High-efficiency and high-reliability deep-UV light-emitting diodes using transparent Ni-implanted AlN ohmic electrodes

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ABSTRACT Significant efforts have been devoted to improve the external quantum efficiency (EQE) of AlGaN-based top-emitting deep-UV light-emitting diodes (DUV LEDs). However, issues such as ohmic contact and challenges related to p-AlGaN doping and growth have hampered advancement. In this paper, a record-high EQE of 3.2% is reported for AlGaN-based lateral-type top-emitting DUV LEDs in which Ni-doped AlN (Ni:AlN) DUV-transparent ohmic electrodes are used. The ohmic electrode exhibits a transmittance of more than 90% at 280 nm and a reasonably good ohmic behavior with the p-Al₀.₆₆Ga₀.₃₄N contact layers. The Ni:AlN-based DUV LED demonstrates outstanding performance (i.e., operating voltage of 8.3 V at 20 mA, light output power of 11.6 mW at 100 mA) relative to the conventional thin ITO- and Ni/Au-based DUV LEDs. Furthermore, the proposed device is highly reliable, as evidenced by the fact that it maintained more than 80% of its light output power after 500 h of operation, and the operating voltage increased by only 2.7% over the operating time of 1 × 10⁵ s.

INDEX TERMS Deep ultraviolet, Light emitting diodes, Electrical doping process, Transparent conductive electrode.

I. INTRODUCTION

AlGaN-based deep ultraviolet light-emitting diodes (DUV LEDs) have attracted considerable attention for use in the fields of deodorization, purification, disinfection, and sterilization [1]–[3]. Recently, the COVID-19 pandemic has accelerated the growth of DUV-related industries and markets, which in turn, has provided a boost to the research on DUV LEDs. However, the external quantum efficiency (EQE) and wall-plug efficiency of DUV LEDs are significantly lower than those of visible or near-UV LEDs [4], [5], mainly because most of the DUV light generated in the AlₓGa₁₋ₓN (x > 0.6)-based active layer is absorbed in the conventional p-GaN or p-AlₓGa₁₋ₓN (x < 0.4) contact layers [6], [7]. Typically, the Al content of the p-type AlGaN contact layer is lower than that of the AlGaN/AlGaN-based active layer by design to facilitate hole injection from the p-type electrode to the active region [8]. The development of a DUV-transparent electrode is another critical and challenging step toward the realization of high-EQE top-emitting (or lateral-type) DUV LEDs. Indium tin oxide (ITO) exhibits high transmittance and conductivity in the visible and near-UV (~365 nm) regions [9]. However, in the DUV region, the transmittance of ITO decreases abruptly, and the difference between its work function and that of the p-AlGaN contact layer increases, which significantly reduces the quantum efficiency of ITO-based DUV LEDs. Although such problems can be mitigated using flip-chip structures [6], [10], top-emitting DUV LED structures continue to be studied actively because of their advantages, such as low cost and simple fabrication process [11]. In this regard, various electrode structures, such as Ni/Mg [8], mesh p-GaN/ITO [12], Mo/Al [13], and Cu nanowires [14] have been used to solve the issues related to ohmic contact with the p-(Al)GaN layer while minimizing DUV light absorption through the electrode. In addition, device structures have been redesigned using AlN/h-BN heterostructures [1], GaN/AlN quantum-disk nanorods [15], Graded AlGaN alloy structures [16], wavy quantum well [17], UVB micro-LED [18], and micropixel DUV LED [19] to further improve the quantum efficiencies of DUV LEDs. Despite these efforts, the EQE...
values of AlGaN-based top-emitting DUV LEDs (even with tunnel heterojunctions) reported thus far do not exceed 2.8% [20]–[24]. In addition to these low EQE values, device reliability during practical usage of AlGaN-based DUV LEDs must be considered. More specifically, the lifetime of DUV LEDs must be extended by identifying the factors contributing to device degradation at high operating voltages or temperatures [25]. These factors involve defect generation due to heating or current crowding, which must be compensated for when the p-type electrode is designed.

