Optimization of Device Architecture for Enhanced Performance in Deep-Ultraviolet Light-Emitting Diodes

Yangyue Zhang

Department of Physics, Xiamen University of Malaysia, Seri Kembangan, Malaysia

PHY2309501@xmu.edu.my

Abstract. Deep-UV LEDs typically refer to ultraviolet LEDs that emit wavelengths of approximately 200–280 nm or <300 nm. Their primary material system is AlGaN, and by adjusting the Al content, the bandgap can be shifted into the deep ultraviolet region to achieve the desired wavelength. Deep-UV LEDs offer advantages such as long lifespan, tunable wavelengths, and mercury-free operation, making them highly promising for sterilization and disinfection, water treatment, medical disinfection, lithography, and specific sensing applications. However, deep ultraviolet LEDs still face bottlenecks such as low internal quantum efficiency, limited external quantum efficiency, and insufficient device lifetime. One core factor contributing to these issues is the challenge in device structural design. Based on understanding the principles of deep-UV LEDs, this paper explores various methods for optimizing device architecture, such as tunnel junctions, nanostructured patterns, and ultra-thin quantum wells, and their impact on the performance of deep-UV LEDs. Ultimately, through these discussions, this review hopes to provide a reference for designing highly efficient, long-lasting deep-UV LEDs and promote their practical application in public health, environmental protection, and industrial manufacturing.

Keywords: Deep-UV LEDs, Optimization, Device Architecture, Enhanced Performance.

1. Introduction

Deep-ultraviolet (DUV) light-emitting diodes typically operate in the 200–280 nm band, which relies on the AlGaN/AlN material system whose bandgap can be tailored by the Al composition with GaN ≈ 3.4 eV and AlN ≈ 6.2 eV, following $\lambda \approx 1240/E_g$ nm. The photon energy in this wavelength range is 4.4–6.2 eV, directly destroying DNA and RNA. Therefore, it can be used for water treatment, air purification, and surface sterilization (such as in hospitals, drinking water systems, and air circulation systems) [1]. In another field, traditional low-pressure mercury lamps (254 nm) are the mainstream DUV light source, but they contain mercury and are hazardous to the environment [2]. AlGaN deep ultraviolet LEDs are mercury-free and environmentally friendly. Official materials from various countries and industry organizations also regard mercury-free LEDs as a medium- to long-term replacement option [3]. Due to the unique properties of AlGaN and the wavelength of light it emits, DUV LEDs are also widely used in other fields.

However, DUV LEDs also face technical bottlenecks and scientific issues. Due to limitations in their materials and structure—namely, the use of high-Al-content AlGaN materials and multi-quantum-well structures (MQWs)—DUV LEDs face the following three primary challenges: difficulties in p-type doping with low hole injection efficiency, low light extraction efficiency (LEE) with high material defect density, and strong polarization electric fields with electron-hole wavefunction separation. These are the core physical bottlenecks currently limiting the development of DUV LEDs [1, 4, 5]. To address these bottlenecks, we are exploring approaches from the perspective of optimizing the device architecture of DUV LEDs. Three methods that can tackle the challenges above are tunnel junction (TJ), nanopatterned structure (NPS), and ultrathin quantum wells (UTQWs). This paper will explain these methods' mechanisms and analyze the performance improvements they bring to DUV LEDs. Furthermore, it will explore their advantages and disadvantages, the potential for complementary combinations, current limitations, and future development directions. Ultimately, it aims to provide a reference for designing highly efficient, long-lasting deep-UV LEDs that can play increasingly vital roles across various fields.

2. Research Progress on Deep Ultraviolet LEDs

2.1 Principles of Deep UV LEDs

The core principle of deep UV LEDs is the same as that of ordinary visible light LEDs based on semiconductor bandgap luminescence. The difference is that its materials and structure are more difficult to achieve. Its material principle is to change the bandgap of AlGaN by altering the Al content to obtain photons of specific wavelengths and energies. This is our most basic principle and one that we repeatedly emphasize.

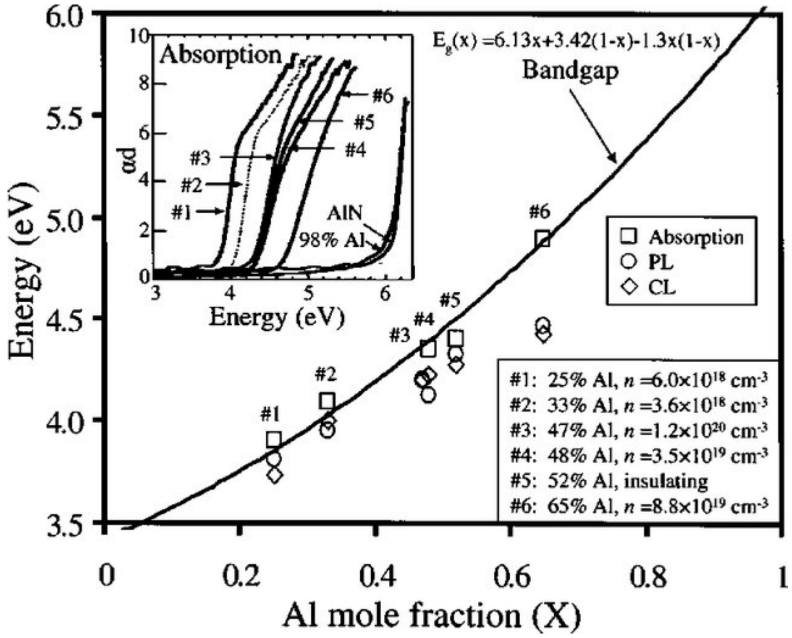


Figure 1: Theoretical graph of AlGaN band gap as a function of Al mole fraction [6].

