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Enhancing the Light-Extraction Efficiency of AlGaN-Based Deep-Ultraviolet Light-Emitting Diodes by Optimizing the Diameter and Tilt of the Aluminum Sidewall

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Abstract: To realize high-efficiency AlGaN-based deep-ultraviolet light-emitting diodes (DUV-LEDs), enhancing their light-extraction efficiency (LEE) is crucial. This paper proposes an aluminum-based sidewall reflector structure that could replace the conventional ceramic-based packaging method. We design optimization simulations and experimental results demonstrated the light power output could be enhanced 18.38% of DUV-LEDs packaged with the aluminum-based sidewall.

Keywords: light emitting diode; deep-ultraviolet light-emitting diode; reflector inclined plane; metal diameter of cavity bottom

1. Introduction

Deep-ultraviolet light-emitting diodes (DUV-LEDs) with aluminum gallium nitride (AlGaN) components are gaining substantial attention given their potential for use in such applications as secure communication, chemical decomposition, disinfection, water and air purification, and biological detection systems [1–4]. DUV-LEDs are more advantageous than are mercury UV lamps given their more favorable characteristics, such as long life, robustness, low energy consumption, high environmental friendliness, and being free of mercury [5,6]. However, compared with white LEDs, DUV-LEDs have a lower emission wavelength of 250–300 nm and have lower luminous efficiency and long-term reliability [7–15]. Currently, white LED devices are typically packaged by combining LED chips with a transparent organic resin [16–18]. But DUV-LEDs use the same way as white light LED resin packages. Such resins degrade over time, resulting in considerable UV absorption. The consequent high contact resistance and low light-extraction efficiency (LEE) degrades the long-term reliability, high forward voltage, and very low external quantum efficiency (EQE). To ameliorate these drawbacks, silicon-glass overcaps and hermetic packaging have been used extensively [19–29]. However, the reflectivity of ceramic package decreased rapidly in Deep-UV region [30–34]. In this study, the characteristics of the DUV-LEDs, namely the diameter of the bottom cavity and the tilt angle of the reflector and to simulation comparison to aluminum, gold, and silver metal materials with better reflectivity, were optimized to improve the LEE of proposed DUV-LED structure.

Light Extraction Efficiency

In principle, an LED's external quantum efficiency is calculated using the following equation [35]:

$$\begin{gathered} \mathrm{EQE} = \mathrm{IQE\ X\ LEE} \\ \mathrm{LEE} = \frac{\text{No. of photons emitted (per second) into free space}}{\text{No. of photons emitted (per second) from the active surface}} \\ \mathrm{EQE} = \frac{\text{No. of photons emitted (per second) into free space}}{\text{No. of electrons injected (per second) into the LED per second}} \end{gathered} \tag{1}$$

where EQE and IQE are the external and internal quantum efficiency, respectively, and LEE is the light extraction efficiency from the LED chip to air.

2. Optical Design of DUV-LED Reflector Inclined Plane

Figure 1 illustrates the structures of the cavities of (a) a conventional DUV-LED (b) and a DUV-LED with the metal tilt reflector proposed in this study; both structures are composed of the same type of reflector plate and ultraviolet-transmitting glass. The conventional cavity is protected by ceramic, whereas the proposed cavity design uses metal and tilt reflection for cavity protection. In the proposed design, the LEE of the DUV-LED chip can be increased by optimizing the distance between the chip and the metal sidewall as well as the tilt reflection angle.

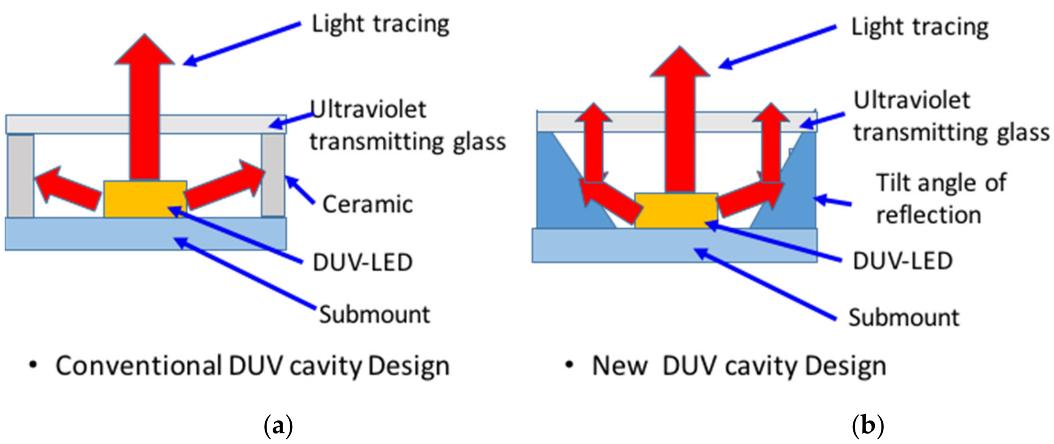

Figure 1. (**a**) Conventional deep-ultraviolet (DUV) cavity and (**b**) proposed metal tilt reflector design. LED: light-emitting diodes.

