# Light extraction enhancement of AlGaN-based vertical type deep-ultraviolet light-emitting-diodes by using highly reflective ITO/Al electrode and surface roughening

YOUN JOON SUNG,[1,2,4] MIN-SUNG KIM,[1] HWANKYO KIM,[1] SUNGHAN CHOI,[1] YOUNG HOON KIM,[1] MYUNG-HOON JUNG,[1] RAK-JUN CHOI,[1] YONG-TAE MOON,[1] JEONG-TAK OH,[1] HWAN-HEE JEONG,[1] AND GEUN YOUNG YEOM[2,3,5]

[1] *Department of LED Business, Chip development group, LG Innotek Co, Ltd, Paju, 10842, South Korea*
[2] *School of Advanced Materials Science and Engineering, Sungkyunkwan University, Suwon 16419, South Korea*
[3] *SKKU Advanced Institute of Nano Technology (SAINT), Sungkyunkwan University, Suwon 16419, South Korea*
[4] *yjsung@lginnotek.com*
[5] *gyyeom@skku.edu*

**Abstract:** AlGaN-based vertical type high power ultraviolet-C light emitting diodes (UV-C LEDs), which have a Ga-face *n*-contact structure, were fabricated on a LED epilayer transferred to a carrier wafer through a laser lift-off (LLO) process. A significant light extraction enhancement of the vertical chip by using a highly reflective ITO/Al *p*-type electrode is demonstrated, along with surface roughening. A GaN-free LED epi structure is employed to prevent light absorption in the UV-C wavelength region. The vertical chip with the ITO/Al reflector and *n*-AlGaN surface roughening exhibited a high light output power of 104.4mW with a peak wavelength of 277.6nm at an injection current of 350mA. Comparing the device characteristics of the vertical chip and the flip chip showed that the light output power of the vertical chip was 1.31 times higher than that of the flip chip at 350mA. In particular, with the high power vertical type UV-C LED, a maximum light output power of 630mW could be achieved at a current of 3.5A, and this is mainly attributed to efficient heat dissipation through a metal substrate and the resulting relatively lower junction temperature of the vertical chip.

## 1. Introduction

Aluminum gallium nitride (AlGaN)-based deep ultraviolet lighting emitting diodes (DUV LEDs) have attracted attention for a wide variety of applications such as water purification, surface disinfection, biomedicine, and material detection [1–4]. However, despite the compact design, DUV LEDs, which are more cost-effective and eco-friendly than UV lamps, cannot easily replace UV lamps due to their low optical output power. The low light output power and external quantum efficiency (EQE) are mainly attributable to the low light extraction efficiency (LEE) and high epitaxial crystalline defects in AlGaN-based DUV LEDs. Recently, a number of studies have investigated highly reflective electrodes [5,6], ways to improve surface roughness [7–9], and ways to improve crystalline quality to increase internal quantum efficiency (IQE) [10–12]. In order to further increase the LEE in the DUV LEDs, light absorption in the epi structure should be minimized by replacing *p*-GaN with transparent *p*-AlGaN (Al > 45%). In addition, in order to employ the transparent *p*-AlGaN epi structure in the UV-C region, a proper reflective *p*-ohmic electrode scheme should be considered.

Ag, as a reflective electrode, has high reflectivity over 90% in the visible region and low reflectivity under 30% in the UV-C region. Therefore, Ag is not a suitable reflective electrode for UV-C LEDs. On the other hand, Al has high reflectivity over 90% in the UV region, but shows difficulty in obtaining the ohmic contact to *p*-GaN [13]. Thin Ni/Mg, Rh, and thin Ni/Al have been reported as reflective electrodes in the *p*-AlGaN structure [6,14]. The use of a *p*-type reflective electrode with high reflectivity and ohmic contact to *p*-AlGaN is necessary to improve LEE and suppress Joule heating in UV-C LEDs. Thin ITO/Al is one of the promising candidate *p*-ohmic reflector schemes in the UV-C region. It is desirable to use thin ITO/Al *p*-reflector in combination with *n*-AlGaN surface roughening to maximize the LEE for the vertical-type high power UV-C LEDs. A number of studies have reported GaN-based vertical type LEDs fabricated using a laser-lift off (LLO) process with surface roughening [15–17]. However, AlGaN-based vertical type UV-C LEDs with a Ga-face *n*-contact structure have yet to be reported, which is mainly attributable to the difficulty of separating the sapphire wafer through the LLO process [18]. During the LLO process, thermal shock by laser irradiation [11,18] and rigid Al from thermal decomposition [19] lead to cracking in the epi structure. In order to realize a crack-free LLO process, it is necessary to optimize the laser conditions and epi structures [20].

