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# Improvements in for N-Side-Up GaN/Mirror/Si LEDs Using High Reflective Ohmic Contacts

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## 1. Introduction

GaN-related alloy semiconductors with wide band gap ranging from 3.4 to 6.2 eV at room temperature are the focus of current research for UV or blue emitters and detectors. Recent development of GaN-based LEDs with increased brightness and output power, applications including backlights for liquid-crystal displays, exterior automotive lighting, traffic signals, and backlights for cell phones have become possible. However, the performance of GaN LEDs is poor for high power applications if the LEDs were fabricated on the sapphire substrate due to the poor thermal conductivity. The high thermal resistance of the sapphire substrate and relatively high current densities combine to degrade the device performance due to excessive heating from the active layer during operation. To solve this problem, the GaN epilayers can be transferred to the other substrate with good thermal conductivity such as Si or metallic materials by wafer bonding and laser lift-off (LLO) techniques [1]. A p-side-up GaN/mirror/Si LED for vertical current injection has been fabricated by using laser lift-off and wafer bonding techniques [2]. The mirror in the p-side-up structure can easily find for n-GaN ohmic contact layer such as silver and aluminum. However, the n-side-up GaN/mirror/Si LEDs could not find a suitable mirror layer for p-GaN ohmic contact layer.

The ohmic contact metals for p-GaN must possess a high work function (such as Au, Ni, Pd, and Pt) to obtain a low-resistance contact. However, these materials show poor optical reflectivity. The high transmittance material was widely used as the p-GaN transparent conductive layer (TCL) via oxidation of Ni/Au, or using a Ni/indium tin oxide (ITO). Recently, the Si-doped InGaN/GaN short-period superlattice (SPS) tunneling contact layers have replaced the high-resistivity p-GaN as a top contact layer [3]. It was found that ITO can directly on $n^+$-SPS structure could provide an extremely high transparency (above 93% at 465 nm) and also a reasonably small specific contact resistance of $1.6 \times 10^{-3}$ Ω-cm$^2$. In order to achieve the high reflective mirror in the n-side-up GaN/mirror/Si LEDs, the high reflective metal (Al) and high transparency ohmic contact material (ITO) were utilized to enhance the optical power of the wafer-bonded n-side-up GaN/mirror/Si LEDs. Details of the device characteristics will also be discussed.

## 2. Experimental details

Samples used in this study were grown on (0001)-oriented sapphire substrates by metalorganic chemical vapor deposition. The substrate was cleaned with organic solvents before loading into the chemical vapor deposition system. The LEDs structure consists of a thin GaN nucleation layer was initially grown on sapphire at low temperature, followed by a 1.5 μm-thick undoped GaN, a 2 μm highly conductive Si-doped $n^+$-GaN layer, InGaN/GaN quantum-well active layer, a 0.1 μm Mg-doped p-AlGaN layer, a 0.25 μm Mg-doped $p^+$-GaN layer, and a 3-nm Si-doped $n^+$-GaN on the top contact layer. Details of the device fabrication steps are shown in Figs. 1(a)-1(h).

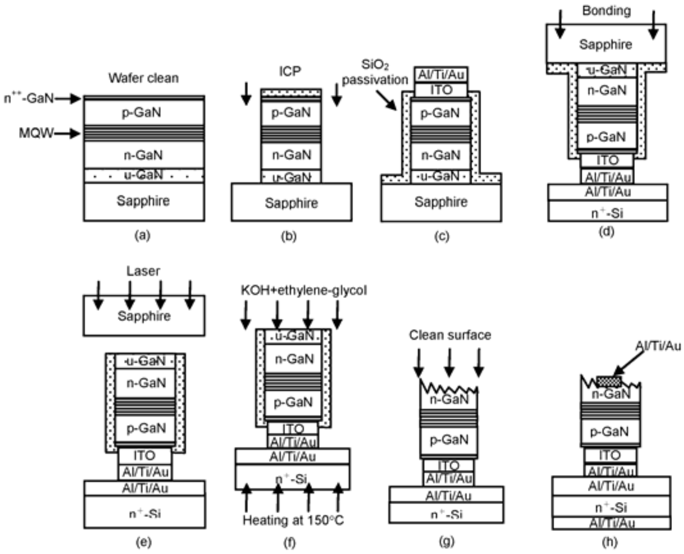


Fig. 1 Schematic diagram of fabrication steps for n-side-up GaN/mirror/Si LED structure

The lift-off process was performed using a Q-switched Nd:YAG laser operating at a wavelength of 355 nm. The laser light was irradiated from the back surface of the sapphire substrate and GaN was locally heated close to the sapphire/GaN interface. After the entire LED wafer was scanned with the laser beam, the sapphire substrate was separated from the LED structure. Then, the GaN LED epilayers were transferred to the Si substrate with a reflective metal mirror.

## 3. Results and discussion

In the n-side-up GaN/mirror/Si LEDs structure, the mirror for p-GaN ohmic contact metal is important. The ohmic contact for p-GaN metal with high work function is required such as Au, Ni, Pt, and Pd with 5.1, 5.15, 5.65, and 5.12 (eV), respectively. The simulation data of reflectivity for the p-GaN suitable ohmic contact metals show in the Fig. 3. The reflectivity at 460 nm is 39, 54, 60, and 66 % of Au, Ni, Pt, and Pd, respectively. The metal can not only be used as the ohmic contact to p-GaN, but also a reflective mirror in the n-side-up GaN/mirror/Si structure. It was found that the suitable metals do not with high reflectivity characteristic at 450 to 470 nm. In this study the highest reflectivity of ohmic contact metal Pd is chose to compare with the n-side-up GaN/mirror/Si with ITO/Al reflectivity mirror in the Fig. 2.

