Extended Abstracts of the 2010 International Conference on Solid State Devices and Materials, Tokyo, 2010, pp715-716

Enhanced Light Output of Vertical GaN-Based Light-Emitting Diodes with a Distributed Bragg Reflector and a Roughened GaO_x Surface Film

Wei-Chi Lee[a], Kai-Ming Uang[b], Tron-Min Chen[b], Der-Ming Kuo[a], Pei-Ren Wang[a], Po-Hong Wang[a], and Shui-Jinn Wang[a*]

[a]Institute of Microelectronics, Department of Electrical Engineering, National Cheng Kung University, Tainan, Taiwan, ROC
[b]Department of Electrical Engineering, WuFeng Institute of Technology, Chiayi, Taiwan, ROC
*Phone: +886-6-2757575-62351, Fax: +886-6-2763882, E-mail: sjwang@mail.ncku.edu.tw

1. Introduction

High-brightness GaN-based LEDs have already been extensively used in display technology and LCD backlight, and automotive forward lighting, *etc.*, and also show a great potential to replace incandescent bulbs and fluorescent lamps [1]. Nevertheless, severe current-crowding effect and heat-conducting problem usually encounter in conventional lateral conducting GaN-based LEDs, which is mainly due to the use of insulating sapphire substrate. Recently, vertical-structure GaN-based LEDs (VLEDs) based on the transfer of sapphire substrate to a metal or semiconductor substrate have been shown being very promising in enhancing the light output, efficiency, and power capability of the GaN-based LEDs [2-3]. In addition, the surface roughening and oxide passivation technique were also demonstrated to increase the light output due to random scattering from the roughened surface [4-5].

In this study, to further improve the optoelectronic properties of GaN-based LEDs, a highly reflective distributed Bragg reflector (DBR) as a current blocking layer (CBL) and n-GaN surface-roughening with GaO_x passivation by KrF laser for the fabrication of VLEDs were proposed and results were discussed.

2. Experiments

Fig. 1 illustrates the key fabrication process of the proposed VLEDs with distributed Bragg reflector and a roughened GaO_x Surface Film. The epitaxial structures (**Fig 1(a)**) were grown on a sapphire substrate by metal-organic chemical vapor deposition (MOCVD). A transparent (>95% at 460 nm) conduction layer composed of indium-tin-oxide (ITO) and DBR layer was pattern deposited onto the p-GaN surface by E-beam evaporator in sequence. For device isolation, an inductively coupled plasma (ICP) dry-etching was conducted to etch the wafer down to the surface of the sapphire substrate, followed by the deposition of passivation layer (SiO_2) in the cutting-street. Prior to nickel-plating, an adhesive and seed layer comprising of a Cr/Ti/Au metal system was deposited by E-beam evaporator, as shown in **Fig. 1(b)**. Subsequently, an 80-μm-thick nickel substrate was formed by electroplating (**Fig. 1(c)**). Through the use of metal mask to define both size and shape of KrF excimer laser beam, the patterned laser lift-off (LLO) process was performed at a reactive energy of 800 mJ/cm^2 (**Fig. 1(d)**). After the removal of sapphire substrate, the exposed buffer layer (u-GaN) was removed and then n-GaN was roughened simultaneously by the same KrF laser with 150 pulses at energy density of 800 mJ/cm^2 (**Fig. 1(e)**). Finally, after pad definition by ICP, chemical-treatment, and the formation of metal pad on n-GaN surface, the proposed VLED (referred to as VLED-A) was obtained (**Fig. 1(f)**). Note that regular VLEDs (with an Al reflector on p-GaN, without DBR structure) and VLEDs with u-GaN removal by ICP (**Figs. 1(g)-1(h)**) (abbreviated as VLED-B) were also fabricated for comparison.