In this paper, for the first time, AlGaN-based high power vertical type UV-C LEDs consisting of a Ga-face *n*-contact structure and fabricated using an LLO process are presented. A significant improvement of light output power of the vertical chip has been demonstrated by using highly reflective ITO/Al *p*-type electrode and *n*-AlGaN surface roughening. Furthermore, the device characteristics between the vertical type and flip type UV-C LEDs are compared.

## 2. Experimental procedure and methods

The AlGaN-based UV-C LED epi structure is grown on a sapphire substrate using a metal organic chemical vapor deposition system. The epi structure includes 3 µm-thick AlN, 200 nm-thick $Al_{0.45}Ga_{0.55}N$, 2.5 µm-thick Si-doped $n$-$Al_{0.7}Ga_{0.3}N$, 0.5 µm-thick $n$-$Al_{0.6}Ga_{0.4}N$, five pairs of $Al_{0.4}Ga_{0.6}N/Al_{0.64}Ga_{0.36}N$ multiple quantum wells (MQWs), 35nm-thick Mg-doped $p$-$Al_{0.75}Ga_{0.25}N$ electron blocking layer, and 50nm-thick Mg-doped *p*-AlGaN for *p*-ohmic contact.

After growing the UV-C LED epi structure, three types of vertical chips are fabricated in order to investigate the effects of *p*-type reflective electrodes and *n*-AlGaN surface roughening on the light output power of UV-C LEDs. Ti/Al/Ni/Au multi-layers are used for *n*-contact on Ga-faced *n*-AlGaN, which is exposed by dry etching. Next, different types of *p*-electrodes are prepared on the *p*-AlGaN contact layer. The ITO of the ITO/Al *p*-electrode scheme is employed for *p*-type contact. ITO is deposited by radio frequency (RF) sputtering at room temperature and then annealed using a rapid thermal annealing system for ohmic contact to *p*-AlGaN epi layer. Once annealing has been completed, Al metal is evaporated on the ITO film as a reflector. In addition, Ni/Au, which is typically adopted as a *p*-electrode, is also evaporated on the *p*-AlGaN epi layer and annealed for ohmic contact. The *n*-type and *p*-type electrodes are then spatially separated by an insulator. Next, for the wafer bonding process, bonding metals are deposited to combine the LED wafer with a metal carrier wafer at a high temperature of 300°C. The coefficient of thermal expansion (CTE) of the metal carrier wafer is similar to that of the LED wafer in order to reduce the warpage of wafers following the wafer bonding process. The epi structure is transferred from the sapphire substrate to the metal carrier wafer by an LLO process. We believe that the stress between the sapphire and metal carrier needs to be well controlled to reduce through CTE matching of the wafers in order to obtain a crack-free epilayer after the LLO process. The LLO process is carried out using a high energy laser. After the LLO process, the LED structure on the metal carrier wafer is dipped into a HCl solution for 1 min to remove Al and Ga metal droplets, then etched by an inductively coupled plasma (ICP) etcher until exposing the N-face *n*-AlGaN. The exposed *n*-AlGaN surface is roughened through a crystallographic wet etching process with

an alkali solution. The sample without surface roughening is also prepared using an ITO/Al *p*-electrode for comparison.

In order to compare the device characteristics of the vertical chip with an ITO/Al reflector and surface roughening with the conventional chip, a flip type chip is fabricated using the same LED epi structure and ITO/Al reflective electrode. Figure 1 shows schematic drawings of Fig. 1(a) cross-sectional and Fig. 1(b) tile-view of the fabricated vertical UV-C LEDs structure with the Ga-face *n*-contact.
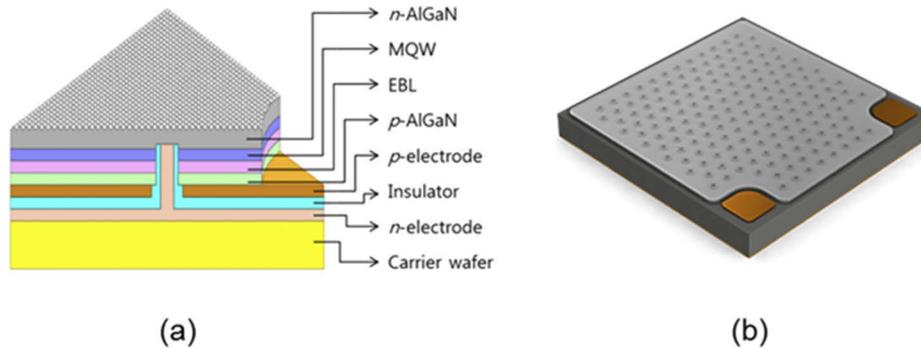