2.1. DUV-LED Specifications

In this study, we used DUV-LED chips (Lextar Electronics Corporation, Hsinchu, Taiwan) of approximately 0.45×0.75 mm^2, whose emission spectra were captured at a 100-mA forward current. These chips exhibited a peak wavelength of 285 nm, with a full width at half-maximum of 10 nm (Figure 2). All data was measured using an integrating sphere (Isuzu Optical, Hsinchu, Taiwan). Figure 3 presents the chips' relative far-field emission pattern (arb. unit) as measured by a LEDGON goniometer (Instrument Systems GmbH, Munich, Germany). Table 1 lists the specifications (i.e., surface and material characteristics) of all components in the DUV-LED reflector cavity; these data were used in ray-tracing simulations to optimize the proposed DUV-LED design. To simplify numerical values, the subsequent simulations and experiment did not include the ultraviolet transmitting glass.

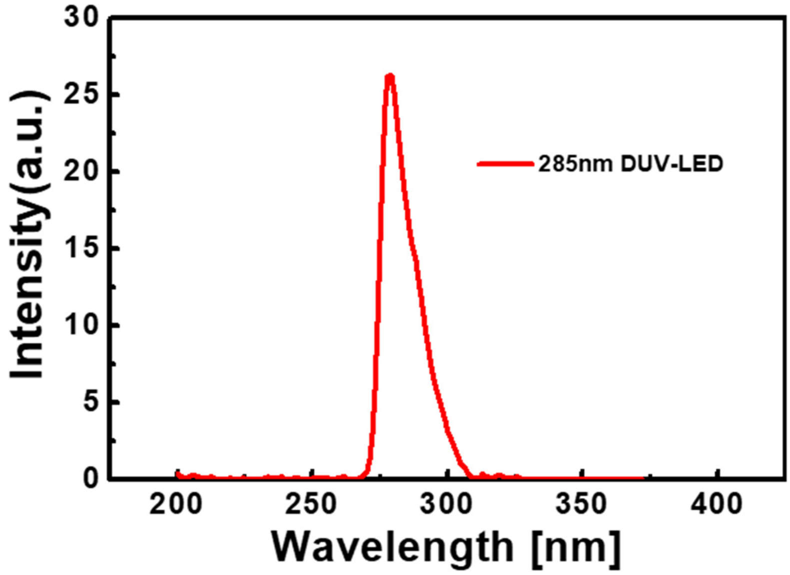

Figure 2. Normalized emission spectrum generated at 100 mA forward current of the proposed.

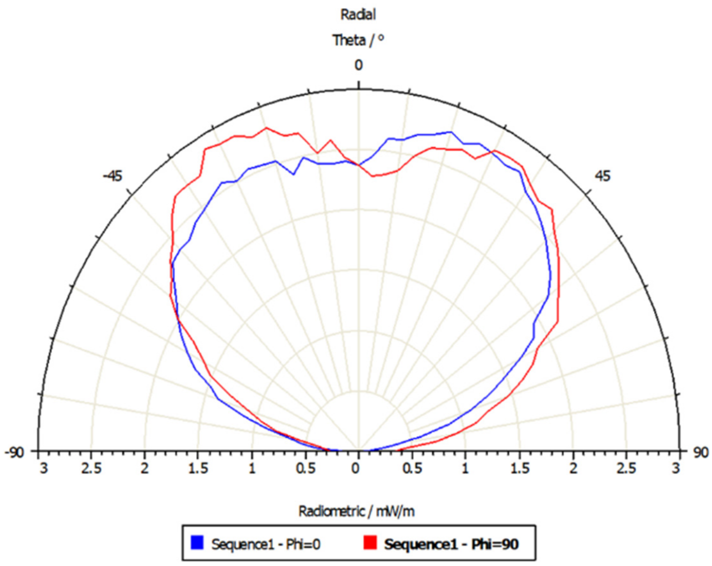

Figure 3. DUV-LEDs' relative far-field emission pattern (arb. unit).

Table 1. Surface and material characteristics of all components in the reflector cavity of the proposed deep-ultraviolet light-emitting diodes (DUV-LED).

Component	Characteristics	Material
DUV-LED	Peak wavelength = 285 nm	AlGaN
	Mirror R = 92%	Aluminum
Cavity sidewall [36]	Mirror R = 40%	Gold
	Mirror R = 25%	Silver
Packing structure	Polished	Ceramics

2.2. Ray-Tracing Simulation of DUV-LED Metal Diameter of Cavity Bottom

Ray-tracing simulation was performed using Light Tools™ (Synopsys Inc., Mountain View, CA, USA). Through simulation, we optimized the cavity design (Figure 4) of the proposed DUV-LED module by identifying the cavity diameter that yielded the optimal LEE.

