Proceedings of CONF-MSS 2026 Symposium: Advanced Composite Materials and Polymer Chemistry
DOI: 10.54254/2755-2721/2026.AD34745

Deep Ultraviolet Light-Emitting Diodes: Efficiency Limitations, Mechanisms, and Design Strategies

Yuwei Huang

School of Physics & Optoelectrionic Engineering, Guangdong University of Technology, Guangzhou, China
3124006284@mails.gdut.edu.cn

Abstract. The external quantum efficiency of Deep Ultraviolet Light-Emitting Diodes (DUV LEDs) remains significantly lower than that of mature blue LEDs, which continues to be a key bottleneck hindering their development. This paper reviews the research background, current performance status, and efficiency limitation mechanisms of DUV LEDs. It systematically analyzes technical challenges ranging from internal quantum efficiency, light extraction efficiency, and thermal management to electrical losses, along with their corresponding solutions. The analysis indicates that to improve DUV LED performance, it is essential to comprehensively optimize internal quantum efficiency, light extraction efficiency, and electrical and thermal properties. The study also summarizes future development trends. Future research focuses on silicon-based epitaxial growth, novel light extraction structures, and integrated thermal management. Industrial progress relies on large-scale substrate production, higher yields and local manufacturing to reduce costs and expand applications, aiming to provide theoretical and technical references for performance enhancement and industrial applications of DUV LEDs.

Keywords: Deep Ultraviolet Light-Emitting Diodes, AlGaN, Internal Quantum Efficiency, Light Extraction Efficiency

1. Introduction

AlGaN is a wide-bandgap direct semiconductor material and a representative material of third-generation semiconductors. By adjusting the Al composition, the bandgap of AlGaN can be continuously tuned from approximately 3.4 eV to 6.1 eV, covering the ultraviolet wavelength range from 210 nm to 360 nm, which makes it an ideal material for Deep Ultraviolet Light-Emitting Diodes (DUV LEDs) [1]. Traditional ultraviolet light sources, such as mercury lamps, suffer from inherent limitations, including high operating voltage, bulky size, short lifespan, and poor spectral monochromaticity. In addition, regulatory restrictions on mercury usage, such as the Minamata Convention on Mercury, further limit their applicability in modern UV technologies. In comparison, AlGaN-based DUV LEDs have emerged as a promising alternative due to their advantages of low power consumption, compact size, rapid startup, tunable wavelength, and environmental

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.AD34745

friendliness. With the rapid growth of market demand and gradual commercialization, DUV LEDs show great potential in applications such as sterilization, medical diagnostics, and UV curing.

Despite these advantages, the external quantum efficiency (EQE) of DUV LEDs remains significantly lower than that of mature blue LEDs, which is still a critical bottleneck restricting their future development. This paper reviews the research background, current performance status and efficiency-limiting mechanisms of DUV LEDs; systematically analyzes the technical challenges and corresponding solutions in terms of internal quantum efficiency (IQE), light extraction efficiency (LEE), thermal management, and electrical loss; and summarizes the future development trends, thereby providing theoretical and technical references for the performance enhancement and industrial application of DUV LEDs.

2. Recent progress in AlGan-based DUV LEDs

2.1. Advances in EQE

As a core performance index of DUV LEDs, EQE is jointly influenced by IQE and LEE. The primary factors affecting IQE include the crystal quality of AlGaN thin films, dislocation density, carrier injection efficiency, and the design of the epitaxial structure, all of which affect carrier transport and recombination in the multi-quantum well (MQW) active region [1].

Aiming at poor carrier transport and low radiative recombination efficiency in the MQW region, various structural engineering strategies have been proposed. For instance, gradient aluminum-doped quantum wells and customized multi-quantum barrier structures were developed through structural engineering design. These optimized structures can effectively suppress the quantum confinement Stark effect (QCSE), enhance the overlap degree of electron-hole wave functions, and reduce electron leakage, thus improving the IQE of devices [2, 3].

In the optimization of the p-type region, the cross-layer superlattice structure is innovatively introduced to replace traditional electron barrier layer (EBL) designs. This design can simultaneously enhance hole injection efficiency and reduce electron leakage. Devices based on such optimized structures have set a historical record of 6.3% EQE [4].