**Fig. 1.** Schematic drawing of (a) cross-sectional and (b) tile-view of Ga-face *n*-contact type vertical LED structure.

## 3. Results and Discussion

Figure 2 shows the Fig. 2(a) tilt-view and Fig. 2(b) plane-view of SEM images obtained from the roughened N-face *n*-AlGaN surface of the vertical chip, where the cone density is approximately $6.8\times10^8$/cm$^2$ and the average cone diameter is about 0.5 µm. There is no exposed flat area on the roughening surface. The wet etching conditions of surface roughening are set in an attempt to achieve an optimal cone size to improve the light extraction.
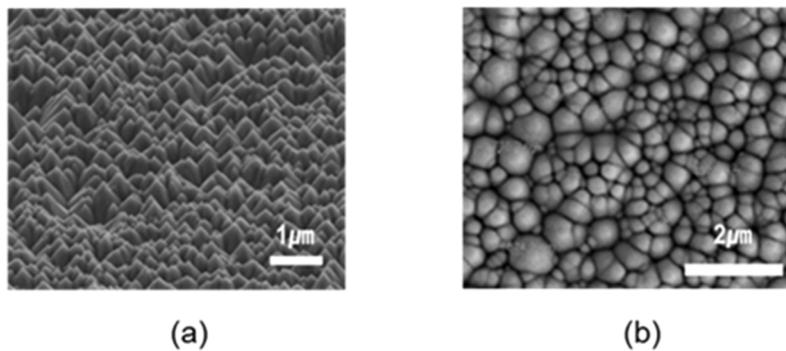


**Fig. 2.** Scanning electron micrograph of the roughened N-face *n*-AlGaN surface etched by an alkali solution. (a) The tilt-view image and (b) plane-view after the passivation deposition on the extractor surface with a diameter of approximately 0.5 µm.

In order to evaluate the reflectance of the *p*-electrode materials in the UV-C wavelength region, the four different metal layer schemes of Ni/Au, ITO/Al, Ru(150nm), and Ni(2nm)/Al(150nm) are deposited on 430 µm-thick sapphire, after which the reflectivity is measured. The reflectivity is calibrated based on aluminum/sapphire, the reflectivity of which is 92% at 280nm. The results are shown in Fig. 3, and the reflectivities of Ni/Au, ITO/Al, Ru, and Ni/Al are 35.7, 67.8, 61.2,

and 55.79% at 280nm, respectively, indicating that the ITO/Al scheme is a promising reflector in the UV-C wavelength region. In order to investigate the effects of reflective *p*-type electrodes and *n*-AlGaN surface roughening on the light extraction of UV-C LEDs, $1 \times 1mm^2$ vertical chips with either the Ni/Au reflector or the ITO/Al reflector are prepared with surface roughening as shown in Figs. 2(a) and 2(b). Further, the vertical chips with and without the surface roughening are also prepared using the ITO/Al electrodes.
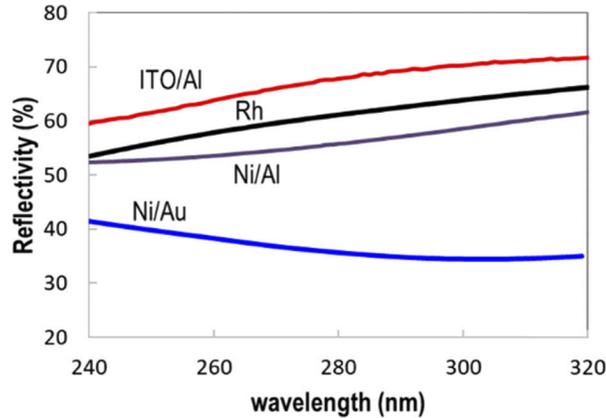


**Fig. 3.** Relative reflectivities of ITO/Al, Ni/Au, Ni(2 nm)/Al(150 nm), and Rh(150 nm) layers deposited on sapphire substrate. Reflectivity was calibrated based on aluminum 92%.

