Improvement of Light Extraction Efficiency of AlGaN-based Deep-Ultraviolet Light Emitting Diodes

Yanan Guo, Yun Zhang*, Jianchang Yan, Xiang Chen, Tongbo Wei, Junxi Wang and Jinmin Li

Institute of Semiconductors, Chinese Academy of Sciences
A35 Qinghua East Road, Haidian District, Beijing 100083, China
*e-mail: yzhang34@semi.ac.cn Phone: +86 (010)82304283

Keywords: light extraction efficiency; AlGaN; deep ultraviolet light emitting diodes; Al reflector

Abstract

AlGaN-based deep-ultraviolet light emitting diodes (DUV LEDs) suffer serious light extraction issues. In this work, we report on using an aluminum (Al) reflector layer combined with well-designed mesas to enhance the sidewall scattering and promote the light to transport to the bottom side. The light output power (LOP) of 278-nm DUV LEDs was improved by 30.1% and exceeded 5.5 mW at 100 mA. To further improve the light extraction efficiency (LEE), picosecond pulse laser was also introduced to form air voids inside the sapphire substrate, increasing the LEE by 5.5%.

INTRODUCTION

Deep-ultraviolet light emitting diodes (DUV LEDs) have been attracting increasing attention because of their important applications such as purification, sterilization, bio-medical, etc. Compared with mercury lamps, AlGaN-based DUV LEDs have benefits of environmental friendliness, instant startup, compact size and variable wavelength.

However, the external quantum efficiency (EQE) of AlGaN-based DUV LEDs grown on sapphire is typically below 5%. A major issue responsible for such a low EQE is the inefficient light extraction efficiency (LEE). First of all, due to the anisotropic optical polarization properties of c-plane AlGaN alloys, the emission intensity of TM-polarized light (electric filed $\vec{E} \perp c$) increases compared with TE-polarized light ($\vec{E}//c$) as the wavelength gets shorter than 300 nm[1]. The TM-polarized light propagates parallel to *c*-plane and is detrimental to surface emission. So the conventional designs and methods adopted in visible LEDs performing TE-polarized dominated emission are not suitable for AlGaN-based DUV LEDs. New methods for enhanced extraction of TM-polarized emission are necessary[2, 3]. Besides, DUV LEDs usually adopt flip-chip bonding package and emit light from substrate backside due to the light absorption in the p-GaN top layer, so certain treatments with the sapphire substrates are also important to improve the light extraction at the interfaces between the epi-layers, substrates and air, such as substrate patterning[4, 5], surface and sidewall roughness[6, 7], photonic crystals[8], and chip shaping[9, 10].

In this study, we developed an easy-facilitative Al reflector technique combined with well-designed mesas to enhance the sidewall light scattering, which was in favor of TM-polarized light extraction. The light output power (LOP) of 278-nm LEDs was improved by 30.1% and exceeded 5.5 mW at an injection current of 100 mA. Air voids inside the sapphire substrate induced by picosecond pulse laser were also introduced as a convenient and low-cost way to enhance light scattering at the interface between the sapphire and air, showing a 5.5% increase of LOP at 100 mA.

DEVICE FABRICATION

The wafers were grown in a home-made low pressure metalorganic chemical vapor deposition (LP-MOCVD) system. Trimethylauminum (TMAl), Trimethygallium (TMGa) and ammonia were used as aluminum, gallium and nitrogen sources, respectively. Figure 1 shows the schematic structure of AlGaN-based DUV LEDs on sapphire substrate. The LED structure consists of a 1 μm-thick AlN, 20 pairs of AlN/AlGaN superlattices (SLs), a 2 μm-thick n-$Al_{0.5}Ga_{0.5}N$ layer, five pairs of $Al_{0.4}Ga_{0.6}N/Al_{0.5}Ga_{0.5}N$ MQWs with 3 nm-thick wells and 10 nm-thick barriers, a 30 nm-thick p-$Al_{0.65}Ga_{0.35}N$ electron blocking layer, a 50 nm-thick p-$Al_{0.5}Ga_{0.5}N$ cladding layer and a 150 nm-thick highly doped p-GaN contact layer.

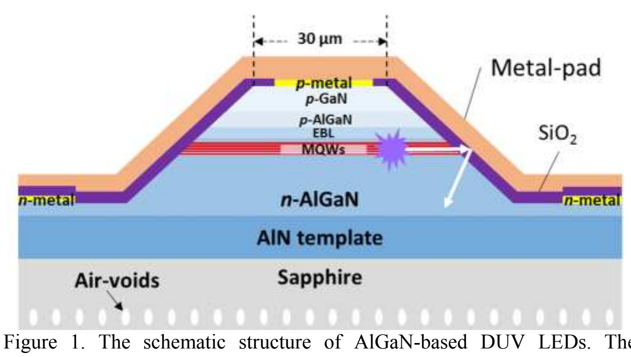

Figure 1. The schematic structure of AlGaN-based DUV LEDs. The trapezoid mesa has an inclined angle of ~45°.