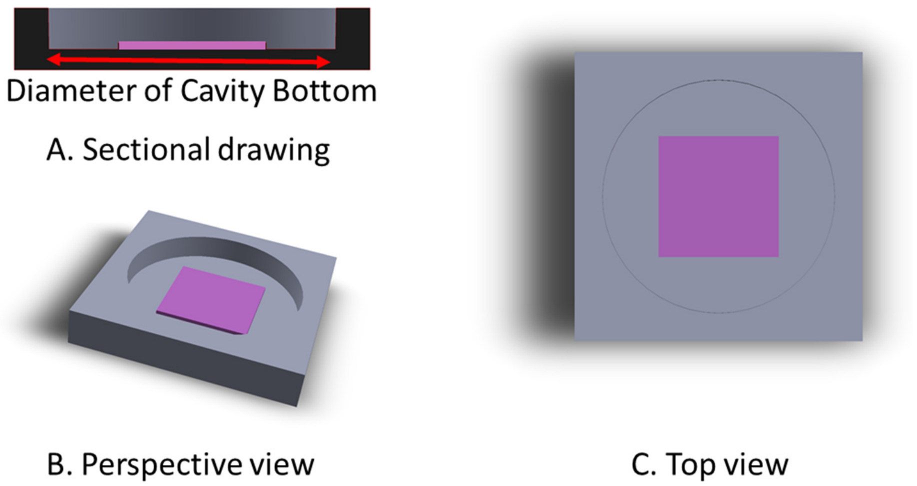

Figure 4. 3D model of a DUV-LED's cavity.

Figure 5 present the simulated LEEs of DUV-LEDs with Al, Au, or Ag metal cavity bottom reflectors of various diameters, whose reflectivity at a wavelength of 185 nm were 92%, 40%, and 25%, respectively. As evident, the cavity with the Al reflector exhibited the highest LEE at a given diameter, and with a gradual increase in the diameter of the cavity bottom, the LEE increased only slightly. These results indicate that Al reflectors outperform the other two types of reflectors.

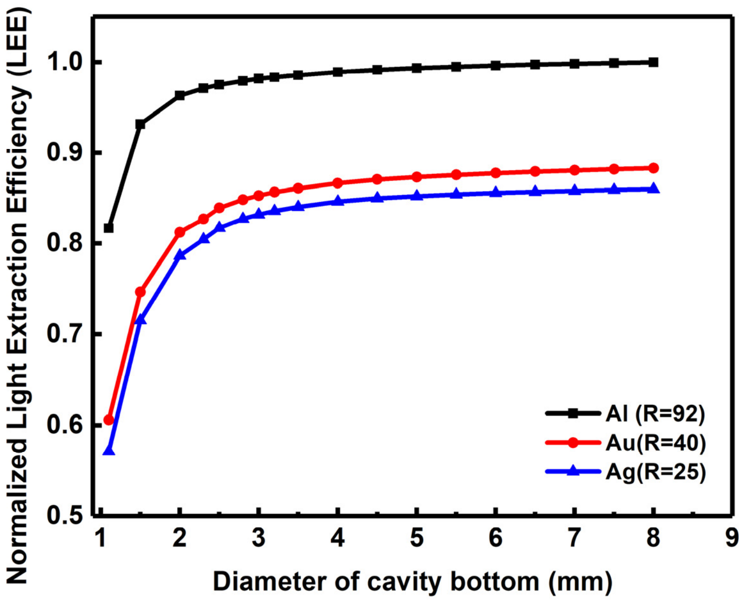

Figure 5. Simulated light-extraction efficiencies (LEEs) of DUV-LEDs with cavity-bottom diameters of 1.1–8 mm.

Figure 6 presents a comparison of the improvement in the LEE performance of the three investigated types of metal cavities. At a cavity diameter of 1.1 mm, Al (42.97%) and Au (6.06%) exhibited larger improvements than did Ag, which had the lowest reflectance; the same trends were found at diameters of 3 and 8 mm, with Al (18% and 16%, respectively) and Au (2.5% and 2.62%, respectively) exhibiting larger improvements than did Ag.