Figure 4 shows the current-voltage (*I-V*) characteristics of $1 \times 1mm^2$ vertical chips fabricated with the Ni/Au and ITO/Al electrodes. At an injection current of 350 mA, the series resistance of the LED with Ni/Au is 1.21ohm, while that with ITO/Al is 1.25ohm. At 350 mA, the *I-V* measurement also shows that the voltage of the vertical chip with the Ni/Au electrode is 6.55 V, while that with ITO/Al is 6.76 V, indicating that the series resistance of p-electrodes or the specific contact resistance of the Ni/Au electrode on *p*-AlGaN is slightly lower than that of the ITO/Al electrode. This may be attributed to the formation of $Al_2O_3$ at the ITO/Al interface [21] and the high barrier height of ITO on p-AlGaN [22,23].
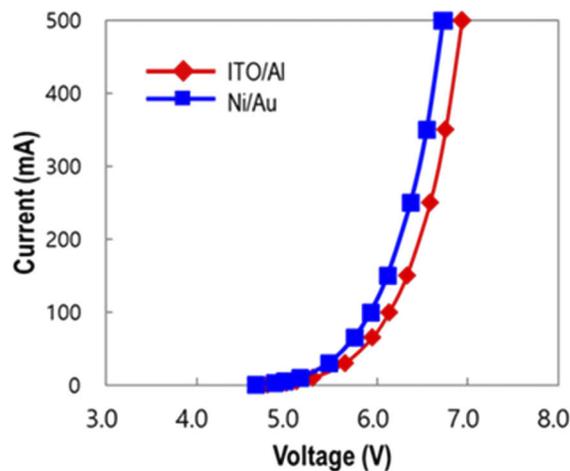


**Fig. 4.** Current-voltage (I-V) characteristics of $1 \times 1mm^2$ vertical chip fabricated with Ni/Au and ITO/Al *p*-type electrodes.

Figure 5 shows the Fig. 5(a) current-light output power (*I-L*) and Fig. 5(b) current-EQE (*I*-EQE) characteristics of the UV-C vertical chip LEDs with variations in the *p*-type electrodes and surface roughness. Figure 5(a) shows that the light output power of the chip with the Ni/Au reflector with the surface roughening is 48.6 mW at an injection current of 350 mA and with a peak wavelength of 276.5 nm. The light output power of the chip with the ITO/Al reflector with the surface roughening is 104.4 mW at an injection current of 350 mA and with a peak wavelength of 277.6 nm. It should be noted that the light output power of the chip with the ITO/Al reflector is 2.15 times higher than that with the Ni/Au reflector. The differences in the light output power between the Ni/Au and ITO/Al electrodes are attributed to the differences in the reflectivity between *p*-AlGaN and the electrode. For the chip with no surface roughening with the ITO/Al electrode, the light output power is 62.8 mW at the injection current of 350 mA and with a peak wavelength of 274.7 nm. The light output power of the surface-roughened chip is 1.66 times higher than that of the chip with no surface roughening, which is due to the suppression of the total internal reflection. This means that the light extraction of the surface roughened chip has an increase of the scattering event which is sufficient to out-couple the light [24], while the chip with no surface roughening has a long travel distance of light, resulting in an internal loss of light due to the large reflection angle. It should be noted that the transparent *p*-AlGaN with the ITO/Al high reflective mirror and surface roughening of *n*-AlGaN is important in improving the light output power in the UV-C region. Figure 5(b) shows that the EQE of the vertical chips for the Ni/Au electrode with surface roughening, the ITO/Al electrode without surface roughening, and the ITO/Al electrode with surface roughening are 3.1, 3.97, and 6.68% at an injection current of 350 mA, respectively. The ITO/Al electrode and the surface roughening improve the EQE by factors of 2.15 and 1.66, respectively, meaning that improving the *p*-electrode reflectivity and surface roughness of *n*-AlGaN can significantly increase the LEE of the UV-C LEDs.
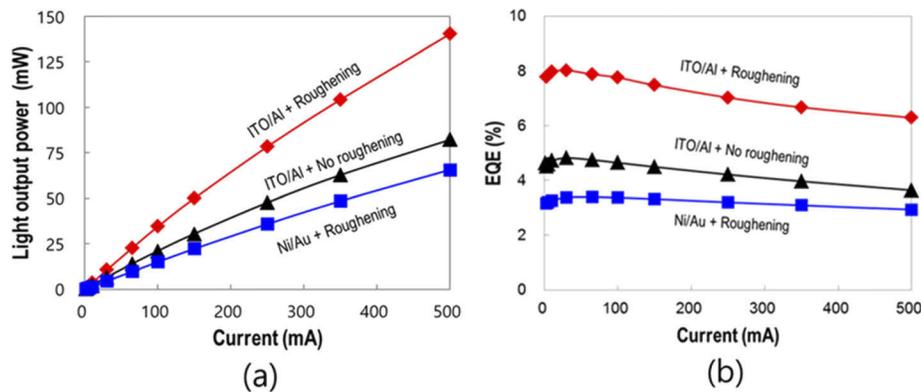