In terms of LEE enhancement, one of the challenges lies in the low extraction efficiency of transverse magnetic (TM)-polarized photons in DUV LEDs. To address this issue, various structural designs have been proposed, such as hybrid nanostructure arrays, inclined sidewall reflectors, and dual-plane structural configurations. These schemes can mitigate total internal reflection effects within the device and improve the extraction efficiency of TM-polarized DUV photons.

2.2. Wavelength scaling and performance trade-offs

While significant progress has been made in improving EQE, the performance of AlGaN-based DUV LEDs is strongly dependent on emission wavelength, leading to critical trade-offs as devices are pushed toward shorter wavelengths. This wavelength-dependent characteristic largely determines their functional performance and application potential. Short-wavelength ultraviolet radiation, especially in the UVC range (200~280 nm), exhibits remarkable application advantages over long-wavelength UVA and UVB LEDs:

Its higher photon energy enables direct damage to microbial DNA and RNA, achieving rapid and complete inactivation within seconds. In contrast, long-wavelength UV LEDs generally exhibit only bacteriostatic effects. In addition, the high energy and short wavelength of UVC light allow for ultra-precise micro- and nanoscale processing in applications such as UV curing and semiconductor

DOI: 10.54254/2755-2721/2026.AD34745

etching, as well as higher detection sensitivity and spectral specificity in medical diagnostics and material analysis. These features meet the demands of high-end manufacturing and precision detection. Meanwhile, DUV LEDs exhibit excellent monochromaticity and high energy efficiency. Their sterilization mechanism is purely physical, avoiding secondary pollution. Combined with their compact size and low-power consumption, they are well suited for portable, integrated, and high-safety applications. As a result, they can meet stringent requirements for inactivation efficiency and precision in special scenarios, such as direct drinking water disinfection and sterile preparation in operating rooms, suppressing the limitations of long-wavelength UV LEDs, which are only applicable to low-demand auxiliary scenarios.

However, wavelength scaling introduces critical performance trade-offs. Achieving shorter emission wavelengths requires increasing the aluminum composition in AlGaN epitaxial layers. This leads to a larger lattice mismatch between AlGaN and commonly used substrates (e.g., sapphire or silicon), resulting in a sharp rise in dislocation density and a corresponding reduction in IQE. Moreover, enhanced spontaneous and piezoelectric polarization effects intensify the QCSE, which reduces the overlap of electron-hole wave functions and suppresses radiative recombination. High aluminum content also renders p-type doping extremely challenging due to increased acceptor activation energy, leading to low hole concentration and inefficient carrier injection. In addition, deep ultraviolet photons are more strongly absorbed in AlGaN materials and packaging layers, which further degrades the LEE and luminous efficiency of the devices [5, 6].

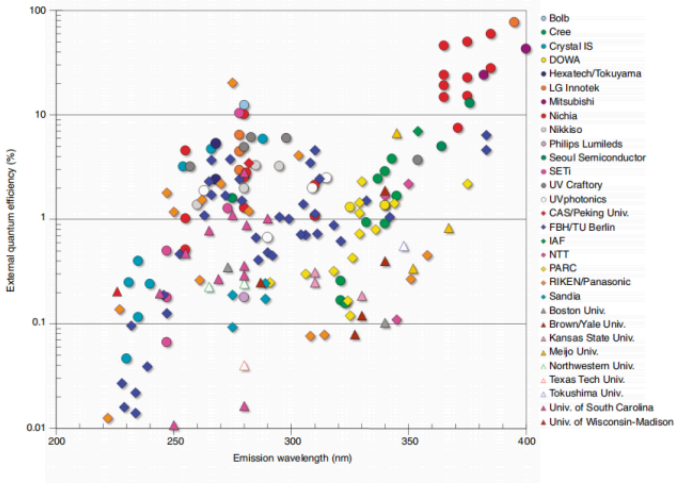

Figure 1. EQEs for group-III-nitride-based LEDs [5]

2.3. Industrialization and commercial applications

Building on the aforementioned advances in EQE improvement and wavelength scaling technology, the industrialization of DUV LEDs has accelerated since 2020. Their commercial applications mainly focus on disinfection, the medical field, semiconductor manufacturing, and consumer electronic products. TrendForce (2026) projects that the global market size will reach $215 million in 2026, with an annual growth rate exceeding 10% [7]. Mordor Intelligence (2026) forecasts that the global UVC LED market will register a compound annual growth rate (CAGR) of 32.18% from 2026 to 2031, with the market scale surging past $559 million by 2031 [8]; Fortune Business Insights (2026) estimates a CAGR of 24.95% for the period of 2026–2034, with the market size expected to hit $1.434 billion by 2034 [9].