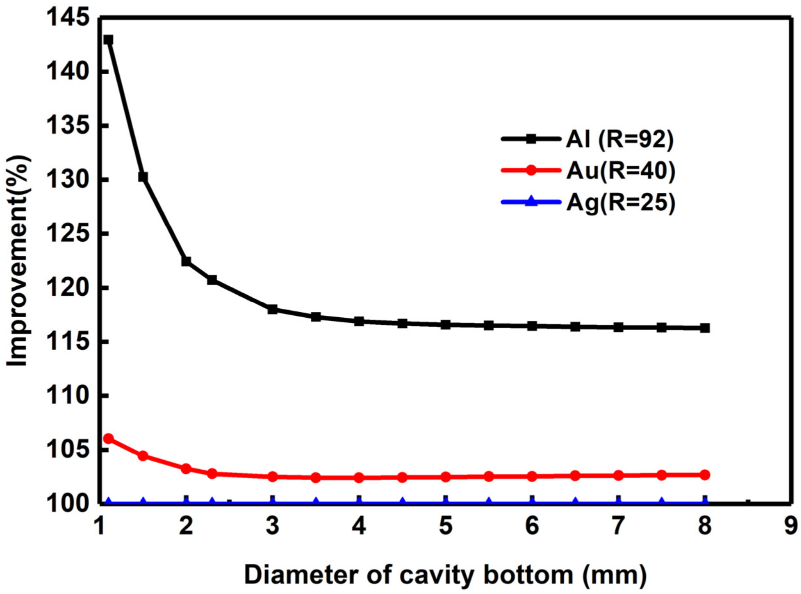

Figure 6. Simulated improvements in the LEE performance levels of DUV-LEDs with Al reflector cavities relative to those of DUV-LEDs with Ag and Au cavities.

2.3. Ray-Tracing Simulation of a DUV-LED's Tilt Angle of Reflection

To improve the LEE of the proposed design, the second optimized parameter was the tilt angle of the DUV-LED module (Figure 7). Figure 8 presents the simulated LEEs of Al-based DUV-LEDs with various tilt angles and cavity diameters; as shown, the shorter the cavity diameter, the wider is the tilt angle and higher is the LEE. Conversely, when the cavity diameter is long, the tilt angle's effect on the LEE does not change significantly. Because the DUV- LED's far-field emission is similar to that of the heart (Figure 3), the chip has a large lateral light. When the aluminum reflective cavity diameter is short or the tilt angle is narrow, the lateral light of the UVC LED is unlikely to be reflected. However, when the cavity diameter is more than 3 mm or the sidewall inclination is greater than 60°, the light output can be complete because of the relationship of the far-field emission light type. This is close to the light output efficiency of the DUV-LED chip without external optical loss. However, the cavity is designed for minimum size and maximum light output efficiency.

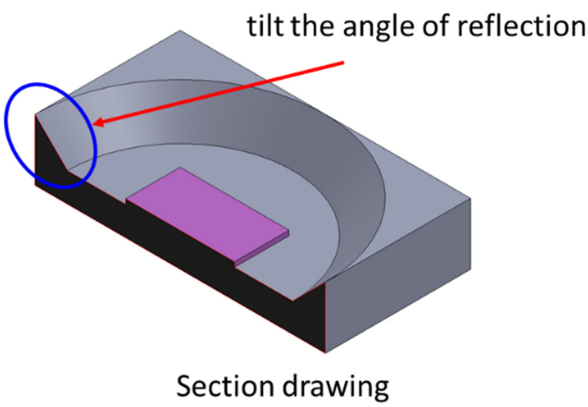

Figure 7. Three-dimensional illustration of the DUV-LED cavity showing the tilt angle of reflection.

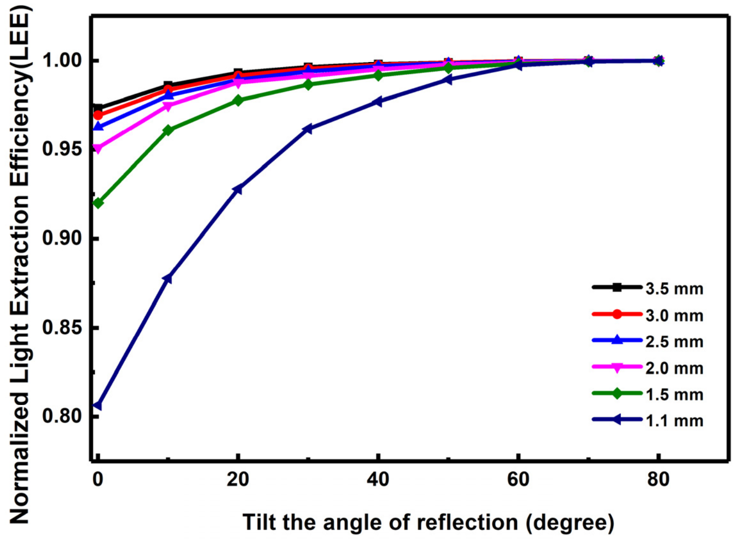

Figure 8. Simulated LEEs of DUV-LEDs with various tilt angles and cavity diameters.

3. Experiment

Fabrication

Figure 9 illustrates the packaging process of the proposed DUV-LED. In this process, (a) an aluminum plate with a sheet thickness of 1 mm and identical in size to the alumina ceramic substrate is submitted for high-precision machining, with an aperture diameter of 3 mm and inclination angle of 60 degrees. When the hole has been finished, (b) the aluminum plate is processed and the holes and sidewalls are polished (c) a ceramic substrate is prepared whose electrode material is alumina, (d) bond the peak wavelength to 285-nm DUV-LED Chip to the ceramic substrate by pressure bonding. Next, (e) the aluminum plate holes are bonded to the DUV-LED ceramic substrate and the wafer is placed on the center point of the aperture. Finally, (f) the finished DUV-LED ceramic substrate is cut, and (g) the ultraviolet LEDs are completed by optimizing the diameter and tilt of the aluminum sidewall.