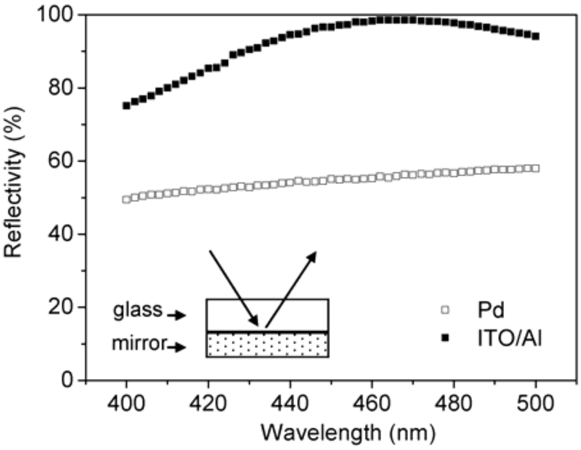


Fig. 2 Reflectivity as a function of wavelength for various metallic mirror materials

As shown in Fig. 3 the luminance intensity-current (L-I) characteristic of the n-side-up vertical GaN/mirror/Si LEDs with various mirror reflectors (ITO/Al and Pd), and original sapphire LEDs. Here the LEDs chips were not encapsulated for the electrical and optical measurements. The GaN/ITO/Al/Au/Si LEDs with surface texturing presented a maximum luminance intensity of 230 mcd (@ 20 mA) with a forward voltage of 3.1 V. The luminance intensity is over five times in magnitude as compared with that of the original planar GaN/sapphire LEDs (45 mcd @ 20 mA). Furthermore, the GaN/mirror (ITO/Al)/Si LEDs with almost two times luminance intensity than Pd mirror (126 mcd @20 mA).

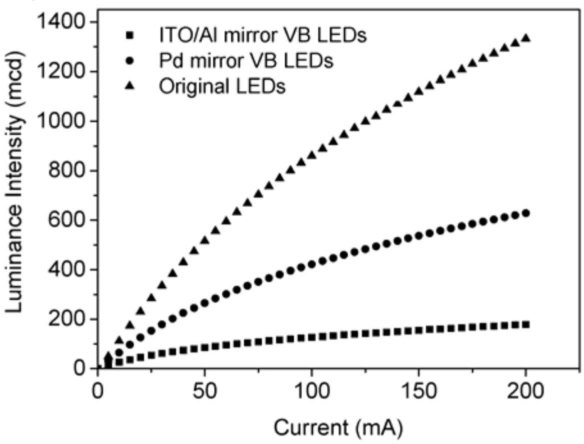


Fig. 3 Luminance intensity as a function of current for various metallic mirror materials

Fig. 4 shows the output power versus injection current characteristics for the GaN/mirror/Si and original GaN/sapphire LEDs, where the chips were encapsulated in lamp form. The output power of the GaN/mirror/Si LED showed 8.9 mW at 20 mA that was higher than original LEDs. It is well know that the device performance in the lamp form condition degrades much easier due to excessive heating. With the current increasing, the light output power for the GaN/mirror/Si LED was more stable than original LEDs. This result suggests that the GaN/mirror/Si LED has a higher current capability than the original GaN/sapphire LED due to the higher thermal-conductivity Si substrate.

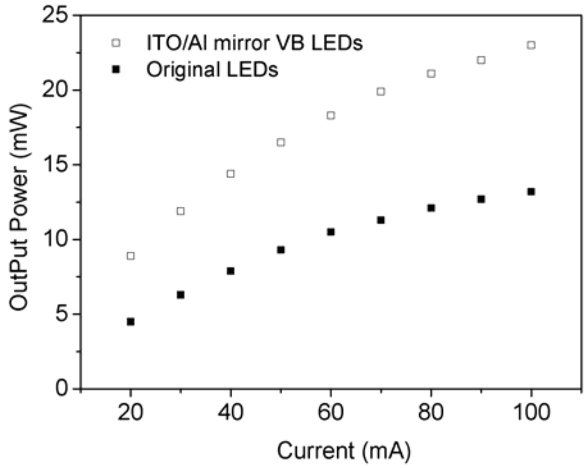


Fig. 5 Output power versus injection current characteristics of vertical n-GaN/mirror/Si and GaN/sapphire LED samples.

## 4. Conclusions

In summary, the GaN/mirror/Si LEDs with vertical electrodes were fabricated by a combination of wafer bonding and LLO techniques. The vertical-conducting GaN LEDs with high reflective ITO/Al mirror can achieve three times and two times in intensity than that of the original GaN/sapphire and Pd-mirror/Si LEDs, respectively. This feature is attributed to the ITO/Al providing a high reflective mirror and surface roughening enhancing the external quantum efficiency.

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## References

[1] W. S. Wong, T. Sands and N. W. Cheung, Appl. Phys. Lett., 72, 599, 1998.

[2] D. S. Wuu, S. C. Hsu, S. H. Huang and R. H. Horng, Phys. Stat. Sol. (a), 201, 2699, 2004.

[3] S. J. Chang, C. S. Chang, Y. K. Su, R. W. Chuang, W. C. Lai, C. H. Kuo, Y. P. Hsu, Y. C. Lin, S. C. Shei, H. M. Lo, J. C. Ke and J. K. Sheu, IEEE Photon. Technol. Lett., 16, 1002, 2004