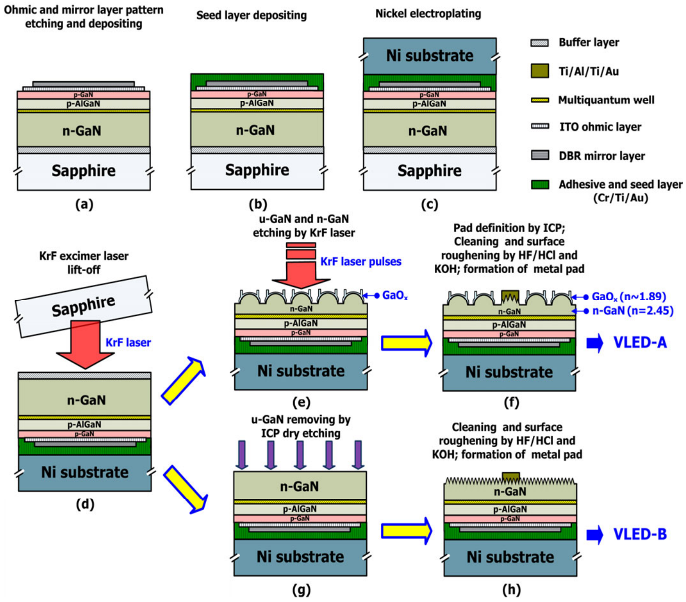

Fig. 1 The key fabrication process of VLEDs employing DBR mirror and blocking layer. The VLED-A is with the atop n-GaN layer roughened by KrF excimer laser irradiation with GaO_x, while the VLED-B is with KOH etching to the surface of the n-GaN layer only.

3. Results and Discussion

The effect of the u-GaN etching by KrF laser process on top GaN surface morphology of the samples was shown in **Fig. 2**. After the removal of sapphire using LLO process, KrF excimer laser irradiation was adopted to etch the u-GaN and then roughen the surface of the exposed n-GaN, producing simultaneously curved protrusions and gallium oxide (GaO_x) due to the reaction of decomposed gallium from u-GaN/n-GaN with oxygen in the air. Note that the surface morphology of the laser etched samples depends strongly on the number of laser pulses. To identify the composition of residuals or protrusions that appeared on the laser-irradiated n-GaN surface, the representative energy dispersive spectroscopy (EDS) spectra at three points (marked “A”, “B”, and “C” on the SEM image shown in the inset) on the 150-pulse-irradiated sample after diluted HCl treatment is shown in **Fig. 3(a)**. The appearance of oxygen peak at the center (point A) and the lip-like portion (point B) of the crater-like protrusions confirms the local formation of GaO_x after sufficient laser irradiation. Note that the difference in refractive index between the GaO_x (n~1.89) and n-GaN (n=2.45) could offer great benefits for reducing the Fresnel reflection. A high reflectivity (>99.93% at wavelength of 460 nm) and the thickness of 1.18 μm for prepared DBR mirror layer as a CBL were obtained (**Fig. 3(b)**), favoring for current spreading for VLED-A and -B.

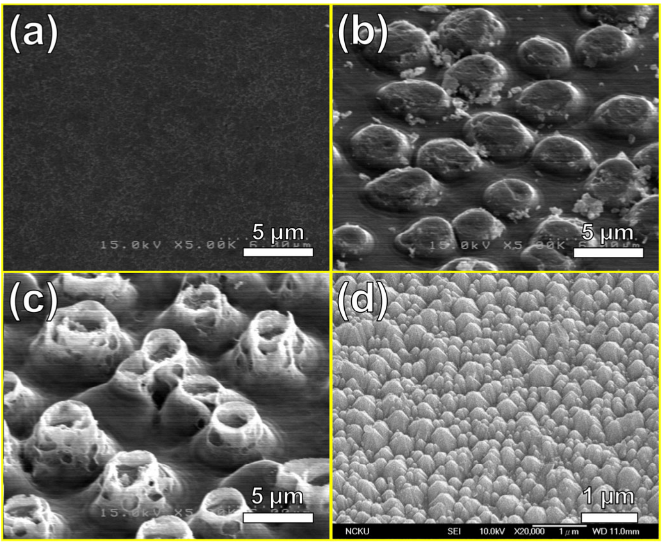

Fig. 2 SEM images of the top GaN surface of the VLED-A. (a) Right after LLO process cleaning by diluted HCl. After re-subjected to KrF laser etching and chemical cleaning with a diluted HCl for (b) 90- and (c) 150-pulse at an energy density of 800 mJ/cm^2. (d) VLED-B and regular VLED.

