Arrays of Truncated Cone AlGaN Deep-Ultraviolet Light-Emitting Diodes Facilitating Efficient Outcoupling of in-Plane Emission

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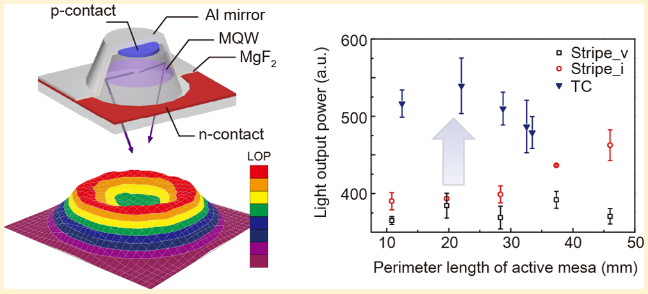
Supporting Information

ABSTRACT: Despite a rapidly growing demand for efficient man-made deep-ultraviolet (DUV) light sources, widespread adoption of AlGaN-based DUV light-emitting diodes (LEDs) is currently obstructed by extremely poor extraction of DUV photons due to the intrinsic material properties of the AlGaN active region. Here, we present 280 nm AlGaN DUV LEDs having arrays of truncated cone (TC)-shaped active mesas coated with MgF_2/Al reflectors on the inclined sidewalls of the cone to effectively extract the intrinsically strong transverse-magnetic-polarized emission. Ray tracing simulations reveal that the TC DUV LEDs show an isotropic emission pattern and much enhanced light-output power in comparison with stripe-type DUV LEDs with the same MgF_2/Al reflectors. Consistent with the ray tracing simulation results, the TC DUV LEDs show an isotropic emission pattern with much higher light-output power as well as lower operating voltage than the stripe-type DUV LEDs. On the basis of our results, strategies for designing high-performance DUV LEDs to further enhance the optical and electrical performances simultaneously are suggested.



KEYWORDS: *deep-ultraviolet, aluminum gallium nitride, light-emitting diode, transverse-magnetic polarization, light extraction efficiency, efficiency droop*

Electromagnetic radiation in the wavelength range of 200−280 nm is referred to as ultraviolet-C (UV-C) or simply deep-ultraviolet (DUV) radiation. Specifically, DUV light sources emitting in the range 250−280 nm are of great interest due to their ability to effectively damage or destroy the DNA or RNA of microbes including bacteria, viruses, and cancer cells, thus giving rise to many potential applications such as purification of air and water and sterilization in food processing.[1−3] For over 100 years, the mercury-vapor lamp has been widely used as a DUV light source, but it has many serious problems such as the toxicity of mercury, bulky size, high power consumption, large heat generation, short lifetime, and broad emission wavelength band. Since AlGaN-based light-emitting diodes (LEDs) have none of the above drawbacks, they have become increasingly attractive as a potentially ideal DUV light source.[4] However, widespread adoption of AlGaN DUV LEDs is currently obstructed by a low external quantum efficiency (EQE) (typically less than 10% for 280 nm) caused by both poor internal quantum efficiency (IQE) and light extraction efficiency (LEE).[5−7]

The LEE of AlGaN DUV LEDs is particularly poor mainly due to two reasons: First, a large amount of DUV light is absorbed in the p-type GaN contact layer. Second, DUV photons generated from high Al content AlGaN grown on a *c*-plane sapphire substrate are highly transverse-magnetic (TM) polarized with a preferred in-plane emission pattern; thus, they are likely to be trapped and absorbed inside the device. In contrast, InGaN-based visible LEDs generate mainly isotropic transverse-electric (TE)-polarized light.[8−10] Conventional LEE-enhancing techniques such as integration of micro/nanolens arrays on either a sapphire substrate or GaN,[11,12] substrate patterning,[13] and introducing highly reflective mirrors on top of the p-(Al)GaN are effective for InGaN visible LEDs,[14] but turned out to be very ineffective for extracting TM-polarized anisotropic emission from AlGaN DUV LEDs,[7] thereby calling for a new, alternative approach. Lee et al. reported that sapphire-thickness-dependent LEE of AlGaN DUV LEDs is quite different from that of InGaN visible LEDs, and the LEE of DUV LEDs with flip-chip configuration can be improved by the roughened sidewall of the sapphire substrate by extracting the TM-polarized light more easily through the lateral directions.[15]