In this study, a Ni-doped AlN (Ni:AlN) thin-film electrode is applied as a DUV-transparent ohmic electrode in AlGaN-based lateral-type DUV LEDs. To provide adequate conductivity and control the work function of the p-type electrode, a 15-nm-thick AlN film is doped with Ni atoms by following the electrical doping process (EDP) under alternating current pulse biases [26]. The doping profiles of the Ni atoms on the AlN surface are investigated to determine the ohmic behavior between the Ni:AlN and p-AlGaN:AlGa0.3N contact layer by means of X-ray photoelectron spectroscopy (XPS) analysis. Based on these studies, AlGaN-based top-emitting DUV LEDs with Ni:AlN electrodes are fabricated, and these devices are used to demonstrate record-high EQE values (over 3%), along with low operating voltage, high light output power, and reliable operation.

II. EXPERIMENT

The epitaxial layers of AlGaN-based DUV LEDs were grown through metal-organic chemical vapor deposition (MOCVD) on sapphire substrates, and the basic characteristics of the epitaxial layers were checked by following the quick check method. Figure 1(a) shows the structure of the DUV LED, which comprises a 4-μm undoped AlN layer, a 1.5-μm n-type AlGaN buffer layer (Si > 5 × 10^{18} \text{cm}^{-3}), three multi-quantum wells consisting of approximately 2-nm-thick AlGaN wells and 10-nm-thick AlGaN barriers, a 5-nm-thick undoped AlGaN capping barrier, two blocks of Mg-doped AlGaN/AlGaN multi-quantum barriers (block: 20 nm, valley: 5 nm), and importantly, a 70-nm-thick p-type AlGa0.6Ga0.3N contact layer (Mg > 1 × 10^{18} \text{cm}^{-3}) [27]. Herein, the use of the conventional p-type GaN contact layer was excluded owing to its strong DUV light absorption [27]. The device size (or single chip) was 390 μm × 390 μm. For device fabrication, first, a mesa structure was formed for the n-AlGaN contact by means of inductively coupled plasma reactive ion etching. After the mesa process, a 15-μm-thick AlN layer was deposited by means of sputtering, and thermal annealing was performed at 450 °C for 30 s to recrystallize the AlN layer using rapid thermal annealing in a nitrogen atmosphere. Then, to facilitate the use of an Ni:AlN thin film as the ohmic electrode on the p-AlGaN contact layer, EDP was performed on a circular Ni pad (with a thickness of 20 nm and radius of 50 μm) under voltage biases. The fabrication details are presented in Fig. S1. To minimize damage to the thin AlN film and the AlGaN multilayer, a pulse bias with an amplitude of 8 V and pulse width of 500 ns was applied using a pulse generator instead of a direct current bias. Finally, Ni/Au metal pads with thicknesses of 50 nm and 150 nm were deposited sequentially on the n and p regions. In Fig. 1(b), the contents of Al and Ga atoms in the p-AlGaN layer, determined by performing energy-dispersive X-ray spectroscopy (EDX) analysis, are 64% and 36%, respectively. Figure 1(c) shows a schematic diagram of the quick-check method, in which a part of the p-region is mechanically etched on the wafer to ensure contact with the n-region, and an Ni/Au p-electrode is deposited on the top to verify device performance. Notably, the quick-check method is often used to pre-evaluate the uniformity of light emission and peak wavelength before full optimization of the LEDs. Figures 1(d) and (e) show the electroluminescence (EL) and photoluminescence (PL) spectra measured at the top/middle/bottom of a 2-inch wafer by using the quick check method. Despite the difficulties encountered in the uniform growth of high-quality AlGaN-based DUV epi-layers (with high Al contents), all of the EL peaks were observed at wavelengths close to 280 nm, as designed, for the entire wafer. However, even on the same
wafer, the wavelengths of the EL peaks were blue-shifted relative to those of the PL peaks owing to the band-filling effect [28].