DOI: 10.54254/2755-2721/2026.AD34745

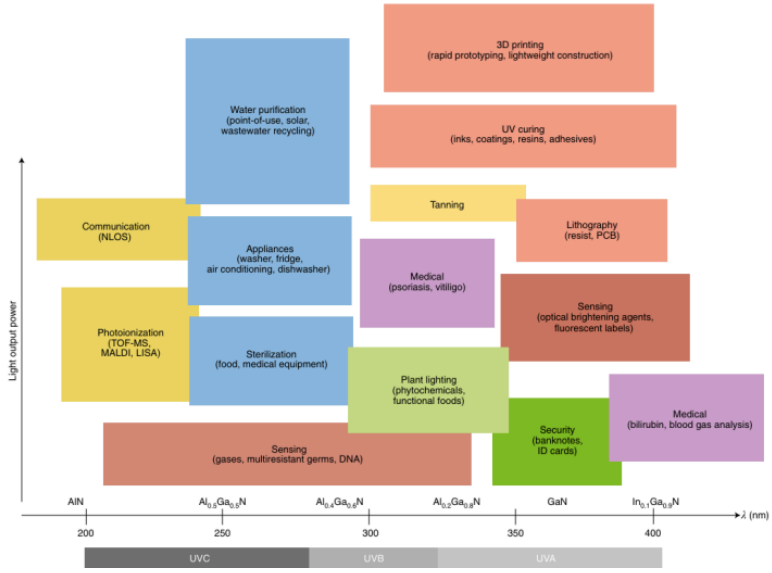

Figure 2. Applications of UVA, UVB and UVC LEDs [6]

From a technological perspective, key progress has been achieved in the industrialization of DUV LEDs. The mass production of high-power chips (100 mW class) has been realized; the EQE is gradually approaching 10%; the packaging lifetime has been extended to 5,000–10,000 hours; and the reliability and stability have been significantly improved, which can now meet the demands of household appliances, water purification, and some industrial scenarios.

In terms of cost, the price of mass-produced DUV LED chips has decreased to approximately $0.50–2 per mW, which represents a notable reduction compared with early stages, yet is still higher than that of traditional mercury lamp systems. With the advancement of 6-inch substrates, yield improvement and domestic substitution, the cost is expected to decline continuously from 2026 to 2028, gradually approaching the inflection point for large-scale replacement [7, 9].

3. Core technical challenges for DUV LEDs

3.1. Challenges of IQE

Because the QCSE extends the carrier transport lifetime and reduces radiative recombination efficiency, the emission wavelength undergoes a redshift. Even without external bias voltage, the spontaneous and piezoelectric polarization fields in AlGaN can reach the order of MV/cm, significantly reducing the IQE of UV LEDs [10]. In addition to QCSE, Auger recombination (AR) is another important factor affecting the IQE of DUV LEDs. Under high-temperature and high-current injection conditions, the AR process is significantly intensified, leading to increased carrier loss and pronounced efficiency droop; that is, the IQE decreases with increasing injection current density [11, 12]. These two factors together lead to the low IQE of DUV LEDs, which is a primary technical challenge in their development.

3.2. Challenges of LEE

The challenges of DUV LED LEE include polarization effects, total internal reflection, and excessive light absorption. Therefore, improving LEE is a key breakthrough direction [13]. Traditional light extraction technologies for visible LEDs, such as surface roughening and patterned

DOI: 10.54254/2755-2721/2026.AD34745

substrates, are difficult to directly apply to the DUV band. These methods have obvious limitations in process compatibility and optical enhancement in the deep ultraviolet range and thus cannot effectively improve LEE [14].

In addition, packaging material for DUV LEDs is prone to aging and degradation under long-term irradiation of deep ultraviolet light, which will affect the light transmission performance of the packaging layer. Meanwhile, interfacial reflection between the packaging layer and the chip, as well as transmission losses, further reduces the overall LEE. Due to the combined effects of these factors, the LEE of DUV LEDs is much lower than that of conventional visible light LEDs, which has become an important constraint on device performance improvement [15].