Regarding the structural principle, DUV LEDs use a multi-quantum well (MQW) structure: a light-emitting layer is sandwiched between n-type AlGaN and p-type AlGaN. The light-emitting layer of multiple quantum wells (MQWs) consists of alternating quantum wells and barriers of AlGaN/AlGaN. Electrons and holes recombine here, emitting deep ultraviolet light. MQWs can produce quantum confinement effects, confining electrons and holes in thin quantum wells, increasing the probability of encountering each other, and improving the radiation recombination rate. At the same time, they also play a role in wavelength control, precisely controlling the emission wavelength (200–280 nm) by adjusting the Al content and quantum well thickness [7].

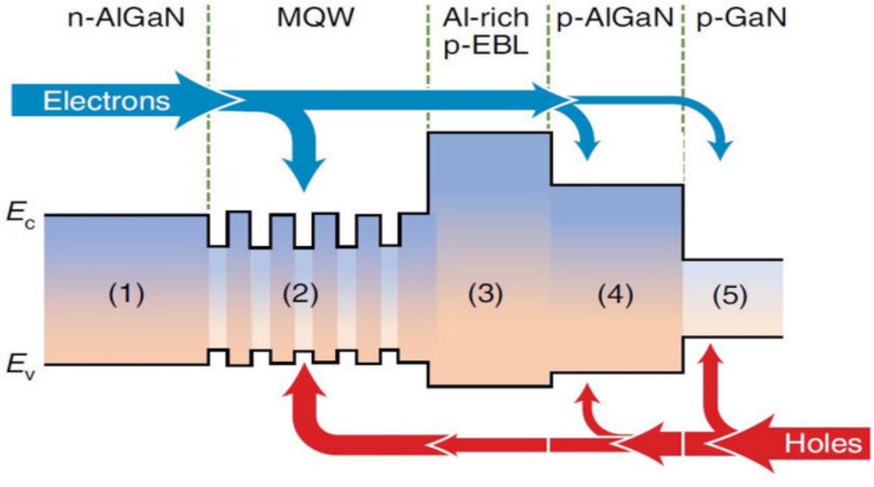


Figure 2: Construction of AlGaN-based Deep UV LED [8]

2.2 Limitations and Issues Arising from the Principles

However, such material and structural principles are also the source of their limitations and problems—first, the difficulty of p-type doping results in low hole concentration. In AlGaN with high Al content, the Mg-doped acceptor level is intense (> 0.5 eV), which results in holes being almost unable to be effectively activated. Consequently, hole injection efficiency, electron-hole imbalance, and recombination efficiency are extremely low. Hole injection is more serious than electron injection and is one of the efficiency bottlenecks of DeTHiep UV LEDs [1].

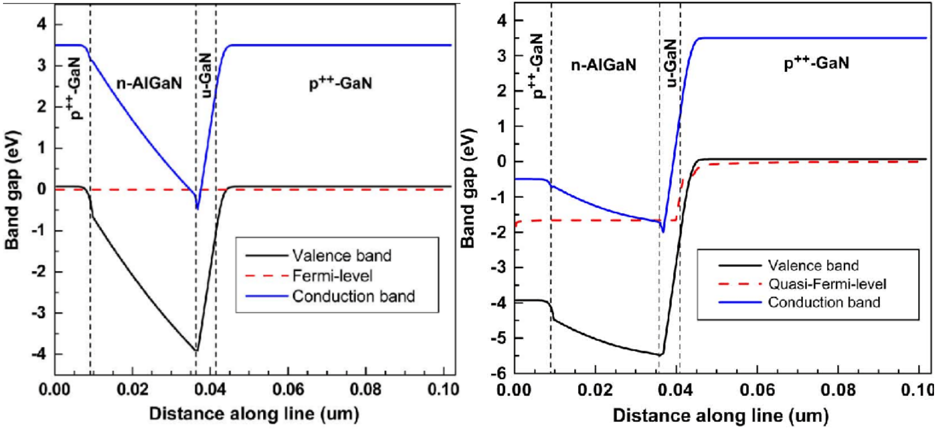
Second, material issues lead to low light extraction efficiency (LEE) and high material defect density. For low LEE, the refractive index of AlGaN is significantly higher than that of air and packaging materials, resulting in a minimal critical angle. Most emitted light undergoes total internal reflection at the interface, forming waveguide or substrate modes within the chip that cannot directly escape as external photons. Meanwhile, traditional p-type contact layers (or p-GaN metal electrodes) exhibit strong absorption in the deep ultraviolet band. This directly absorbs emitted light and dissipates it as heat, reducing LE [5]. Deep-UV LEDs commonly employ AlGaN/AlN epitaxial layers for high material defect density, but in most cases, these are not grown on perfectly matched AlN substrates. Widely used substrates such as sapphire, Si, and SiC exhibit differences in lattice constants and thermal expansion coefficients compared to AlN/AlGaN. This mismatch prevents perfect lattice alignment during the initial epitaxial growth stage, leading to many threading dislocations (TDs) [9]. Dislocations act as non-radiative recombination centers for SRH pairs. When electrons and holes recombine here, their energy is dissipated as heat rather than converted into light. Consequently, the probability of photon emission decreases, reducing the internal quantum efficiency (IQE).