III. RESULTS AND DISCUSSION

Figure 2(a) shows the calculated transmittance of the 10-nm-thick ITO and 15-nm-thick AlN films before and after Ni doping by using the finite-difference time-domain (FDTD) method (FDTD Solutions, Lumerical Inc.). The calculation was performed considering the refractive index and absorption coefficient of each material. The refractive indices and absorption coefficients of AlN, Ni, and ITO, determined by ellipsometry measurements (F20-UV, Filmetrics Inc.), were 2.32, 1.43, 1.76, and 0.0013, 2.96, 0.1258, respectively, at 280 nm. The transmittance spectra were calculated by placing a plane wave source below the glass substrate and a detection monitor on the top of the perfectly matched layer box (Fig. S2).

Specifically, the transmittance of the Ni:AlN layer was calculated considering the Ni-based conductive channels with an inverted fractal tree shape formed in the AlN layer after EDP and simulation parameters such as refractive index. The transmittance of the 10-nm-thick ITO film was 57%, whereas the transmittances of the 15-nm-thick AlN electrodes, before and after Ni doping were 94.7% and 93.1%, respectively, at 280 nm. Figure 2(b) shows the measured transmittance curves for the same electrodes fabricated by means of radio-frequency (RF) sputtering. The measured transmittance of the 15-nm-thick AlN layer was ~98% and ~95% before and after Ni doping, respectively, at 280 nm, whereas that of the 10-nm-thick ITO was ~50%, which makes it unsuitable for use as an electrode in DUV LEDs. Next, the ohmic behaviors of the ITO and Ni:AlN electrodes were evaluated using their respective current-voltage (I–V) curves, as shown in Figs. 2(c) and (d), respectively. As a result, the ITO electrodes were found to exhibit non-ohmic behavior, as shown in Fig. 2(c), whereas the Ni:AlN electrodes exhibited ohmic-like behavior, as shown in Fig. 2(d). Assuming a linear graph of the I–V curve, the contact resistance between the p-AlGaN/Ni:AlN layer before and after EDP, and the Ni:AlN electrode, calculated considering the spacing of 100 μm × 100 μm electrodes and following the transmission line method (TLM), was approximately 5.5 × 10² Ωcm². (Fig. S3a). For reference, the TLM patterns of the Ni:AlN electrode were prepared by depositing Ni dopants on the AlN layer, forming conducting channels by means of EDP, and removing Ni. (Fig. S3b) To determine why this device structure exhibited improved ohmic behavior, we analyzed the p-AlGaN/Ni:AlN layer before and after EDP by using XPS depth profiles, as shown in Fig. 3. For this analysis, the device was etched at a rate of 29 Å/min. The O1s peak exists owing to the atmospheric oxidation of each layer rather than oxidation during the fabrication process. A comparison of Figs. 3(a) and (b) reveals that some of the Ni atoms diffused into the AlN film after Ni doping by means of EDP. Accordingly, the atomic composition of Ni increased on the p-AlGaN and in the AlN layer while that of Ga atoms increased in the direction of the AlN layer after EDP, as compared to the compositions of Ni and Ga atoms before EDP. This

![Figure 2](image-url)  
**FIGURE 2.** (a) Simulated and (b) measured transmittance spectra of AlN electrode (15 nm) before and after Ni doping and reference ITO (10 nm). I–V curves of (c) ITO and (d) Ni:AlN for different TLM pattern spacings (10, 15, 20, and 25 μm).