3.3. Challenges of thermal management and electrical loss

The miniaturization of DUV LED devices increases the ratio of sidewall surface area to substrate volume, which can enhance heat dissipation through sidewall-assisted radiation and also contribute to LEE improvement [16].

However, DUV LEDs usually work under high current densities, and the series resistance generates significant Joule heat, leading to severe self-heating. This effect causes a rapid rise in the internal chip temperature, resulting in thermal efficiency degradation and becoming a major bottleneck for realizing high light output power [17].

The electrical loss of DUV LEDs mainly comes from intrinsic material properties and structural defects. In p-type AlGaN, the high acceptor activation energy and obvious carrier compensation result in low hole concentration and high ohmic contact resistance, which reduces carrier injection efficiency and exacerbates Joule heating and series resistance losses.

Meanwhile, the lattice mismatch between AlGaN and heterogeneous substrates leads to high-density threading dislocations, enhancing defect-assisted nonradiative recombination. In addition, strong polarization fields in the quantum well induce QCSE, which further increases nonradiative recombination, leading to higher electrical losses and reduced device efficiency [18, 19].

4. Performance enhancement strategies and device design for high-efficiency DUV LEDs

To address these challenges, recent progress in the design and performance enhancement of AlGaN-based DUV LEDs has centered on synergistic optimization of IQE, carrier injection, LEE, and thermal management.

Key design strategies involve structural engineering of AlGaN MQW active regions, such as the adoption of stepped or graded electron blocking layers to suppress QCSE and reduce electron leakage, as well as the use of tunnel junctions combined with advanced current spreading structures to enhance hole injection and alleviate current crowding.

For LEE improvement, nanostructured substrates, tilted sidewalls, and high-reflectivity electrodes are employed to enhance the extraction of TM-polarized emission. In addition, a novel scattered volume emitter micropixel architecture (SVEP) has been proposed and developed. It achieves ultra-high LEE without relying on nanoscale light extraction structures, high-refractive-index substrates, or external lenses, at the cost of an expanded emission area relative to the MQW active region. Its optical performance has been validated through combined wave and ray optics simulations [20].

Moreover, DUV LEDs integrated with tailored MQWs, low-optical-loss p-electrode/ohmic contact layers, and insulating IS-SiO_2 have demonstrated outstanding performance, delivering a light output power of 140.1 mW at 850 mA and a 4.5-fold increase in EQE compared with conventional

DOI: 10.54254/2755-2721/2026.AD34745

devices [6]. This design effectively suppresses efficiency droop (ED) and significantly improves device reliability, thus driving the development of high-power, high-efficiency DUV LEDs for deep ultraviolet emission below 280 nm.

5. Conclusion

As an ideal replacement for conventional mercury lamps, AlGaN-based DUV LEDs possess superior performance, environmental compatibility, and broad application prospects. With a rapidly expanding market, they are becoming a core development direction for future deep-UV light sources.

Although the technology is gradually moving toward commercialization, low external quantum efficiency remains the primary bottleneck, rooted in three major challenges: insufficient IQE, low LEE, and poor electrical and thermal management.

The improvement of IQE mainly depends on the optimization of substrate selection, epitaxial growth process, and electron blocking layer structure; the enhancement of LEE can be realized through flip-chip packaging, polarization modulation, and transparent contact design. The alleviation of electrical and thermal losses relies on advanced doping technology, ohmic contact optimization, and efficient thermal management structures. Collaborative optimization across these three aspects constitutes the core strategy for boosting the efficiency of DUV LEDs.

In the future, research on AlGaN-based DUV LEDs will focus on three key directions: first, epitaxial growth on silicon substrates to reduce lattice mismatch and improve crystal quality; second, the development of novel light extraction structures without encapsulation to address material degradation under deep ultraviolet irradiation; and third, integrated thermal management technologies for high-power DUV LEDs to suppress self-heating effects. In terms of industrialization, key breakthroughs include large-scale production of 6-inch substrates, improved device yield, and accelerated localization (domestic substitution), which will further reduce costs and promote large-scale applications of DUV LEDs in fields such as semiconductor manufacturing and environmental monitoring.

References

[1] Wu, F., Dai, J. N., & Chen, C. Q. (2020) Research progress of AlGaN-based deep-ultraviolet light-emitting diodes. Journal of Synthetic Crystals, 49(11): 2079–2097. https: //doi.org/10.16553/j.cnki.issn1000-985x.2020.11.004

[2] Sun, Y., et al. (2025) Ultra-thin last quantum barrier engineering for suppressed defect formation and enhanced IQE in DUV LEDs. IEEE Electron Device Letters, 46(4): 598–601.