Contact photo lithography and ICP etching defined the LED mesa. By adjusting the ICP etching power and etching rate, the mesa formed a trapezoidal cross-sectional shape with a dip angle of ~45°. The total device area is 500 × 500 μm^2 or 1000 × 1000 μm^2. We designed micro-pixel mesas with a hexagonal shape. The side length of each independent hexagonal mesa was 30 μm. A Ti/Al/Ti/Au metal stack was deposited on the exposed n-AlGaN layer using an e-beam evaporator and then annealed at 850 ℃ in N_2. A Ni/Au metal stack was deposited on p-GaN and then annealed at 600 ℃ in air. After passivation with 300 nm-SiO_2 by PECVD, standard Cr/Al/Ti/Au (70/1700/50/200 nm) metal system was deposited as anode and cathode electrodes. Cr/Al/Ti/Au system is widely used in traditional 450-nm blue LED fabrication, but Cr metal is not a good UV reflector. In our fabrication, the DUV LEDs employed Al/Ti/Au (1700/50/200 nm) as metal pad instead, because Al has high reflectivity in the DUV range.

To confirm the metal reflectivity, we deposited Al, Al/Ti/Au and Cr/Al/Ti/Au stacks respectively on the front-side of double-side polished sapphire substrates. The reflectivity ($R_{meas.}$) was measured from the backside of the substrate using a Cary 5E UV-VIS-NR spectrophotometer. Taking the transmittance ($T_{subs.}$) of the substrate into consideration, the real reflectivity of metals equals $R_{meas.}/T_{subs.}^2$. Figure 2 shows the reflectivity of Al/Ti/Au stack is above 80%, while that of Cr/Al/Ti/Au stack is only about 30% in the DUV range.

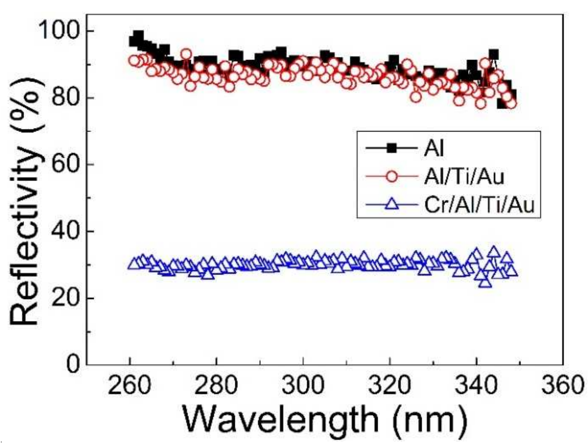

Figure 2. The reflectivity of Al, Al/Ti/Au and Cr/ Al/Ti/Au measured by Cary 5E UV-VIS-NR spectrophotometer.

The LED substrates were grinded and polished to 150 μm. After that, the chips were separated by conventional nanosecond laser dicing. Finally, the LED chips were flip-chip bonded on silicon submounts with gold bumps and subsequently attached onto boards with sliver paste for device testing. To further improve the LEE, the boards with flipped chips were settled on a moving stage backside up for air voids formation inside the substrate using a picosecond pulse laser. The fabrication method is described elsewhere[11]. Due to the non-linear multi-photon absorption effect of extremely short and intense laser inside the sapphire, the Al-O bond can be broken and air voids will be generated around the focus of the laser. The picosecond pulse laser used had a wavelength of 1064 nm, a repetition rate of 60 kHz, a pulse duration of 15 ps, and an output power of 0.158 mW. The picosecond pulse laser was focused at a depth of 45 μm from the backside of the sapphire, which was safe enough to avoid heat damage of the epi-layers.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Figure 3 shows the distributions of the leakage current at revised voltage 10 V and the forward voltage at an injection current of 20 mA based on 330 chips with Al/Ti/Au (i.e. with Al reflector) or with Cr/ Al/Ti/Au (i.e. without Al reflector) as metal pad. All the chips were coming out of two quarters from the same 2-inch wafer. The chip size is 500 × 500 μm^2. For the LEDs with Al reflector, 76% of chips have leakage current below 100 nA at -10 V, while nearly 70% below 10 nA at -10 V; Over 86% of chips shows forward voltage at 20 mA between 5 to 7V. The distributions of leakage current and forward voltage didn't show obvious differences between chips with and without Al reflector. These results indicate quite good compatibility of Al reflector technique in our process.