![Figure 3](image-url)  
**FIGURE 3.** Measured XPS depth profiles of the p-AlGaN/Ni:AlN layers (a) before and (b) after EDP.
phenomenon confirmed that the Ni atoms diffused from the Ni pads to the p-Al_{0.6}Ga_{0.4}N surface through the AlN film while Ga atoms in the p-Al_{0.6}Ga_{0.4}N surface diffused outward into the p-Al_{0.6}Ga_{0.4}N and AlN interface, where they substituted the Ni atoms. Through this process, we expect that an ultra-thin Ni:N layer with a work function energy higher than that of ITO can be formed at the p-Al_{0.6}Ga_{0.4}N/AlN interfacial layer, which would facilitate efficient hole injection into the p-AlGaN contact layer [26]. For reference, the relative Al composition in the AlN layer appeared to be lower than that in the Al_{0.6}Ga_{0.4}N layer, which might be associated with oxygen-related impurities (always detected in the AlN layer before and after EDP) and the sputtering conditions used to deposit the AlN layer [29]. For example, an Ar and N\textsubscript{2} gas mixture with a ratio 20 and 12.5 was used in this study. Based on these studies, we fabricated AlGaN-based DUV LEDs with Ni:AlN electrodes and AlGaN-based DUV LEDs with thin ITO and Ni/Au-pad-only reference electrodes. Figure 4(a) shows top view images of optical microscope and schematics of the electrodes used in this study. For the Ni/Au-based DUV LED, tripod-shaped Ni/Au was deposited directly on the p-Al_{0.6}Ga_{0.4}N layer without any transparent conducting electrode, while the other two devices had thin ITO and Ni:AlN transparent conducting electrodes between the p-Al_{0.6}Ga_{0.4}N and tripod-shaped Ni/Au pad. The setup used for various measurements of the fabricated top-emitting DUV LEDs is illustrated in Fig. 4(b). Each DUV LED was measured after packaging on the Al metal chip mounter. The device efficiency was measured by applying a voltage bias through the n/p metal pad contact and detecting the light emitted toward the p-AlGaN layer. Figure 4(c) shows a comparison of the light output power-current-voltage (L–I–V) curves of the AlGaN-based DUV LEDs with 10-nm-thick ITO, 15-nm-thick Ni:AlN, and Ni/Au (50 nm/150 nm) electrodes deposited on the p-AlGaN contact layers. The comparison reveals that the ITO-based DUV LED had an operating voltage of 13.5 V at 20 mA, whereas the Ni:AlN-based DUV LED had an operating voltage of 8.3 V at 20 mA. In other words, the operating voltage of the Ni:AlN-based DUV LED decreased by 38.5% compared to that of the ITO-based DUV LED, indicating that more current flowed in the Ni:AlN-based DUV LED at the same voltage. This improvement was attributed to the reduced contact resistance at the interface of p-Al_{0.6}Ga_{0.4}N and Ni:AlN and enhanced hole injection efficiency through work function alignment between the p-Al_{0.6}Ga_{0.4}N and Ni:AlN electrode by means of EDP. In addition, the light output power of the Ni:AlN DUV LED was 11.6 mW at 100 mA, which is 611% higher than the 1.9 mW light output power of the ITO-based DUV LED. By contrast, the Ni/Au-based DUV LED (fabricated without any transparent conducting layer) was operational only when the current was 20 mA or lower due to limited current spreading; its operating voltage was -9.9 V, and the light output was 1.5 mW at 20 mA. In the same fashion, the EL intensity of the Ni:AlN-based DUV LED was 502% higher than that of the ITO-based DUV LED at 100 mA, as shown in Fig. 4(d), mainly due to the significantly higher transmittance of Ni:AlN than that of ITO at 280 nm. In particular, ITO-based DUV LED shows a slight red shift, which may be associated with strong absorption of light in ITO via surface-enhanced Raman scattering in the UV region [30]. The EL intensity of the Ni/Au-based device at 20 mA was slightly lower than that of the ITO-based device at 100 mA, which is consistent with the L–I curve result presented in Fig. 4(c). Furthermore, from the EQE versus injection current curve presented in Fig. 4(e), the EQE increased by up to 3.2% at 20 mA in case of the Ni:AlN-based DUV LEDs, whereas the EQE values of the Ni/Au- and ITO-based devices were 0.1% at 10 mA and 0.6% at 20 mA, respectively. Again, Ni/Au-based device without transparent conducting layer operated up to 20 mA due to the limited current spreading; accordingly, its EQE was also evaluated up to 20 mA. Compared to the ITO-based device (50%), the Ni:AlN-based DUV LED exhibited a considerably lower efficiency droop (18.8%) at 100 mA, which might be ascribed to the improved current injection through and spreading effect of the Ni:AlN electrode. Moreover, it was lower than the efficiency droop of the DUV LED reported in the literature [20]. The wall plug efficiency (WPE) of the Ni:AlN-based DUV LED considering the operating voltage, as calculated using Eq. (1), was approximately 1.7%, which was 8.5
42.5 times higher than that of the ITO-based device (0.2%) and Ni/Au-based device (0.04%).