[3] Zhang, L., et al. (2025) Graded Al composition quantum structures for screening QCSE and improving carrier injection in DUV LEDs. Applied Physics Express, 18(7): 075502.

[4] Kim, J. H., et al. (2025) High-efficiency DUV LEDs without EBL enabled by high-Al-content spanning superlattice p-type region. ACS Applied Materials & Interfaces, 17(42): 48293–48302.

[5] Kneissl, M., Seong, T. Y., Han, J., et al. (2019) The emergence and prospects of deep-ultraviolet light-emitting diode technologies. Nature Photonics, 13: 233–244. https: //doi.org/10.1038/s41566-019-0359-9

[6] Khan, A., et al. (2021) Highly efficient AlGaN-based deep-ultraviolet light-emitting diodes: From bandgap engineering to device craft. Advanced Materials, 33(25): 2007896.

[7] TrendForce. (2026) 2026 deep ultraviolet LED market trend and product analysis. https: //www.trendforce.com/research/download/RP260327SE

[8] Mordor Intelligence. (2026) UVC LED market size & share analysis (2026–2031). https: //www.mordorintelligence.com/industry-reports/uvc-led-market

[9] Fortune Business Insights. (2026) UV-C LED market report 2026–2034. https: //www.fortunebusinessinsights.com/uv-c-led-market-109338

DOI: 10.54254/2755-2721/2026.AD34745

[10] Wang, J. X., Yan, J. C., Guo, Y. N., et al. (2015) New research progress of nitride deep-ultraviolet LEDs. Scientia Sinica Physica, Mechanica & Astronomica, 45(6): 37–56.
[11] Wang, W. D., Chu, C. S., Zhang, D. Y., et al. (2021) Impact of Auger recombination, electron leakage and hole injection on efficiency droop for DUV LEDs. Chinese Journal of Luminescence, 42(7): 897–903. https: //doi.org/10.37188/CJL.20210102
[12] Iveland, J., Speck, J., Martinelli, L., et al. (2014) Auger effect identified as main cause of efficiency droop in LEDs. SPIE Newsroom. https: //doi.org/10.1117/2.1201406.005109
[13] Lang, J., Xu, F. J., Wang, J. M., et al. (2025) Research progress on light extraction efficiency of AlGaN-based deep ultraviolet light-emitting diodes (Invited). Chinese Journal of Lasers, 52(5): 61–72.
[14] Manley, P., Walde, S., Hagedorn, S., et al. (2020) Nanopatterned sapphire substrates in deep-UV LEDs: Is there an optical benefit? Optics Express, 28(3): 3619–3635. https: //doi.org/10.1364/OE.379438
[15] Kang, W. Y., Yin, J., Huang, J. X., et al. (2025) Design and optimization of highly efficient light extraction encapsulation for deep ultraviolet LEDs. Chinese Journal of Luminescence, 46(4): 553–564. https: //doi.org/10.37188/CJL.20240321
[16] Chen, H. S., Yeh, D. M., Lu, C. F., et al. (2006) Mesa-size-dependent color contrast in flip-chip blue/green two-color InGaN/GaN multi quantum-well micro-light-emitting diodes. Applied Physics Letters, 89(9): 093501.
[17] Liu, Z. Q., Jia, T., Xu, X. Y., Chu, C. S., Zhang, Y. H., & Zhang, Z. H. (2023). Research progress on AlGaN-based deep ultraviolet micro-light-emitting diodes (Invited). Infrared and Laser Engineering, 52(8), 100–118.
[18] Li, J., Zhang, L., Liu, J., et al. (2021) The influence of threading dislocations propagating through an AlGaN UVC LED. Applied Physics Letters, 118(16): 162101.
[19] Ahmad Fajri, F. A., Mukherjee, A., Naskar, S., et al. (2024) A scattered volume emitter micropixel architecture for ultra efficient light extraction from DUV LEDs. Scientific Reports, 14: 14108. https: //doi.org/10.1038/s41598-024-64689-y
[20] Chen, Y. X., Ben, J. W., Xu, F. J., et al. (2021) Review on the progress of AlGaN-based ultraviolet light-emitting diodes. Fundamental Research, 1(6): 717–734.