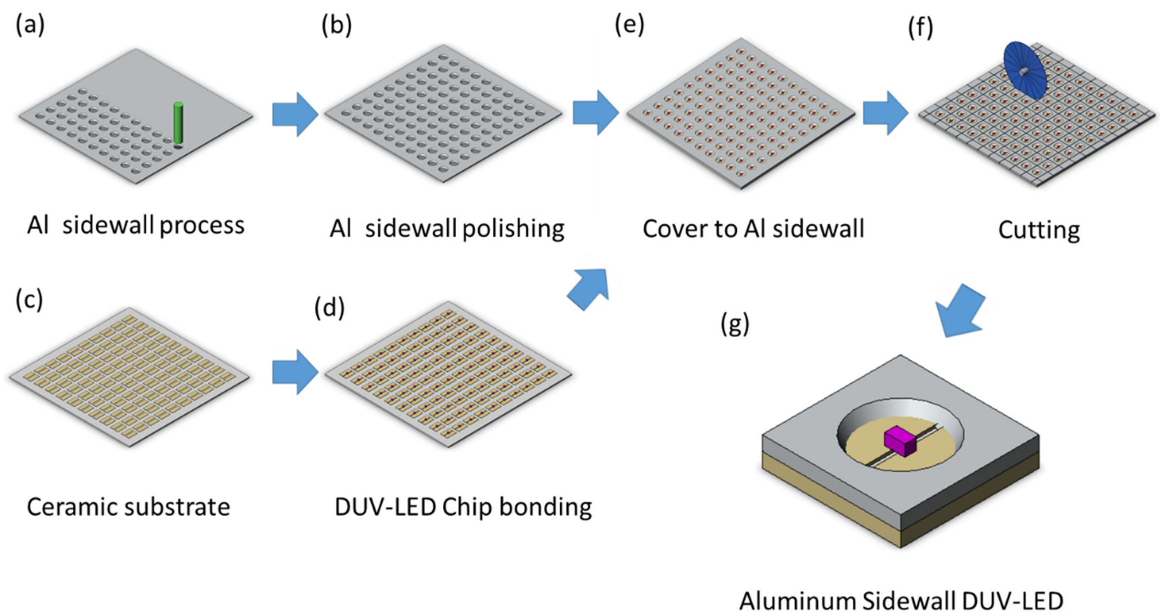

Figure 9. Procedure used to fabricate (**a**,**b**) aluminum sidewall and (**c**,**d**) bonding DUV-LED on the ceramic substrate; (**e**–**g**) the aluminum plate holes was covered to obtain the ultraviolet LEDs are completed by optimizing the diameter and tilt of the aluminum sidewall.

4. Results and Discussion

Figure 10 displays a top view of the packaged aluminum sidewall DUV-LED sample and the emission pattern of the 285-nm DUV-LED. Figure 11 presents a comparison of EQEs measured for DUV-LEDs packaged using both the conventional and proposed packaging methods at various forward currents, and Figure 12 shows the corresponding light output values measured at driving currents of 0–100 mA. As shown, in this driving current range, the proposed DUV-LED with the optimized aluminum cavity sidewall outperformed the conventionally packaged DUV-LED in terms of output power and lighting efficiency. For example, at 100 mA, the light output values of the conventional and optimized DUV-LEDs were 4.46 and 5.28 mW, respectively, representing an optimized increase of 18.38%. In addition, at 60 mA, the normalized EQE of the optimized DUV-LEDs was 14.38% higher than that of the conventional ones. The conventional package generated leakage in the low current region; no such problem was observed in the high current region. These improvements are attributable to two factors, namely the high reflectivity of the aluminum cavity and sidewall in the UV range and the use of an optimized cavity diameter and tilt angle for reflection.

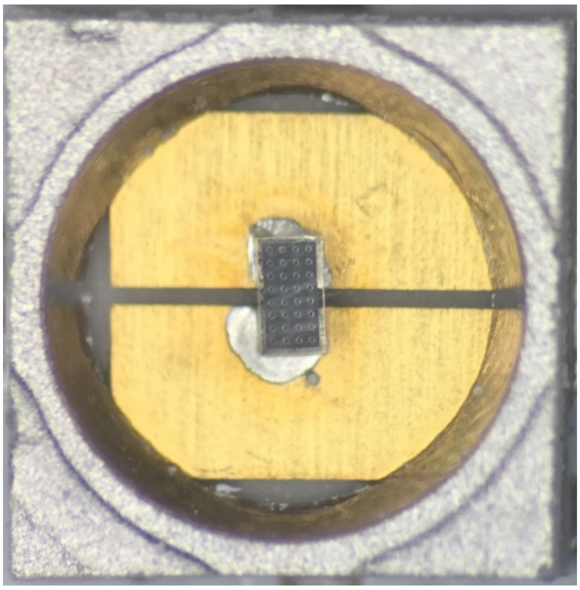

Figure 10. Top views of a packaged aluminum sidewall DUV-LED.