\[
WPE = \eta_{\text{EQE}} \frac{h\nu}{eV} = \eta_{\text{EQE}} \frac{1240}{\lambda V} \quad (1)
\]

where \(\eta_{\text{EQE}}\) is the EQE, \(h\) is Planck’s constant, \(\nu\) is photon frequency, \(e\) is elementary electric charge, \(V\) is voltage, and \(\lambda\) is photon wavelength.

These enhancements are the result of ultra-high DUV transparency and improved ohmic behavior with p-Al\(_{0.65}\)Ga\(_{0.35}\)N owing to usage of the Ni:AlN films as p-type electrodes in the DUV LEDs. To ensure the reliability of the obtained data, the EQE values of 30 samples were estimated, and the average EQE was calculated to be 3.02%, as shown in Fig. 4(f).

Finally, the reliability of the Ni:AlN-based DUV LEDs was investigated by observing the change in light output power and operating voltage over time, as illustrated in Fig. 5. Figure 5(a) shows a graph of the decrease in light output power with operation time at room temperature. This result was obtained by continuously applying a voltage bias for 500 h and measuring the light output power at a fixed time while light was emitted. In this condition, the Ni/Au and ITO devices operated in an excessively unstable manner, which made it difficult to record lifetime data. However, the Ni:AlN-based DUV LED was able to maintain 80% of the initial light output power for 500 h at 100 mA, which is longer than the previously reported lifetime [31]–[33]. Furthermore, the proposed Ni:AlN-based DUV LED exhibited a longer lifetime than the flip-chip-mounted DUV LED [32], [33]. In general, when the light output power (\(P\)) of a device decreases to 50% of the initial power, the device lifetime (\(t\)) is calculated using an exponential function of time [32], as expressed in Eq. (2).

\[
P = P_0 e^{(-\beta t)} \quad (2)
\]

where \(P_0\) is the initial power, and \(\beta\) is the slope of decrease in light output power, and it is calculated using the degradation coefficient (\(k_0\)), an exponential function of temperature (T), the Boltzmann constant (K), and activation energy (E\(_a\)), as indicated in Eq. (3):

\[
\beta = \beta_0 e^{\frac{E_a}{kT}} \quad (3)
\]

From the Arrhenius plot created using the slope of decreasing power output, the \(\beta\) value was calculated to be -0.000329; thus, the lifetime of the Ni:AlN-based DUV LEDs, or the time it takes for the light output to decrease to 50%, was estimated to be approximately 2107 h. In addition, the operating voltage increased by 2.7% after 10\(^5\) s of device operation at room temperature and by approximately 10.6% at 85°C, as indicated in Fig. 5(b).