**Fig. 5.** (a) *I-L* and (b) *I*-EQE characteristics of UV-C vertical LEDs according to p-type mirror electrode and surface roughness. ($1 \times 1mm^2$ vertical chip)

Figure 6(a) shows the output power-current-voltage (*L-I-V*) characteristics of the vertical chip and of the flip chip with $1.3 \times 1.3mm^2$ chip size. The top and bottom insets in Fig. 6(a) show the charge-coupled device (CCD) emission images of the vertical chip (upper) and flip chip (lower), respectively, at an injection current of 350mA. Based on the CCD images, it is considered that the emission distribution is quite uniform, implying that the current spreading is uniform. The two different types of chips are fabricated using the ITO/Al *p*-electrodes. For the flip chip, the light output power is 89.1mW at 350mA with a peak wavelength of 278.0nm, and it increases as the current increases up to 2.0A. The maximum output power of 268.5mW is obtained. Then, the light output power decreases over the current of 2.0A. For the vertical chip, the light output power is 116.9mW at 350mA with a peak wavelength of 278.2nm. It should be noted that the

light output power at 2A is 501.5mW. The light output power of the vertical chip is 1.31 times higher than that of the flip chip at 350mA and 1.87 times higher than that at 2A. As the injection current increases, the ratio of the light output power of the vertical chip to the flip chip gradually increases. The light output power of the vertical chip increases with the injection current up to 3.5A. To avoid the heat effect on light output power, the integration time of measurement in an integrated sphere is decreased from 600ms for low current conditions to 18ms (3.5A) for high current conditions in Fig. 6(a). The maximum light output power is 630mW at 3.5A. These results indicate that the vertical type chip structure is very suitable for realizing high power UV-C LEDs with efficient heat dissipation. The increase of light output power of the vertical chip is mainly attributed to the higher LEE due to the surface roughening and the higher thermal conductivity by the conductive substrate, compared to the flip chip [16,25]. To the best of our knowledge, the light output power of 630mW is the highest value that has been reported to date in the UV-C region.
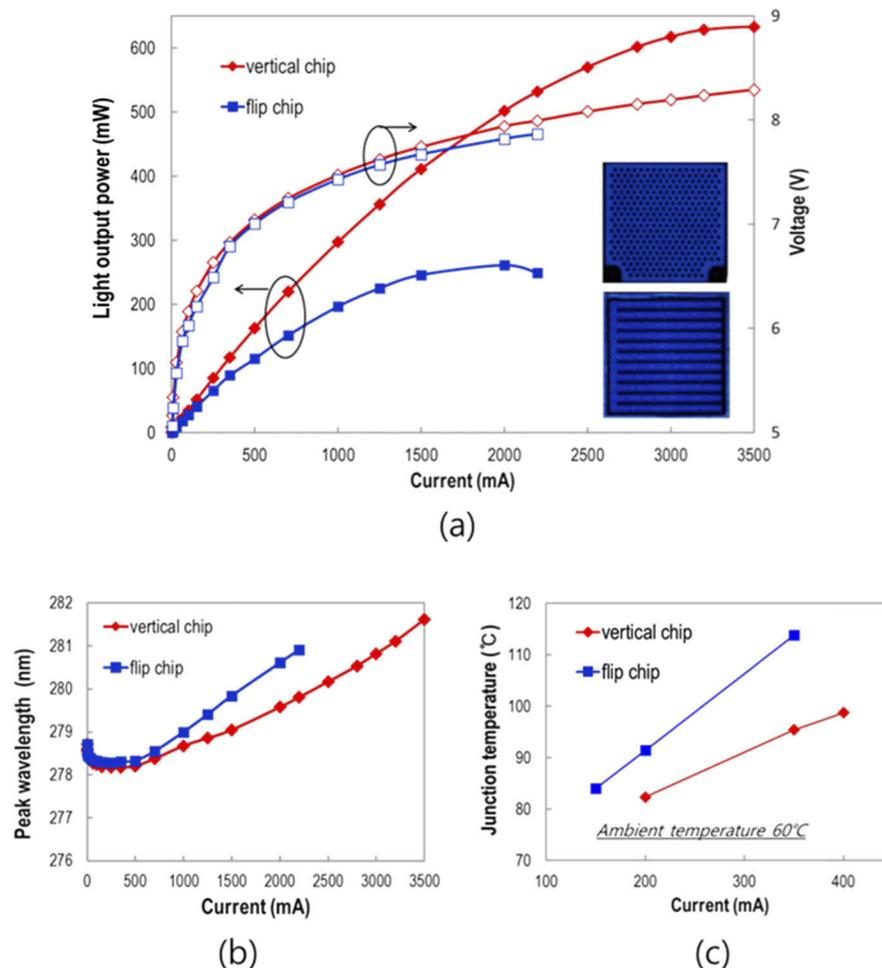