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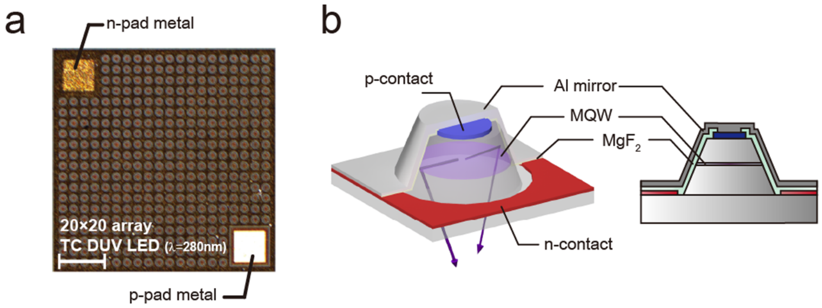

Figure 1. Images for TC LEDs. (a) Optical microscope image for TC LED having a 20 × 20 array of TCs (scale bar: 250 μm). (b) 3D and cross-sectional schematic illustrations for one TC structure. A MgF_2 passivation layer is deposited on the whole area except p-contact regions, while an Al overlayer is deposited on the whole area in order to reflect and redirect sidewall-heading DUV photons. The Al mirror electrically connects to the p-contact metal of each TC.

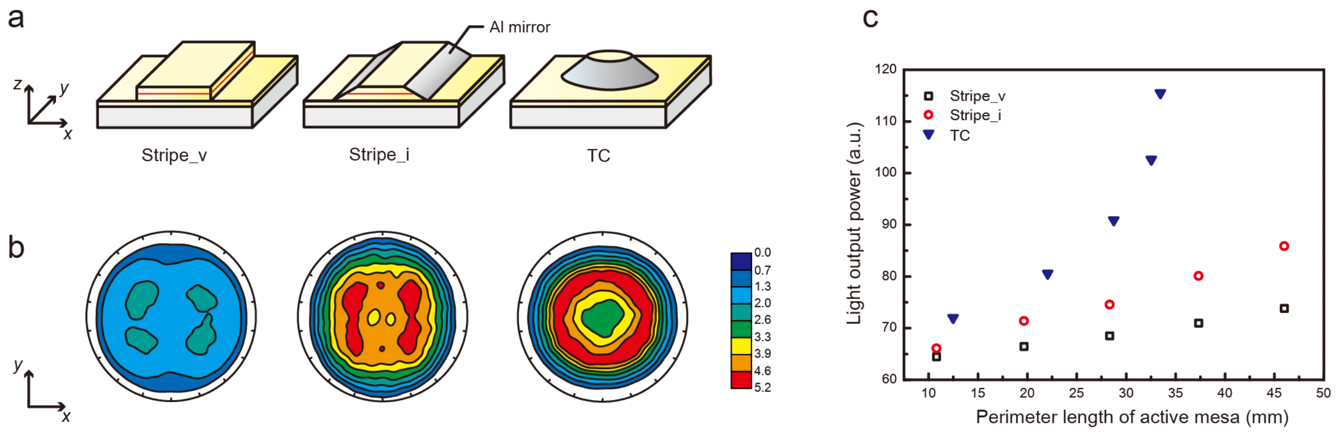

Figure 2. Ray tracing simulation results. (a) Schematic illustrations of unit stripes for Stripe_v and Stripe_i LEDs and a unit TC LED. (b) 2D contour map of light emission from LEDs calculated from the hemisphere-shaped detector located beneath the sapphire substrate. (c) LOP of the three types of DUV LEDs as a function of the perimeter length of the active mesa.

Recently, sidewall-emission-enhanced DUV LEDs with active mesa stripes having reflectors on their inclined sidewalls were demonstrated to effectively extract TM-polarized DUV photons down through the sapphire substrate, thus showing a significant enhancement in EQE.[16] However, the anisotropic geometry of the stripe-shaped active-mesa structures causes anisotropy in light extraction; that is, light extraction is effective for DUV photons propagating along the stripes' width direction, whereas it is ineffective along the stripes' length direction. Therefore, the elimination of geometric anisotropy of the active mesa is strongly required in order to extract DUV light effectively and in an isotropic manner, that is, independent of the horizontal or azimuthal emission angle.