**IV. CONCLUSION**

In this study, we demonstrated record-high EQE values (up to 3.2%) for AlGaN-based top-emitting DUV LEDs by directly forming ohmic contacts with p-Al\(_{0.65}\)Ga\(_{0.35}\)N with the use of 15-nm-thick Ni:AlN DUV-transparent electrodes, along with highly reliable device operation. To this end, we grew high-quality DUV LED epi-layers (with a target wavelength of 280 nm) on 2-inch sapphire substrate wafers by means of MO-CVD and fully characterized their performances by using the quick check method before device fabrication. Then, the electrical and optical properties of the Ni:AlN electrodes on the p-Al\(_{0.65}\)Ga\(_{0.35}\)N contact layers were evaluated by performing TLM and XPS analyses, as well as FDTD simulation and transmittance measurements. In addition to the record-high EQE, the proposed device operated with a high level of reliability; more than 80% of the initial light output power was maintained for 500 h, and the lifetime at 50% light output power was calculated to be approximately 2107 h by using the Arrhenius plot. In addition, the Ni:AlN-based DUV LED exhibited stable operation with an operating voltage of 8.3 V at 20 mA and light output power of 11.6 mW at 100 mA; the corresponding values for the thin ITO-based DUV LED were 13.5 V at 20 mA and 1.9 mW at 100 mA. The Ni/Au-based DUV LED was able to operate only at currents of up to 20 mA owing to limited current spreading, and the operating
voltage and light output power at 20 mA were ~9.9 V and 1.5 mW, respectively. These results indicate that the proposed EDP-based Ni:AlN electrodes open up a new avenue for the implementation of DUV LEDs based on highly efficient AlGaN or other related materials.

REFERENCES

[1] D. A. Laleyan, S. Zhao, S. Y. Woo, H. N. Tran, H. B. Le, T. Szkopek, H. Guo, G. A. Botton, and Z. Mi, “C AlN/b-BN heterostructures for Mg dopant-free deep ultraviolet photonics,” Nano Lett., vol. 17, no. 6, pp. 3738–3743, Jun. 2017.

[2] M. Kneissl, T.-Y. Seong, J. Han, and A. Amano, “The emergence and prospects of deep-ultraviolet light-emitting-diode technologies,” Nat. Photonics, vol. 13, no. 4, pp. 233–244, Apr. 2019.

[3] Y. Nagasawa and A. Hirano, “A review of AlGaN-based deep-ultraviolet light-emitting diodes on sapphire,” Appl. Sci., vol. 8, no. 8, Apr. 2019, Art. no. 1264.

[4] Z. Ren, Y. Lu, H.-H. Yao, H. Sun, C.-H. Liao, J. Dai, C. Chen, J.-H. Ryou, J. Yan, J. Wang, J. Li, and X. Li, “III-nitride deep UV LED without electron blocking layer,” IEEE Photonics J., vol. 11, no. 2, Apr. 2017, Art. no. 8200511.

[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, vol. 10, no. 3, Mar. 2017, Art. no. 031002.

[6] Y. Zheng, Y. Zhang, J. Zhang, C. Sun, C. Chu, K. Tian, Z.-H. Zhang, and W. Bi, “Effects of meshed p-type contact structure on the light extraction effect for deep ultraviolet flip-chip light-emitting diodes,” Nanoscale Res. Lett., vol. 14, May 2019, Art. no. 149.

[7] M. Guttmann, A. Susilo, L. Sulmoni, N. Susilo, E. Ziffer, T. Wernicke, and M. Kneissl, “Light extraction efficiency and internal quantum efficiency of fully UV-transparent AlGaN-based LEDs,” J. Phys. D: Appl. Phys., vol. 54, no. 33, Aug. 2021, Art. no. 335101.

[8] M. A. Khan, N. Maeda, M. Jo, Y. Akamatsu, R. Tanabe, Y. Yamada, and H. Hirayama, “13 mW operation of a 295–310 nm AlGaN UV-B LED with a p-AlGaN transparent contact layer for real world applications,” J. Mater. Chem. C, vol. 7, no. 1, pp. 143–152, Jan. 2019.

[9] J.-Y. Kim, J.-H. Jeon, and M.-K. Kwon, “Indium tin oxide-free transparent conductive electrode for GaN-based-ultraviolet light-emitting diodes,” Appl. Mater. Interfaces, vol. 7, no. 15, pp. 7945–7950, Apr. 2015.

[10] 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., vol. 53, no. 10, Oct. 2014, Art. no. 100209.

[11] F. Jiang, J. Zhang, Q. Sun, and Z. Quan, Light-Emitting Diodes: Materials, Processes, Devices and Applications. Cham, Switzerland: Springer International Publishing, 2019, pp. 133–170.