(a)



(b)



(c)

**Fig. 6.** Characteristics of (a) light output power-current-voltage (*L-I-V*), (b) peak wavelength-current, and (c) junction temperature-current at ambient temperature of 60°C for the 1.3 × 1.3mm$^2$ vertical chip and flip chip of UV-C LED.

Figure 6(b) shows the peak wavelength shift behavior of the vertical and flip chips with varying injection currents. For the flip chip, as the current increases from 3 to 250 mA, the

peak wavelength moves to a slightly shorter wavelength from 278.6 to 278.3 nm due to the band filling effect [26]. As the current increases from 250 mA to 2.2 A, the peak wavelength moves to a longer wavelength of 280.9 nm due to the thermal bandgap lowering effect [25]. For the vertical chip, as the current increases from 3 to 350 mA, the peak wavelength moves to a slightly shorter wavelength, from 278.6 to 278.2 nm, similar to the flip chip. Further, as the current increases from 350 mA to 2.2 A, the peak wavelength moves to a longer wavelength of 279.8 nm. Compared to the 2.6 nm shift of the flip chip, the vertical chip shows a smaller long wavelength shift of 1.6 nm. This indicates that the thermal effect of the vertical chip is relatively smaller than that of the flip chip with increasing current [27]. In order to verify this, two different types of chips are attached to the package with a heat sink to measure the junction temperature of the LEDs. As shown in Fig. 6(c), at 350 mA and with the ambient temperature of 60°C, the junction temperature of the vertical chip is 95.4°C while that of the flip chip is 113.7 °C. The metal substrate of the vertical chip, which dissipates the heat throughout all of the area, has a good thermal conductivity. Thus, it is expected for the vertical chip to effectively reduce the junction temperature under a high injection current. The junction temperature affects the electrical and optical properties as well as the reliability of the LEDs [28]. Therefore, compared to the flip chip, it is concluded that the vertical type chip structure in high power UV-C LEDs can significantly improve the light output power and the capability of heat dissipation.

## 4. Conclusion

The characteristics of novel AlGaN-based vertical type UV-C LEDs, which consist of a Ga-face *n*-contact structure, using an LLO process to transfer a LED epilayer to a carrier wafer are reported here. The vertical type UV-C LED fabricated with a highly reflective ITO/Al *p*-electrode and *n*-AlGaN surface roughening exhibits a high output power of 104.4 mW with a peak wavelength of 277.6 nm at 350 mA. Comparing the vertical chip and the flip chip showed that the light output power of the vertical chip is 1.31 times higher than that of the flip chip at 350 mA. A maximum light output power of 630 mW at 3.5A is obtained from the vertical type high power UV-C LED. The vertical chip exhibits better thermal characteristics than the flip chip, mainly due to its efficient heat dissipation efficiency through a metal substrate.