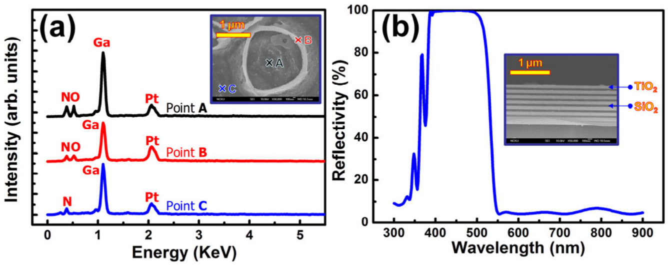

Fig. 3 (a) The representative EDS spectra at three points on the top view of 150-pulse-irradiated VLED-A sample after diluted HCl treatment. (b) The reflectivity and cross section SEM image of DBR mirror layer.

The comparison of I-V characteristics of various VLEDs with the same chip size were shown in **Fig. 4(a)**. The slightly higher forward voltage of the VLED-A than that of the regular VLEDs can be attributed to relatively smaller area of ohmic contact and residual n-GaN thick. The slightly lower forward voltage of the 150-pulse case of VLED-A than VLED-B can be ascribed to KrF laser irradiation and ICP etching before the formation of n-pad. The good ohmic characteristics could be ascribed to the significant enhancement of the carrier concentration near the n-GaN surface with KrF laser and ICP etching [6]. **Fig. 4(b)** shows the comparison of L-I characteristics of various VLEDs schemes. Compared with regular VLEDs, VLED-A with a 150-pulse KrF laser etching shows an enhancement in light output power by 68% and 51% at 350 and 750 mA, respectively. Improvements in Lop of the VLED-A could be attributed to the photon scattering from the roughened surface and the use of a highly reflective DBR as CBL on p-GaN. Moreover, even as compared to the VLED-B, it still gains about 25% and 24% increment in Lop at 350 and 750 mA, respectively, indicating that surface roughening via KrF laser irradiation and surface oxide passivation would be beneficial for photons escape from device.

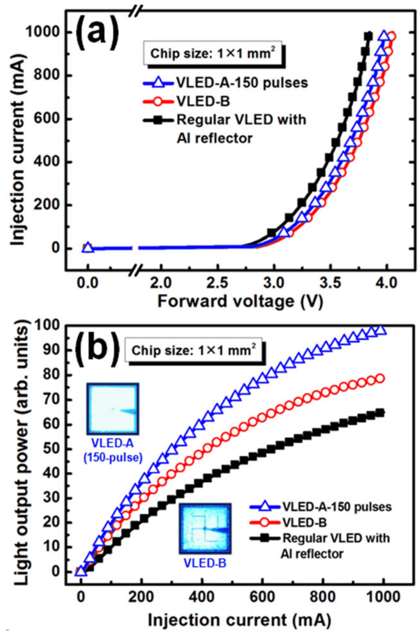

Fig. 4 Comparisons of (a) I-V, and (b) L-I characteristics among VLED-A, VLED-B, and regular VLED with Al reflector.

4. Conclusion

In summary, the use of a highly reflective DBR as CBL and surface roughening by KrF excimer laser process for the fabrication of high-power VLEDs has been demonstrated and investigated. As compared to regular VLEDs, the proposed VLED-A with distributed Bragg reflector and a roughened GaO_x Surface Film have been shown having an enhancement in Lop by 68% and 51% at 350 and 750 mA, respectively. It is expected that the proposed KrF excimer laser etching process and high-reflection DBR as CBL on p-GaN would be a potential candidate for the fabrication of high power GaN-based LEDs for solid-state lighting in the near future.

Acknowledgements

This work was supported by the National Science Council (NSC) of Taiwan, Republic of China, under Contract No. NSC-97-2221-E-274-013, NSC-96-2221-E-006-285-MY3 and the Landmark Project Grant for NCKU's Top-University Project. The authors would like to thank the Advanced Optoelectronic Technology Center and the Center for Micro/Nano Science and Technology, National Cheng Kung University, Taiwan, for equipment access and technical support.

References

[1] E. F. Schubert *et al*., Science, **308**, 1274, (2005)
[2] S. J. Wang *et al*., Appl. Phys. Lett. **87**, 011111, (2005)
[3] C. F. Chu *et al*., Phys. Stat. Sols. C 6 S2, S909, (2009)
[4] C. E. Lee *et al*., IEEE. Photon. Technol. Lett. **20**, 803, (2008)
[5] C. F. Lin *et al*., IEEE. Photon. Technol. Lett. **17**, 2038, (2005)
[6] H. W. Jang *et al*., Appl. Phys. Lett. **82**, 580, (2003)