[12] S.-Y. Kuo, C.-J. Chang, Z.-T. Huang, and T.-C. Lu, “Improvement of light extraction in deep ultraviolet GaN light emitting diodes with mesh P-contacts,” Appl. Sci., vol. 10, Sep. 2020, Art. no. 5783.

[13] H. K. Cho, N. Susilo, M. Guttmann, J. Rass, I. Ostermay, S. Hagedorn, E. Ziffer, T. Wernicke, S. Einfeldt, M. Weyers, and M. Kneissl, “Enhanced wall plug efficiency of AlGaN-based deep-UV LEDs using Mo/Al as p-contact,” IEEE Photonics Technol. Lett., vol. 32, no. 14, pp. 891–894, Jul. 2020.

[14] Z. Huang, Z. Zhong, H. Wang, S. Lu, J. Wang, G. Liu, T. Wei, J. Yan, J.-H. Min, W. L. Jeong, D.-S. Lee, X. Cai, F. Xu, X. Chen, D. Cai, J. Wang, and J. Kang, “Enhanced emission of deep ultraviolet light-emitting diodes through using work function tunable Cu nanowires as the top transparent electrode,” J. Phys. Chem. Lett., vol. 11, no. 7, pp. 2559–2569, Apr. 2020.

[15] T. Wei, S. M. Islam, U. Jahn, J. Yan, K. Lee, S. Bharadwaj, X. Ji, J. Wang, J. Li, V. Protasenko, H. Xing, and D. Jena, “GaN/AlN quantum-disk nanorod 280 nm deep ultraviolet light emitting diodes by molecular beam epitaxy,” Opt. Lett., vol. 45, no. 1, pp. 121–124, Apr. 2020.

[16] H. Zhang, C. Huang, K. Song, H. Yu, C. Xing, D. Wang, Z. Liu, and H. Sun, “Compositionally graded III-nitride alloys: building blocks for efficient ultraviolet optoelectronics and power electronics,” Rep. Prog. Phys., vol. 84, Mar. 2021, Art. no. 044401.

[17] H. Sun, S. Mitra, R. C. Subedi, Y. Zhang, W. Guo, J. Ye, M. K. Shakfa, T. K. Ng, B. S. Ooi, I. S. Roqan, Z. Zhang, J. Dai, C. Chen, and S. Long, “Unambiguously enhanced ultraviolet luminescence of AlGaN wavy quantum well structures grown on large misoriented sapphire substrate,” Adv. Funct. Mater., vol. 29, no. 48, Sep. 2019, Art. no. 1905445.

[18] H. Yu, M. M. Memon, D. Wang, Z. Ren, H. Zhang, C. Huang, M. Tian, H. Sun, and S. Long, “AlGaN-based deep ultraviolet micro-LED emitting at 275 nm,” Opt. Lett., vol. 46, no. 13, pp. 3271–3274, May 2021.

[19] R. Floyd, M. Gaevski, K. Hussain, A. Mamun, M. ChandraShekhar, G. Simin, and A. Khan, “Enhanced Light Extraction Efficiency of Micropixel Geometry AlGaN DUV Light-Emitting Diodes,” Appl. Phys. Express, vol. 14, no. 8, Jul. 2021, Art. no. 084002.

[20] L. Li, Y. Zhang, S. Xu, W. Bi, Z.-H. Zhang, and H.-C. Kuo, “On the hole injection for III-nitride based deep ultraviolet light-emitting diodes,” Materials, vol. 10, no. 10, Oct. 2017, Art. no. 1221.

[21] N. Susilo, S. Hagedorn, D. Jaeger, H. Miyake, U. Zeimer, C. Reich, B. Neuschul, L. Sulmoni, M. Guttmann, F. Mehnke, C. Kuhn, T. Wernicke, M. Weyers, and M. Kneissl, “AlGaN-based deep UV LEDs grown on sputtered and high temperature annealed AlN/sapphire,” Appl. Phys. Lett., vol. 112, no. 4, Jan. 2018, Art. no. 041110.