## References

1. H. Hirayama, "Quaternary InAlGaN-based high-efficiency ultraviolet light-emitting diodes," J. Appl. Phys. **97**(9), 091101 (2005).
2. K. B. Nam, J. Li, M. L. Nakarmi, J. Y. Lin, and H. X. Jiang, "Achieving highly conductive AlGaN alloys with high Al contents," Appl. Phys. Lett. **81**(6), 1038–1040 (2002).
3. A. Khan, K. Balakrishnan, and T. Katona, "Ultraviolet light-emitting diodes based on group three nitrides," Nat. Photonics **2**(2), 77–84 (2008).
4. M. Kneissl, T. Kolbe, C. Chua, V. Kueller, N. Lobo, J. Stellmach, A. Knauer, H. Rodriguez, S. Einfeldt, and Z. Yang, "Advances in group III-nitride-based deep UV light-emitting diode technology," Semicond. Sci. Technol. **26**(1), 014036 (2011).
5. T. Takano, T. Mino, J. Sakai, N. Noguchi, K. Tsubaki, and H. Hirayama, "Deep-ultraviolet light-emitting diodes with external quantum efficiency higher than 20% at 275 nm achieved by improving light-extraction efficiency," Appl. Phys. Express **10**(3), 031002 (2017).
6. H. Hirayama, N. Maeda, S. Fujikawa, S. Toyoda, and N. Kamata, "Recent progress and future prospects of AlGaN-based high-efficiency deep-ultraviolet light-emitting diodes," Jpn. J. Appl. Phys. **53**(10), 100209 (2014).

7. L. Zhou, J. E. Epler, M. R. Krames, W. Goets, M. Gherasimova, Z. Ren, J. Han, M. Kneissl, and N. M. Johnson, "Vertical injection thin-film AlGaN/AlGaN multiple-quantum-well deep ultraviolet light-emitting diodes," Appl. Phys. Lett. **89**(24), 241113 (2006).

8. M. Khizar, Z. Y. Fan, K. H. Kim, J. Y. Lin, and H. X. Jiang, "Nitride deep-ultraviolet light-emitting diodes with microlens array," Appl. Phys. Lett. **86**(17), 173504 (2005).

9. Y. Guo, Y. Zhang, J. Yan, H. Xie, L. Liu, X. Chen, M. Hou, Z. Qin, J. Wang, and J. Li, "Light extraction enhancement of AlGaN-based ultraviolet light-emitting diodes by substrate sidewall roughening," Appl. Phys. Lett. **111**(1), 011102 (2017).

10. K. Ban, J.-i. Yamamoto, K. Takeda, K. Ide, M. Iwaya, T. Takeuchi, S. Kamiyama, I. Akasaki, and H. Amano, "Internal quantum efficiency of whole-composition-range AlGaN multi quantum wells," Appl. Phys. Express **4**(5), 052101 (2011).

11. Z. Bryan, I. Bryan, J. Xie, S. Mita, Z. Sitar, and R. Collazo, "High internal quantum efficiency in AlGaN multiple quantum wells grown on bulk AlN substrates," Appl. Phys. Lett. **106**(14), 142107 (2015).

12. P. Dong, J. Yan, J. Wang, Y. Zhang, C. Geng, T. Wei, P. Cong, Y. Zhang, J. Zeng, Y. Tian, L. Sung, Q. Yan, J. Li, S. Fan, and Z. Qin, "282-nm AlGaN-based deep ultraviolet light-emitting diodes with improved performance on nano-patterned sapphire substrates," Appl. Phys. Lett. **102**(24), 241113 (2013).

13. K. Takehara, K. Takeda, S. Ito, H. Aoshima, M. Iwaya, T. Takeuchi, S. Kamiyama, I. Akasaki, and H. Amano, "Indium–Tin Oxide/Al reflective electrodes for ultraviolet light-emitting diodes," Jpn. J. Appl. Phys. **51**(4R), 042101 (2012).

14. N. Maeda, J. Yum, M. Jo, and H. Hirayama, "Enhancing the light-extraction efficiency of AlGaN deep-ultraviolet light-emitting diodes using highly reflective Ni/Mg and Rh as p-type electrodes," Jpn. J. Appl. Phys. **57**(4S), 04FH08 (2018).