In this paper, we demonstrate 280 nm AlGaN DUV LEDs having arrays of truncated cone (TC)-shaped active mesas coated with a MgF_2/Al reflector on the inclined sidewalls of the cone to effectively extract the strong TM-polarized photons regardless of their in-plane (azimuthal) emission direction. TC LEDs show a remarkable enhancement in light emission, by 37.1%, and better electrical properties in comparison with stripe-type LEDs with a comparable perimeter length of the active mesa. On the basis of the experimental results, we suggest strategies to realize an optimum DUV LED with enhanced optical as well as electrical performance.

The DUV LED epitaxial structures for the peak wavelength of 280 nm were grown on 4-inch *c*-plane sapphire substrates by metal–organic vapor phase epitaxy. A low-temperature AlN buffer layer and AlGaN/AlN superlattice layer were grown on the sapphire substrate, followed by the growth a 2-μm-thick Si-doped ([Si] = 1×10^{18} cm^{-3}) n-type $Al_{0.53}Ga_{0.47}N$, five periods of multiple quantum wells (MQWs) composed of 1.5-nm-thick $Al_{0.43}Ga_{0.57}N$ quantum wells, and 10-nm-thick $Al_{0.50}Ga_{0.50}N$ quantum barriers. The MQWs are followed by a 15-nm-thick Mg-doped ([Mg] = 2×10^{18} cm^{-3}) $Al_{0.75}Ga_{0.25}N$ electron-blocking layer, a 2-nm-thick Mg-doped ([Mg] = 2×10^{18} cm^{-3}) p-$Al_{0.53}Ga_{0.47}N$ layer, a 15-nm-thick p-AlGaN cladding layer having Al composition grading from 53% to 0%, a 160-nm-thick Mg-doped ([Mg] = 2×10^{20} cm^{-3}) p-GaN layer, and a 20-nm-thick highly Mg-doped ([Mg] > 4×10^{20} cm^{-3}) p^+-GaN contact layer. DUV LEDs with TC active mesas with various array sizes ranging from 5 × 5 to 25 × 25 were fabricated using a 1 × 1 mm^2 chip size. The inclined sidewalls of the TC active mesas were formed by thermal reflow of photoresist[17] followed by inductively coupled plasma etching using a Cl_2/BCl_3-based chemistry. Figure 1a shows an optical microscope image of a DUV LED having a 20 × 20 array of TC mesas, taken before depositing the MgF_2/Al reflective layer. Three-dimensional and cross-sectional schematic illustrations of one TC active mesa are shown in Figure 1b. The 350-nm-thick MgF_2 layer on the inclined sidewalls, which is highly transparent in the DUV wavelength region,[18] functions as a passivation layer for the active mesa as well as an omnidirectional reflector having a thick Al overlayer[19] that strongly reflects sidewall-heading photons down through the substrate. Note that the Al overlayer electrically connects to every p-contact metal of each TC since the top of the TC is not covered by MgF_2.Various stripe-type

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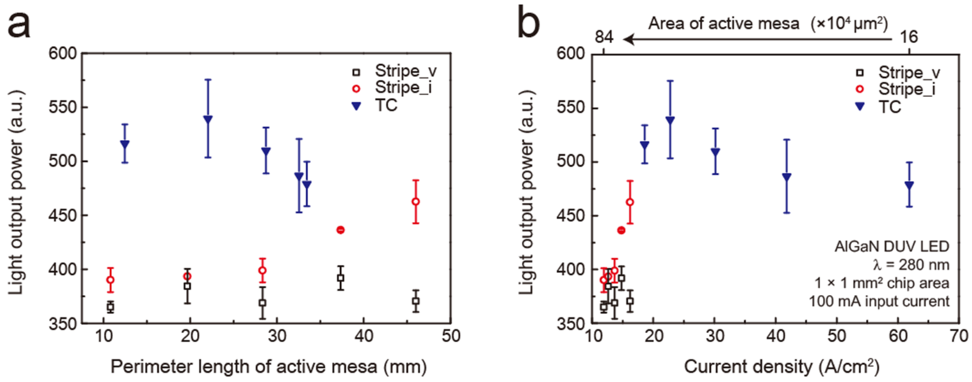

Figure 3. Optical property results. (a) LOP as a function of perimeter length of the active mesa. Within the whole range of perimeter lengths, the TC LED shows a much greater LOP than the stripe-type LEDs. (b) LOP as a function of current density at forward current of 100 mA. TC LEDs with high current density show a decrease in LOP owing to the efficiency droop.