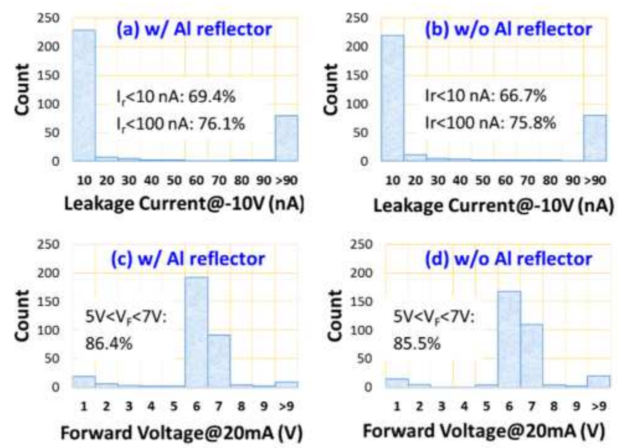

Figure 3. Histograms showing distributions of the leakage current at -10 V (a)(b) and the forward voltage at 20 mA (c)(d) of chips with or without Al reflector.

We randomly picked 46 packaged LEDs with and without Al reflector for comparison. The packaged LEDs were measured in a calibrated UV integrating sphere system at room temperature continuous-wave mode. As shown in Figure 4, the average LOP was increased by 30.1% at 100 mA by using the Al reflector design. This improvement is ascribed to the less light absorption of metal pads and the more efficient light scattering at the sidewalls. Especially the TM-mode light from the active region can be reflected to the sapphire backside and thus the LEE was improved.

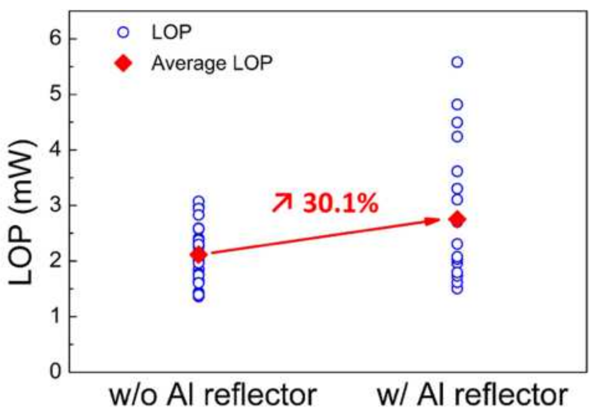

Figure 4. The LOP comparison of DUV LEDs with and without Al reflector measured at an injection current of 100 mA.

Figure 5 shows the optical performance of one LED with Al reflector under injection current from 10 mA to 100 mA. The LOP is almost linearly increased with the injection current. At 100 mA, the LOP reaches 5.58 mW, with a corresponding EQE of 1.24%. The insert of Figure 5 shows the DUV LED has a peak wavelength at 275.4 nm, with a full width at half maximum of 9.7 nm at an injection current of 100 mA. No shoulder peak is observed in the electroluminescence (EL) spectrum, indicating good carrier confinement in the active region.

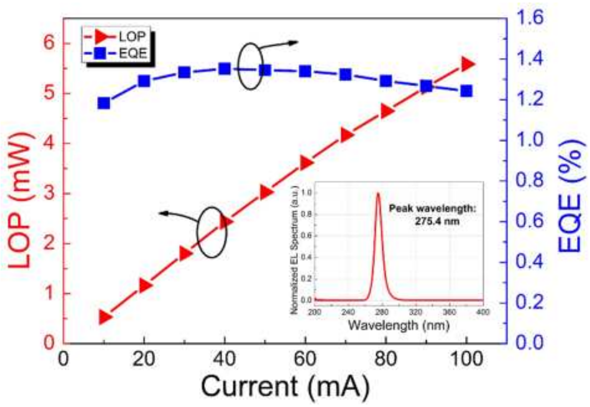

Figure 5. The LOP and EQE versus injection current of one DUV LED with Al reflector structure.

The Al reflector technique was applied to DUV LED chips with size of 1000 × 1000 μm². We performed a reliability test of the packaged DUV LEDs using Al reflector during the fabrication process. The applied stress and measurement conditions are cw-100 mA and room temperature without heat sinks. During the 1500 more hours aging test, the LOP initially increased by about 7% might owing to Mg activation effect in p-AlGaN layer. When the Mg activation efficiency enhancement occurs, the conductivity of p-AlGaN increases and more holes inject into quantum wells, leading to an improved internal quantum efficiency. The forward voltage decreased slightly at the same time, which is accordance with the assumption. The LOP slightly decreased with aging time then. After 1500 h, the LOP dropped to 93% of its initial value. The voltage showed a slight increasing trend. The mechanism is not clear at present.