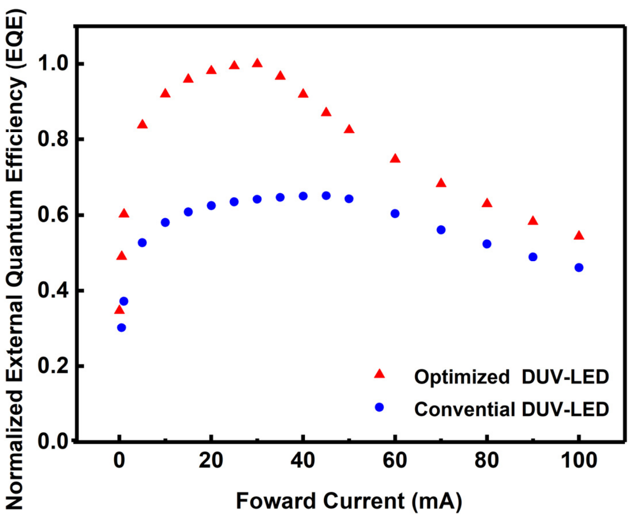

Figure 11. Measured external quantum efficiency (EQEs) of the DUV-LEDs packaged through the conventional and proposed packaging methods plotted against forward current.

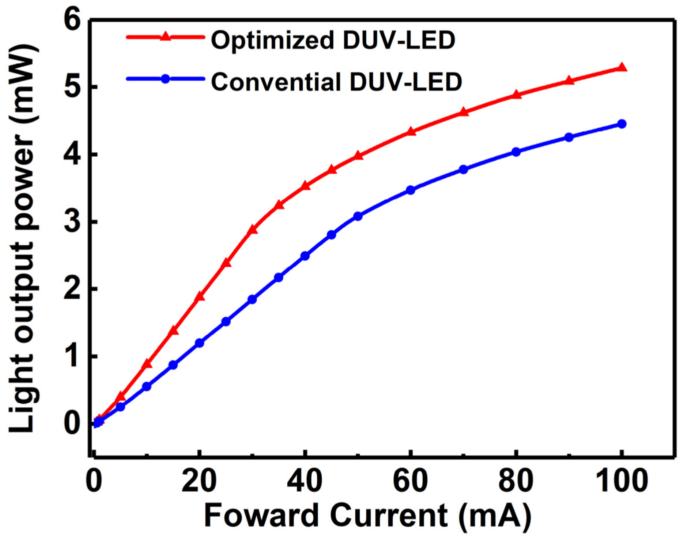

Figure 12. Measured light output values of the DUV-LEDs packaged through conventional and proposed packaging versus forward current methods plotted against forward current.

5. Conclusions

The aluminum cavity bottom diameter and sidewall tilt angle of a typical DUV-LED were optimized through ray-tracing simulations to determine the optimum parameters for improving light output power. The experiments demonstrated that the optimized 285-nm DUV-LED with a sidewall tilt angle of 60 degrees and packaging size of more than 3.0 mm had increased light output power by 18.38%. The proposed architecture is feasible as a compact solution to AlGaN-based DUV-LED packaging with high light-extraction efficiency.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Taniyasu, Y.; Kasu, M.; Makimoto, T. An aluminium nitride light-emitting diode with a wavelength of 210 nanometres. *Nature* **2006**, *441*, 325. [CrossRef] [PubMed]
2. Shur, M.S.; Gaska, R. Deep-ultraviolet light-emitting diodes. *IEEE Trans. Electron. Devices* **2010**, *57*, 12–25. [CrossRef]
3. Muramoto, Y.; Kimura, M.; Nouda, S. Development and future of ultraviolet light-emitting diodes: Uv-led will replace the uv lamp. *Semicond. Sci. Technol.* **2014**, *29*, 084004. [CrossRef]
4. Shatalov, M.; Sun, W.; Jain, R.; Lunev, A.; Hu, X.; Dobrinsky, A.; Bilenko, Y.; Yang, J.; Garrett, G.A.; Rodak, L.E. High power algan ultraviolet light emitters. *Semicond. Sci. Technol.* **2014**, *29*, 084007. [CrossRef]
5. Khizar, M.; Fan, Z.; Kim, K.; Lin, J.; Jiang, H. Nitride deep-ultraviolet light-emitting diodes with microlens array. *Appl. Phys. Lett.* **2005**, *86*, 173504. [CrossRef]
6. Hirayama, H.; Maeda, N.; Fujikawa, S.; Toyoda, S.; Kamata, N. Recent progress and future prospects of algan-based high-efficiency deep-ultraviolet light-emitting diodes. *Jpn. J. Appl. Phys.* **2014**, *53*, 100209. [CrossRef]
7. Fujioka, A.; Asada, K.; Yamada, H.; Ohtsuka, T.; Ogawa, T.; Kosugi, T.; Kishikawa, D.; Mukai, T. High-output-power 255/280/310 nm deep ultraviolet light-emitting diodes and their lifetime characteristics. *Semicond. Sci. Technol.* **2014**, *29*, 084005. [CrossRef]