LEDs[16] named Stripe_v and Stripe_i were also fabricated for comparison. Stripe_v denotes a stripe-type LED with vertical sidewalls, whereas Stripe_i denotes a stripe-type LED with inclined sidewalls having a MgF$_2$/Al mirror layer. Stripe-type LEDs have a chip area of 1 × 1 mm^2 and a variable number of stripes, ranging from 5 to 25. Note that the mesa perimeter length of TC- or stripe-shaped active mesa is proportional to the exposed sidewall area and increases with the number of TCs or stripes used in a particular LED having a fixed chip area. Additional information on fabrication processes, images of fabricated devices, design rules, and geometrical parameters of the fabricated devices are provided in Figure S1 and Table S1.

Ray tracing simulations were performed for Stripe_v, Stripe_i, and TC LEDs with various numbers of stripes and TCs in order to investigate the differences in optical properties with respect to the geometrical shape and the perimeter length. For the simulations, we assumed that the same number of point light sources having both TE and TM emission patterns with the intensity ratio of polarization of ∼1 is distributed uniformly within the MQW active layer. Note that the intensity ratio of polarization is the experimentally measured value, consistent with reported values.[8,10] See Figure S2 for the details of the ray tracing simulation. Schematic illustrations of a unit stripe for Stripe_v and Stripe_i and a unit TC are shown in Figure 2a. Figure 2b shows the contour maps of extracted DUV light rays hitting the hemisphere-shaped detector located beneath the sapphire substrate for the Stripe_v and Stripe_i LEDs with 25 stripes and the TC LED with a 25 × 25 cone array whose chip areas are 1 × 1 mm^2 for all LEDs. The overall light-output power (LOP) for Stripe_i is much greater than that of Stripe_v as a result of enhanced light extraction by the Al/MgF$_2$ omnidirectional mirror. Note that both stripe-type LEDs show anisotropic light emission patterns because of the inherent geometric anisotropy of stripes. Meanwhile, the LOP for the TC LED shows an isotropic (concentric) distribution because the TC structure enables photons to have equal probability of reflection by the Al/MgF$_2$ omnidirectional mirror down through the substrate. Figure 2c shows the simulated LOP from the three types of DUV LEDs as a function of the perimeter length. The LOP of Stripe_i LEDs increases with increasing the perimeter length with higher slope than Stripe_v LEDs, which is consistent with the previous results.[16] On the other hand, the LOPs of the TC LEDs are higher than those of the stripe-type LEDs with similar perimeter lengths, and the difference in LOP becomes remarkably larger with increasing the perimeter length, which can be attributed to the following reasons: First, the elimination of geometric anisotropy of the stripes results in an effective extraction of sidewall-heading photons, especially the strong TM-polarized photons, regardless of their in-plane emitting direction. Second, the average propagation distance of sidewall-heading photons to be reflected and extracted becomes shorter as the perimeter length increases (i.e., as the size of TC decreases), leading to a much reduced absorption loss caused by the p-type GaN contact layer as well as by the active layer. Additional information including schematic figures and the polar angle dependent LOP in the *xz* plane are provided in Figure S2.