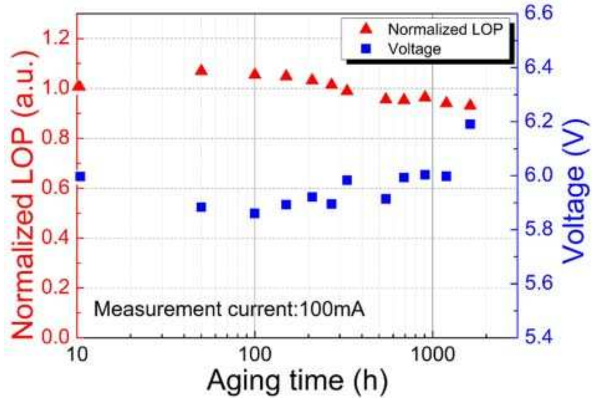

Figure 7. The reliability test of DUV LEDs using Al reflector technique during the fabrication process at cw-100 mA, RT. Chip size: 1×1 mm².

An air voids array was formed inside the sapphire substrate by picosecond pulse laser to further improve the LEE. As shown in the insert of Figure 6, the space between air voids is 16 × 40 μm². We measured the LOPs of the same bare LED chip before and after forming air voids. It can be seen from Figure 6 that the LOP after air voids formed inside reaches 2.61 mW at 100 mA, showing an improvement of 5.5%. We attribute the improvement to the light scattering at the interfaces between air voids and the sapphire, which can increase the light escape probability from the sapphire. However, this improvement is relative slight compared with results achieved in blue LEDs[11]. It might because of the conservative formation depth and sparse density of air voids. Besides, the effect of reduced light emission directly propagating to the substrate backside is not excluded. More detailed study is necessary to explain the phenomenon.

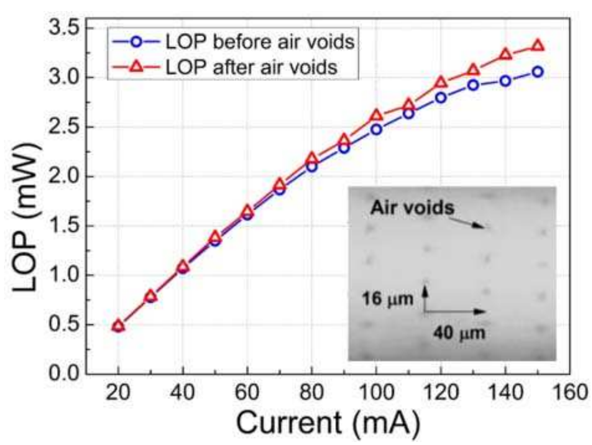

Figure 6. The LOP comparison of the same bare LED chip before and after air voids induced inside the substrate using picosecond pulse laser. Insert: the optical microscope image of air voids induced. Chip size: 1×1 mm².

CONCLUSIONS

In summary, we proposed an Al reflector structure to improve the sidewall scattering and thereby enhance the LEE by 30.1%. The LOP of 278-nm LEDs exceeded 5.5 mW at an injection current of 100 mA. DUV LEDs using Al reflector technique also showed considerable reliability. This design is promised to play a more significant role in DUV LEDs with shorter wavelength. We also demonstrated an improvement of the LOP by inducing arrays of air voids inside the substrate using picosecond pulse laser. The LOP was proven to be enhanced by 5.5% at 100 mA due to the scattering at the interfaces between air voids and the sapphire. Both the Al reflector and picosecond laser technique provide a low-cost, effective and easy-facilitative way to improve the LEE of DUV LEDs and are suitable for mass production.

ACKNOWLEDGEMENTS

This work was supported the National Natural Sciences Foundation of China under Grant No. 61376047, No. 61006038, No. 61204052, No. 61206090 and No. 61204053.

REFERENCES

[1] T. Kolbe, et al., Appl. Phys. Lett. 97, 171105(2010).
[2] J. J. Wierer, et al., Appl. Phys. Lett. 105, 061106 (2014).
[3] D. Y. Kim , et al., Light-Sci. Appl. 4, e263 (2015).
[4] M. Khizar, et al., Appl. Phys. Lett. 86, 173504(2005).
[5] P. Dong, et al., Appl. Phys. Lett. 102, 241113(2013).
[6] S. S. Huang, et al., IEEE Photonic. Tech. L. 18, 2623(2006).
[7] Y. Y. Zhang, et al., Opt Express 20, 6808(2012).
[8] S. Inoue, et al., Appl. Phys. Lett. 106, 131104(2015).
[9] W. Y. Fu, et al., IEEE Photonic. Tech. L. 21, 1078(2009).
[10]S. E. Brinkley, et al., Appl. Phys. Express 5, 032104(2012).
[11] Y. Y. Zhang, et al., Opt Express 21, 32582(2013).

ACRONYMS

DUV LEDs: Deep-ultraviolet Light Emitting Diodes
EQE: External Quantum Efficiency
LEE: Light Extraction Efficiency
LOP: Light Output Power
MOCVD: Metalorganic Chemical Vapor Deposition
EL: Electroluminescence