15. T. Fujii, Y. Gao, R. Sharma, E. L. Hu, S. P. DenBaars, and S. Nakamura, "Increase in the extraction efficiency of GaN-based light-emitting diodes via surface roughening," Appl. Phys. Lett. **84**(6), 855–857 (2004).

16. D. W. Kim, H. Y. Lee, M. C. Yoo, and G. Y. Yeom, "Highly efficient vertical laser-liftoff GaN-based light-emitting diodes formed by optimization of the cathode structure," Appl. Phys. Lett. **86**(5), 052108 (2005).

17. R. H. Horng, X. Zheng, C. Y. Hsieh, and D. S. Wuu, "Light extraction enhancement of InGaN light-emitting diode by roughening both undoped micropillar-structure GaN and p-GaN as well as employing an omnidirectional reflector," Appl. Phys. Lett. **93**(2), 021125 (2008).

18. M. Takeuchi, T. Maegawa, H. Shimizu, S. Ooishi, T. Ohtsuka, and Y. Aoyagi, "AlN/AlGaN short-period superlattice sacrificial layers in laser lift-off for vertical-type AlGaN-based deep ultraviolet light emitting diodes," Appl. Phys. Lett. **94**(6), 061117 (2009).

19. V. Adivarahan, A. Heidari, B. Zhang, Q. Fareed, M. Islam, S. Hwang, K. Balakirshnan, and A. Khan, "Vertical Injection Thin Film Deep Ultraviolet Light Emitting Diodes with AlGaN Multiple-Quantum Wells Active Region," Appl. Phys. Express **2**(9), 092102 (2009).

20. M. Lachab, F. Asif, B. Zhang, I. Ahmad, A. Heidari, Q. Fareed, V. Adivarahan, and A. Khan, "Enhancement of light extraction efficiency in sub-300 nm nitride thin-film flip-chip light-emitting diodes," Solid-State Electron. **89**, 156–160 (2013).

21. S. K. Saha, R. S. Howell, and M. K. Hatalis, "Reaction Mechanisms in Aluminum-Indium Tin Oxide Ohmic Contact Metallization with Co and Ni Barrier Layers for Active-Matrix-Display Applications," J. Electrochem. Soc. **146**(8), 3134–3138 (1999).

22. C. S. Chang, S. J. Chang, Y. K. Su, Y. C. Lin, Y. P. Hsu, S. C. Shei, S. C. Chen, C. H. Liu, and U. H. Liaw, "InGaN/GaN light emitting diodes with ITO p-contact layers prepared by RF sputting," Semicond. Sci. Technol. **18**(4), L21–L23 (2003).

23. T. Margalith, O. Buchinsky, D. A. Cohen, A. C. Abare, M. Hansen, S. P. DenBaars, and L. A. Coldren, "Indium tin oxide contacts to gallium nitride optoelectronic devices," Appl. Phys. Lett. **74**(26), 3930–3932 (1999).

24. E. Fred Schubert, *Light-Emitting Diodes II* (Cambridge University Press, 2006).

25. K. Kawasaki, C. Koike, Y. Aoyagi, and M. Takeuchi, "Vertical AlGaN deep ultraviolet light emitting diode emitting at 322 nm fabricated by the laser lift-off technique," Appl. Phys. Lett. **89**(26), 261114 (2006).

26. C. Lu, L. Wang, J. Lu, R. Li, L. Liu, D. Li, N. Liu, L. Li, W. Cao, W. Yang, W. Chen, W. Du, C. T. Lee, and X. Hu, "Investigation of the electroluminescence spectrum shift of InGaN/GaN multiple quantum well light-emitting diodes under direct and pulsed currents," J. Appl. Phys. **113**(1), 013102 (2013).

27. T. Nishida, T. Makimoto, H. Saito, and T. Ban, "AlGaN-based ultraviolet light-emitting diodes grown on bulk AlN substrates," Appl. Phys. Lett. **84**(6), 1002–1003 (2004).

28. D. Priante, R. T. Elafandy, A. Prabaswara, B. Janjua, C. Zhao, M. S. Alias, M. Tangi, Y. Alaskar, A. M. Albadri, A. Y. Alyamani, T. K. Ng, and B. S. Ooi, "Diode junction temperature in ultraviolet AlGaN quantum-disks-in-nanowires," J. Appl. Phys. **124**(1), 015702 (2018).