Figure 3a shows the LOP of the three types of DUV LEDs as a function of the perimeter length, measured at 100 mA forward current under the pulse width of 5 ms and 1% duty cycle to exclude a thermal effect. In comparison with the Stripe_v, the Stripe_i LEDs show enhanced LOP as the perimeter length increases, which is consistent with the ray tracing simulation result. Notably, the LOPs of the TC LEDs are much higher than those of the stripe-type LEDs at similar perimeter length ranges. For the perimeter length of about 20 mm, the TC LED shows a larger LOP, by 37.1%, and 40.3%, than Stripe_i and Stripe_v LEDs, respectively. However, the trend of the TC LEDs' LOP with increasing the perimeter length is quite different from the monotonic increase obtained by the ray tracing simulation. The LOP starts to decrease near the perimeter length of ∼20 mm. This decrease in LOP originates from the difference in active mesa area for the same perimeter length between the stripe-type and the TC LEDs, as summarized in Table S1, which causes a remarkable difference in the current density at the same 100 mA forward current. Figure 3b shows the measured LOP from the three types of DUV LEDs as a function of current density at 100 mA forward current. Note that the operating current density for the TC LEDs at 100 mA forward current is much higher than that for stripe-type LEDs due to the smaller area of their active mesa. Typical AlGaInN-based LEDs have a peak in efficiency at a certain current density, above which the efficiency gradually decreases, a phenomenon called efficiency droop. The physical origin responsible for efficiency droop is still an active topic of debate, and there are several proposed mechanisms including the asymmetry in carrier transport caused by intrinsic material properties, Auger recombination, and defect-related ones.[20] AlGaN DUV LEDs show efficiency droop, although the amount is typically less than GaInN-based visible LEDs. In

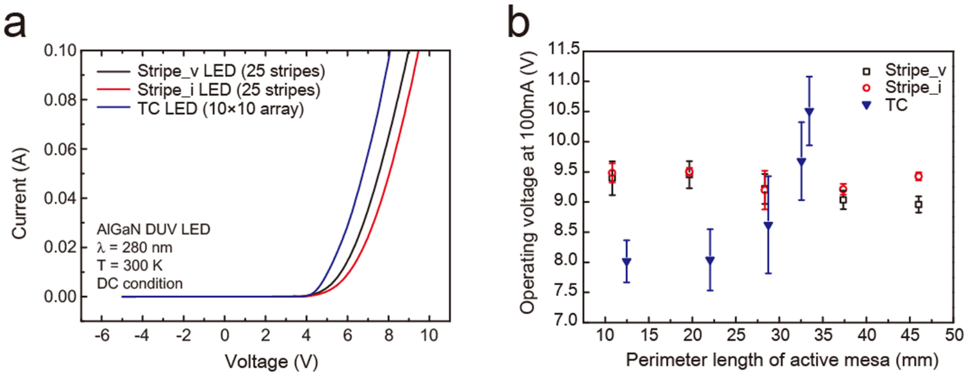

Figure 4. Electrical property results. (a) Current−voltage characteristics for stripe-type LEDs and TC LEDs. TC LEDs show lower forward operating voltage than stripe-type LEDs. (b) Operating voltage at 100 mA as a function of the perimeter length of the active mesa. TC LEDs show smaller operating voltages in the small perimeter length regime, and the voltage increases as the perimeter length increases.

the high current density region, the efficiency droop becomes the dominant factor determining the LOP. Due to the relatively smaller area of the active mesa of the TC LEDs than the striped-mesa LEDs, at the same 100 mA forward current, the current densities for the TC LEDs are already in the droop regime, so that the TC LEDs show a decrease in LOP with increasing current density (see Figure S3 and Figure S4). Nevertheless, the TC LEDs show a much greater LOP than the striped-mesa-type LEDs at comparable perimeter length range, indicating that the TC structures are more effective in light extraction than the stripe ones, and the light extraction can be further improved by optimizing LED designs.

Figure 4a shows representative current−voltage (*I*−*V*) characteristics for the striped-mesa-type LEDs having 25 stripes and the TC LED having a 10 × 10 array that shows the largest LOP among the LED designs used in this study. Each LED shows typical diode *I*−*V* characteristics with a turn-on voltage of ∼4.4 V. At 100 mA forward current, the TC shows a lower operating voltage than the stripe-type LEDs. The operating voltage at 100 mA forward current as a function of the perimeter length is plotted in Figure 4b. The operating voltage of the stripe-type LEDs does not show remarkable change with the perimeter length, while that of TC LEDs shows lower values at low perimeter lengths, then a rapid increase with increasing perimeter length. The operating voltage of an LED is affected sensitively by a series resistance that can be caused by contact resistance on both p-type and n-type semiconductors, as well as by the resistance of neutral regions. As summarized in Table S1, the area of the metal contact on n-type AlGaN for TC LEDs is much greater than stripe-type LEDs, which causes lower contact resistance on the resistive n-type AlGaN, thus a lower operating voltage. However, as the perimeter length increases, the area of the metal contact on p-type GaN decreases steeply especially for TC LEDs, and hence, the contact resistance on p-type GaN becomes a dominant factor increasing the operating voltage. Nevertheless, we note that the 10 × 10 array TC LEDs, which exhibit the largest LOP, show a lower operating voltage by ∼1.5 V than stripe-type LEDs, indicating that properly designed TC LEDs show remarkable enhancement in both optical and electrical properties.

