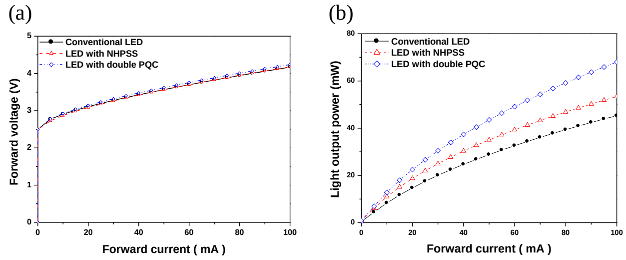

Fig. 3.(a) Show measurement current-voltage (*I-V*) characteristics of conventional LED, LED with NHPSS, and LED with double PQC structure, respectively. (b) Intensity-current (*L-I*) characteristics of conventional LED, LED with NHPSS, and LED with double PQC structure, respectively.

Acknowledgements

The authors thank Luxtaltek Corporation for their technical support. This work was founded by the National Science Council in Taiwan under grant number, NSC96-2221-E-009-095-MY3, and NSC96-2628-E-009-017-MY3

Reference

[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. Select. Topics Quantum Electron., Vol. 8, pp 271-277, 2002.

[2] E. F. Schubert, *Light-Emitting Diodes* (Cambridge University Press, Cambridge, 2003).

[3] S. J. Chang, C. S. Chang, Y. K. Su, C. T. Lee, W. S. Chen, C. F. Shen, Y. P. Hsu, S. C. Shei, and H. M. Lo, "Nitride-based flip-chip ITO LEDs," *IEEE Trans. Adv. Packag.*, vol. **28**, pp. 273-277, 2005.

[4] A. David, T. Fujii, B. Moran, S. Nakamura, S. P. DenBaars, C. Weisbush, and H. Benisty,"Photonic crystal laser lift-off GaN light-emitting diodes," *Appl. Phys. Lett.*, vol. **88**, pp. 133514-3, 2006.

[5] J. K. Kim, Th. Gessmann, H. Luo, and E. F. Schubert, **"**GaInN light-emitting diodes with RuO_2/SiO_2/Ag omni-directional reflector," *Appl. Phys. Lett.*, vol. **84**, pp. 4508-4510, 2004.

[6] T. S. Oh, S. H. Kim, T. K. Kim, Y. S. Lee, H. Jeong, G. M. Yang, and E. K. Suh, "GaN-Based Light-Emitting Diodes on Micro-Lens Patterned Sapphire Substrate," *Jpn. J. Appl. Phys*, vol. 47, No. 7, pp. 5333-5336, 2008.

[7] D. S. Wuu, W. K. Wang, K. S. Wen, S. C. Huang, S. H. Lin, R. H. Horng, Y. S. Yu, and M. H. Pan, "Fabrication of Pyramidal Patterned Sapphire Substrates for High-Efficiency InGaN-Based Light Emitting Diodes," *J. Electrochem. Soc*, vol. **153**, G765-G770, 2006.

[8] H. Gao, F. Yan, Y. Zhang, J. Li, Y. Zeng, and G. Wang, "Enhancement of the light output power of InGaN/GaN light-emitting diodes grown on pyramidal patterned sapphire substrates in the micro- and nanoscale," *J. Appl. Phys.*, vol. **103**, pp. 014314-1–014314-5, 2008.

[9] J. J. Chen, Y. K. Su, C. L. Lin, S. M. Chen, W. L. Li, and C. C. Kao, "Enhanced Output Power of GaN-Based LEDs With Nano-Patterned Sapphire Substrates," *IEEE Photon. Technol. Lett.*, vol. **20**, pp. 1193-1195, 2008.

[10] C. H. Chiu, H. H. Yen, C. L. Chao, Z. Y. Li, P. C. Yu, H. C. Kuo, T. C. Lu, S. C. Wang, K. M. Lau, and S. J. Cheng, "Nanoscale epitaxial lateral overgrowth of GaN-based light-emitting diodes on a SiO2 nanorod-array patterned sapphire template," *Appl. Phys. Lett.*, vol. **93**, pp. 081108-1-081108-3, 2008.

Appendix

Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 300, Taiwan, R.O.C.
Phone:+886-3-5712121#56327
E-mail:shodal98.eo96g@nctu.edu.tw