[22] G.-D. Hao, M. Taniguchi, and S.-I. Inoue, “Enhancement of current injection efficiency of AlGaN-based deep-ultraviolet light-emitting diodes by controlling strain relaxation,” J. Phys. D: Appl. Phys., vol. 53, no. 50, Dec. 2020, Art. no. 505107.

[23] Y. Zhang, Z. Jamal-Eddine, and S. Rajan, “Recent progress of tunnel junction-based ultra-violet light emitting diodes,” Jpn. J. Appl. Phys., vol. 58, Jun. 2019, Art. no. SC0805.

[24] F. Mehnke, C. Kuhn, M. Guttman, L. Sulmoni, V. Montag, J. Glaab, T. Wernicke, and M. Kneissl, “Electrical and optical characteristics of highly transparent MOVPE-grown AlGaN-based tunnel heterojunction LEDs emitting at 232 nm,” Photonics Res., vol. 9, no. 6, pp. 1117–1123, Jun. 2021.

[25] F. J. Arques-Orobon, N. Nuñez, M. Vazquez, C. Segura-Antuñez, and V. Gonzalez-Posadas, “High-power UV-LED degradation:
Continuous and cycled working condition influence,”* Solid. State. Electron.*, vol. 111, pp. 111–117, Sep. 2015.

[26] T. H. Lee, B. R. Lee, K. R. Son, H. W. Shin, and T. G. Kim, “Highly efficient deep-UV light-emitting diodes using AlN-based deep-UV-transparent glass electrodes,”* ACS Appl. Mater. Interfaces*, vol. 9, no. 50, pp. 43774–43781, Dec. 2017.

[27] N. Maeda and H. Hirayama, “Realization of high-efficiency deep-UV LEDs using transparent p-AlGaN contact layer,”* Phys. Status Solidi Curr. Top. Solid State Phys.*, vol. 10, no. 11, pp. 1521–1524, Nov. 2013.

[28] T. Shioda, H. Yoshida, K. Tachibana, N. Sugiyama, and S. Nunoue, “Enhanced light output power of green LEDs employing AlGaN interlayer in InGaN/GaN MQW structure on sapphire (0001) substrate,”* Phys. Status Solidi Appl. Mater. Sci.*, vol. 209, no. 3, pp. 473–476, Mar. 2012.

[29] M. Broas, P. Sippola, T. Sajavaara, V. Vuorinen, A.P. Perros, H. Lipsanen, and M. Paasalo-Kröckel, “Structural and chemical analysis of annealed plasma-enhanced atomic layer deposition aluminum nitride films,”* J. Vac. Sci. Technol. A*, vol. 34, no. 4, Jun. 2016, Art. no. 041506.

[30] J. Ji, Z. Li, W. Sun, and H. Wang, “ITO Induced Tunability of Surface Plasmon Resonance of Tin Thin Film,”* Chem. Phys.*, vol. 540, Oct. 2020, Art. no. 111015.

[31] H. Xiu, Y. Zhang, J. Fu, Z. Ma, L. Zhao, and J. Feng, “Degradation behavior of deep UV-LEDs studied by electro-optical methods and transmission electron microscopy,”* Curr. Appl. Phys.*, vol. 19, no. 1, pp. 20–24, Jan. 2019.

[32] M. Kaneda, C. Pernot, Y. Nagasawa, A. Hirano, M. Ippomatsu, Y. Honda, H. Amano, and I. Akasaki, “Uneven AlGaN multiple quantum well for deep-ultraviolet LEDs grown on macrosteps and impact on electroluminescence spectral output,”* Jpn. J. Appl. Phys.*, vol. 56, no. 6, Jun. 2017, Art. no. 061002.

[33] A. Fujioka, K. Asada, H. Yamada, T. Ohtsuka, T. Ogawa, T. Kosugi, D. Kishikawa, and T. Mukai, “High-output-power 255/280/310 nm deep ultraviolet light-emitting diodes and their lifetime characteristics,”* Semicond. Sci. Technol.*, vol. 29, no. 8, Aug. 2014, Art. no. 084005.