On the basis of the ray tracing simulation and experimental results, we suggest strategies for designing high-performance DUV LEDs. First, a device architecture utilizing the strong TM-polarized in-plane emission by using active mesas with a large exposed sidewall area and inclined sidewall geometry having a DUV-reflecting reflector is recommended. Second, TC-shaped active mesa geometry is preferred over the stripe geometry to eliminate the directional anisotropy of light extraction, thus to enhance the LEE in an isotropic manner, i.e., independent of the horizontal or azimuthal emission angle. Third, in order to further enhance the optical and electrical performances simultaneously, an optimum combination of design parameters including perimeter length, area of active mesa, and area of p- and n-contact region should be carefully considered. Although greater perimeter length is preferred for effective extraction of DUV photons, it causes reduced volume of the active mesa and the area of the p-contact and, hence, efficiency droop as well as increased operating voltage at some point. One of the ways to alleviate the trade-off between the perimeter length and the volume of the active mesa is to design TC arrays in a high-density hexagonal close-packed configuration rather than cubic ones, without sacrificing the electrical properties caused by the reduced area of the metal contact on n-type AlGaN. Lastly, one should carefully consider the current crowding problem caused by the resistive n-type AlGaN layer for realizing an optimum DUV LED design.

In conclusion, we presented 280 nm AlGaN DUV LEDs with TC active mesa arrays having MgF_2/Al reflectors on the inclined sidewalls of the cone in order to effectively extract the strong TM-polarized emission in an isotropic manner. On the basis of ray tracing simulation results, the TC LEDs show isotropic emission and higher LOP than stripe-type LEDs. Consistent with the ray tracing simulation results, the TC LEDs show greater LOP by 37.1% than the stripe-type LEDs. In addition, the operating voltages of TC LEDs with low perimeter lengths are lower than that of the stripe-type LEDs, indicating that both optical and electrical properties can be improved simultaneously by optimization of the LED design. On the basis of our simulation and experimental results, we suggest strategies for designing high-performance DUV LEDs to further enhance the optical and electrical performances simultaneously.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsphotonics.6b00572.

Fabrication processes, design parameters, additional ray tracing results, and investigations on the light extraction efficiency (PDF)

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Notes

The authors declare no competing financial interest.

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REFERENCES

(1) Schubert, E. F.; Kim, J. K. Solid-State Light Sources Getting Smart. *Science* **2005**, *308*, 1274−1278.

(2) Khan, A.; Balakrishnan, K.; Katona, T. Ultraviolet Light-Emitting Diodes Based on Group Three Nitrides. *Nat. Photonics* **2008**, *2*, 77−84.

(3) Schubert, E. F.; Cho, J. Electron-Beam Excitation. *Nat. Photonics* **2010**, *4*, 735−736.

(4) Würtele, M. A.; Kolbe, T.; Lipsz, M.; Külberg, A.; Weyers, M.; Kneissl, M.; Jekel, M. Application of GaN-Based Ultraviolet-C Light Emitting Diodes -UV LEDs- for Water Disinfection. *Water Res.* **2011**, *45*, 1481−1489.

(5) 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.

(6) Kneissl, M.; Kolbe, T.; Chua, C.; Kueller, V.; Lobo, N.; Stellmach, J.; Knauer, A.; Rodriguez, H.; Einfeldt, S.; Yang, Z.; Johnson, N. M.; Weyers, M. Advances in Group III-Nitride-Based Deep UV Light-Emitting Diode Technology. *Semicond. Sci. Technol.* **2011**, *26*, 014036.