8. Inoue, S.-I.; Naoki, T.; Kinoshita, T.; Obata, T.; Yanagi, H. Light extraction enhancement of 265 nm deep-ultraviolet light-emitting diodes with over 90 mw output power via an aln hybrid nanostructure. *Appl. Phys. Lett.* **2015**, *106*, 131104. [CrossRef]
9. Liu, B.; Nie, H.; Zhou, X.; Hu, S.; Luo, D.; Gao, D.; Zou, J.; Xu, M.; Wang, L.; Zhao, Z. Manipulation of charge and exciton distribution based on blue aggregation-induced emission fluorophors: A novel concept to achieve high-performance hybrid white organic light-emitting diodes. *Adv. Funct. Mater.* **2016**, *26*, 776–783. [CrossRef]
10. Liu, B.; Xu, M.; Wang, L.; Tao, H.; Su, Y.; Gao, D.; Lan, L.; Zou, J.; Peng, J. Very-high color rendering index hybrid white organic light-emitting diodes with double emitting nanolayers. *Nano-Micro Lett.* **2014**, *6*, 335–339. [CrossRef]
11. Luo, D.; Chen, Q.; Gao, Y.; Zhang, M.; Liu, B. Extremely simplified, high-performance, and doping-free white organic light-emitting diodes based on a single thermally activated delayed fluorescent emitter. *ACS Energy Lett.* **2018**, *3*, 1531–1538. [CrossRef]
12. Luo, X.; Hu, R.; Liu, S.; Wang, K. Heat and fluid flow in high-power led packaging and applications. *Prog. Energy Combust. Sci.* **2016**, *56*, 1–32. [CrossRef]
13. Shatalov, M.; Sun, W.; Lunev, A.; Hu, X.; Dobrinsky, A.; Bilenko, Y.; Yang, J.; Shur, M.; Gaska, R.; Moe, C. Algan deep-ultraviolet light-emitting diodes with external quantum efficiency above 10%. *Appl. Phys. Express* **2012**, *5*, 082101. [CrossRef]
14. Wu, J.; Zhang, Z.; Zheng, H.; Liu, S. Realization of conformal phosphor coating by ionic wind patterning for phosphor-converted white leds. *IEEE Photon. Technol. Lett.* **2017**, *29*, 299–301. [CrossRef]
15. Zheng, H.; Li, L.; Lei, X.; Yu, X.; Liu, S.; Luo, X. Optical performance enhancement for chip-on-board packaging leds by adding tio 2/silicone encapsulation layer. *IEEE Electron. Device Lett.* **2014**, *35*, 1046–1048. [CrossRef]
16. Huang, J.C.; Chu, Y.P.; Wei, M.; Deanin, R.D. Comparison of epoxy resins for applications in light-emitting diodes. *Adv. Polym. Technol. J. Polym. Process. Inst.* **2004**, *23*, 298–306. [CrossRef]
17. Krames, M.R.; Shchekin, O.B.; Mueller-Mach, R.; Mueller, G.O.; Zhou, L.; Harbers, G.; Craford, M.G. Status and future of high-power light-emitting diodes for solid-state lighting. *J. Disp. Technol.* **2007**, *3*, 160–175. [CrossRef]
18. Liu, S.; Luo, X. *Led Packaging for Lighting Applications: Design, Manufacturing, and Testing*; John Wiley & Sons: Hoboken, NJ, USA, 2011.
19. Qin, Z.; Feng, J.; Zhaohui, C.; Ling, X.; Simin, W.; Sheng, L. Effect of temperature and moisture on the luminescence properties of silicone filled with yag phosphor. *Semicond. Sci. Technol.* **2011**, *32*, 012002.
20. Lobo, N.; Rodriguez, H.; Knauer, A.; Hoppe, M.; Einfeldt, S.; Vogt, P.; Weyers, M.; Kneissl, M. Enhancement of light extraction in ultraviolet light-emitting diodes using nanopixel contact design with al reflector. *Appl. Phys. Lett.* **2010**, *96*, 081109. [CrossRef]
21. Chen, I.-C.; Chen, Y.-D.; Hsieh, C.-C.; Kuo, C.-H.; Chang, L.-C. Highly reflective ag/la bilayer ohmic contacts to p-type gan. *J. Electrochem. Soc.* **2011**, *158*, H285–H288. [CrossRef]
22. Kim, H.; Baik, K.H.; Cho, J.; Lee, J.W.; Yoon, S.; Kim, H.; Lee, S.-N.; Sone, C.; Park, Y.; Seong, T.-Y. High-reflectance and thermally stable agcu alloy p-type reflectors for gan-based light-emitting diodes. *IEEE Photonics Technol. Lett.* **2007**, *19*, 336–338. [CrossRef]
23. Lee, W.H.; Chae, D.J.; Kim, D.Y.; Kim, T.G. Improved electrical and optical properties of vertical gan leds using fluorine-doped ito/al ohmic reflectors. *IEEE J. Quantum Electron.* **2011**, *47*, 1277–1282. [CrossRef]
24. Takehara, K.; Takeda, K.; Ito, S.; Aoshima, H.; Iwaya, M.; Takeuchi, T.; Kamiyama, S.; Akasaki, I.; Amano, H. Indium–tin oxide/al reflective electrodes for ultraviolet light-emitting diodes. *Jpn. J. Appl. Phys.* **2012**, *51*, 042101. [CrossRef]
25. Song, J.-O.; Hong, W.-K.; Park, Y.; Kwak, J.; Seong, T.-Y. Low-resistance al-based reflectors for high-power gan-based flip-chip light-emitting diodes. *Appl. Phys. Lett.* **2005**, *86*, 133503. [CrossRef]
26. Song, J.-O.; Leem, D.-S.; Kwak, J.; Nam, O.; Park, Y.; Seong, T.-Y. Low-resistance and highly-reflective zn–ni solid solution/ag ohmic contacts for flip-chip light-emitting diodes. *Appl. Phys. Lett.* **2003**, *83*, 4990–4992. [CrossRef]
27. Jang, H.W.; Lee, J.-L. Mechanism for ohmic contact formation of ni/ag contacts on p-type gan. *Appl. Phys. Lett.* **2004**, *85*, 5920–5922. [CrossRef]

28. Song, J.O.; Ha, J.-S.; Seong, T.-Y. Ohmic-contact technology for gan-based light-emitting diodes: Role of p-type contact. *IEEE Trans. Electron. Devices* **2010**, *57*, 42–59. [CrossRef]
29. Narendran, N.; Gu, Y.; Freyssinier, J.; Yu, H.; Deng, L. Solid-state lighting: Failure analysis of white leds. *J. Cryst. Growth* **2004**, *268*, 449–456. [CrossRef]
30. Luther, B.; DeLucca, J.; Mohney, S.; Karlicek, R., Jr. Analysis of a thin aln interfacial layer in ti/al and pd/al ohmic contacts to n-type gan. *Appl. Phys. Lett.* **1997**, *71*, 3859–3861. [CrossRef]
31. Chiu, C.; Li, Z.-Y.; Chao, C.; Lo, M.; Kuo, H.; Yu, P.; Lu, T.-C.; Wang, S.; Lau, K.M.; Cheng, S. Efficiency enhancement of uv/blue light emitting diodes via nanoscaled epitaxial lateral overgrowth of gan on a SiO_2 nanorod-array patterned sapphire substrate. *J. Cryst. Growth* **2008**, *310*, 5170–5174. [CrossRef]
32. Inazu, T.; Fukahori, S.; Pernot, C.; Kim, M.H.; Fujita, T.; Nagasawa, Y.; Hirano, A.; Ippommatsu, M.; Iwaya, M.; Takeuchi, T. Improvement of light extraction efficiency for algan-based deep ultraviolet light-emitting diodes. *Jpn. J. Appl. Phys.* **2011**, *50*, 122101. [CrossRef]
33. Peng, Y.; Wang, S.; Cheng, H.; Wang, H.; Chen, M.; Liu, S. Light efficiency enhancement of deep ultraviolet light-emitting diodes packaged by nanostructured silica glass. *J. Disp. Technol.* **2016**, *12*, 1106–1111. [CrossRef]
34. Peng, Y.; Guo, X.; Liang, R.; Cheng, H.; Chen, M. Enhanced light extraction from duv-leds by aln-doped fluoropolymer encapsulation. *IEEE Photonics Technol. Lett.* **2017**, *29*, 1151–1154. [CrossRef]
35. Ichikawa, M.; Fujioka, A.; Kosugi, T.; Endo, S.; Sagawa, H.; Tamaki, H.; Mukai, T.; Uomoto, M.; Shimatsu, T. High-output-power deep ultraviolet light-emitting diode assembly using direct bonding. *Appl. Phys. Express* **2016**, *9*, 072101. [CrossRef]
36. Song, D.-Y.; Sprague, R.; Macleod, H.A.; Jacobson, M.R. Progress in the development of a durable silver-based high-reflectance coating for astronomical telescopes. *Appl. Opt.* **1985**, *24*, 1164–1170. [CrossRef] [PubMed]