(7) Shatalov, M.; Lunev, A.; Hu, X.; Bilenko, O.; Gaska, I.; Sun, W.; Yang, J.; Dobrinsky, A.; Bilenko, Y.; Gaska, R.; Shur, M. Performance and Applications of Deep UV LED. *Int. J. High Speed Electron. Syst.* **2012**, *21*, 1250011.

(8) Nam, K. B.; Li, J.; Nakarmi, M. L.; Lin, J. Y.; Jiang, H. X. Unique Optical Properties of AlGaN Alloys and Related Ultraviolet Emitters. *Appl. Phys. Lett.* **2004**, *84*, 5264.

(9) Taniyasu, Y.; Kasu, M. Improved Emission Efficiency of 210-nm Deep-Ultraviolet Aluminum Nitride Light-Emitting Diode. *NTT Technol. Rev.* **2010**, *8*, 1−5.

(10) Kolbe, T.; Knauer, A.; Chua, C.; Yang, Z.; Einfeldt, S. Optical Polarization Characteristics of Ultraviolet (In) (Al)GaN Multiple Quantum Well Light Emitting Diodes. *Appl. Phys. Lett.* **2010**, *97*, 171105.

(11) Khizar, M.; Fan, Z. Y.; Kim, K. H.; Lin, J. Y.; Jiang, H. X. Nitride Deep-Ultraviolet Light-Emitting Diodes with Microlens Array. *Appl. Phys. Lett.* **2005**, *86*, 173504.

(12) Kim, B. J.; Jung, H.; Shin, J.; Mastro, M. A.; Eddy, C. R., Jr; Hite, J. K.; Kim, S. H.; Bang, J.; Kim, J. Enhancement of Light Extraction Efficiency of Ultraviolet Light Emitting Diodes by Patterning of SiO2 Nanosphere Arrays. *Thin Solid Films* **2009**, *517*, 2742−2744.

(13) Dong, P.; Yan, J.; Wang, J.; Zhang, Y.; Geng, C.; Wei, T.; Cong, P.; Zhang, Y.; Zeng, J.; Tian, Y.; Sun, L.; Yan, Q.; Li, J.; Fan, S.; Qin, Z. 282-nm AlGaN-Based Deep Ultraviolet Light-Emitting Diodes with Improved Performance on Nano-Patterned Sapphire Substrates. *Appl. Phys. Lett.* **2013**, *102*, 241113.

(14) 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.

(15) Lee, K. H.; Park, H. J.; Kim, S. H.; Asadirad, M.; Moon, Y.; Kwak, J. S.; Ryou, J. Light-Extraction Efficiency Control in AlGaN-Based Deep-Ultraviolet Flip-Chip Light-Emitting Diodes: A Comparison to InGaN-Based Visible Flip-Chip Light-Emitting Diodes. *Opt. Express* **2015**, *23*, 20340−20349.

(16) Lee, J. W.; Kim, D. Y.; Park, J. H.; Schubert, E. F.; Kim, J.; Lee, J.; Kim, Y.; Park, Y.; Kim, J. K. An Elegant Route to Overcome Fundamentally-Limited Light Extraction in AlGaN Deep-Ultraviolet Light-Emitting Diodes: Preferential Outcoupling of Strong In-Plane Emission. *Sci. Rep.* **2016**, *6*, 22537.

(17) Popovic, Z. D.; Sprague, R. A.; Connell, G. A. N. Technique for Monolithic Fabrication of Microlens Arrays. *Appl. Opt.* **1988**, *27*, 1281−1284.

(18) Maier-Komor, P.; Friese, J.; Gernhäuser, R.; Homolka, J.; Krücken, R.; Winkler, S. Investigation of Deposition Parameters for VUV Reflective Coatings on the HADES RICH Mirrors. *Nucl. Instrum. Methods Phys. Res., Sect. A* **2004**, *521*, 35−42.

(19) Kim, H.; Lee, S.; Park, Y.; Kim, K.; Kwak, J. S.; Seong, T. Light Extraction Enhancement of GaN-Based Light Emitting Diodes Using MgF_2/Al Omnidirectional Reflectors. *J. Appl. Phys.* **2008**, *104*, 053111.

(20) Cho, J.; Schubert, E. F.; Kim, J. K. Efficiency Droop in Light-Emitting Diodes: Challenges and Countermeasures. *Laser Photonics Rev.* **2013**, *7*, 408−421.

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