Third, for the strong polarization electric fields and electron-hole wavefunction separation, AlGaN, a polarized semiconductor, exhibits spontaneous polarization and piezoelectric polarization, forming a strong built-in electric field within MQWs. This causes electrons and holes to separate within the quantum wells (the Quantum Confinement Stark Effect, QCSE), ultimately reducing the overlap of electron and hole wave functions and decreasing the probability of radiative recombination [4].

3. Optimization of Device Architecture Applied

3.1 Tunneling Junction

A tunneling junction typically consists of a very narrow p^+/n^+ junction with highly doped regions on both sides or a short-range potential barrier formed by a heteroepitaxial layer. When the depletion region is extremely narrow and abundant occupied states exist on both sides, carriers can directly traverse the barrier via quantum mechanical tunneling without thermally crossing the significant energy barrier (Esaki-type/interband tunneling principle) [10].



(a) (b)

Figure 3: (a) The energy band at zero bias, illustrating the structure and initial energy band conditions of the tunnel junction. (b) The energy bands in the operational state, revealing the formation mechanism of the tunneling current [11].

The probability of tunneling generally decreases exponentially with barrier width and height. WKB can approximate it as

$$T \sim \exp\left(-\frac{2}{\hbar}\int\sqrt{2m(V(x)-E)}dx\right)$$

This indicates that thinning the depletion layer or lowering the barrier height can exponentially increase the tunneling current [10].

For the optical gain resulting from the tunnel junction, using a tunnel junction to make the top of the device n-type or employing a transparent/low-absorption TJ layer eliminates the absorption and blocking of DUV light by the p-GaN/p-AlGaN/metal layers, thereby significantly increasing the number of photons escaping from the top surface. This effect is particularly pronounced in top/front-emitting devices. Experiments and device operation have demonstrated that this structure enhances light output power [12]. For the electrical gain introduced by the tunnel junction, n-type AlGaN/n-type contacts facilitate the formation of low-resistance contacts. Introducing TJ reduces the series resistance across the entire device, resulting in more uniform current distribution. This enhances power efficiency and minimizes voltage drop. Multiple experimental sets demonstrate that TJ LEDs exhibit more stable I–V characteristics and EL intensity at high currents [11][13].

3.2 Nanopatterned Structures

Nanopatterned Structures (NPS) introduce submicron/nanoscale periodic or random topographies (pits, cones, pillars, photonic crystal lattices, etc.) onto substrate or epitaxial surfaces. These structures simultaneously enhance Deep-UV LED performance through two primary pathways: optical coupling/sc nanoscale periodic or random topographies (pits, cones, pillars, photonic crystal lattices, etc.) onto substrates or epitaxial surfaces. By simultaneously enhancing light extraction efficiency (LEE) and material quality (reducing dislocation density, TDD) through optical coupling/scattering and epitaxial growth control, NPS significantly boosts the external quantum efficiency (EQE) of deep-UV LEDs [14][15].

Nanopatterns act as scattering centers or diffraction gratings for NPS, enhancing LEE through optical mechanisms. They convert waveguide/substrate modes initially confined into radiative modes via Bragg scattering or weak coupling, enabling extraction into the external light cone. This coupling is most effective for structures with periods close to or slightly smaller than the emission wavelength. Specific patterns can shift the light field away from the near-absorbing top layer (metal or p-GaN) or deflect the emission direction toward the n-layer, thereby reducing the probability of absorption by the p-contact/metal. Under specific optimized geometries, the LEE can be increased from ~4.6% to ~15% [5][15].

For NPS, TDD is reduced through the regulation of epitaxial growth. When AlN/AlGaN grows on nanopatterned sapphire substrates, initial island-like growth occurs along the pattern edges. Lateral merging between islands can bend or block threading dislocations, achieving lower TDD at thinner epitaxial thicknesses. For example, the co-growth thickness of AlN on NPSS can be significantly reduced, facilitating subsequent AlGaN growth. This has been confirmed in multiple studies [16][14]. Meanwhile, the pattern helps locally release strain, prevent crack propagation, and modulate the surface micro-morphology, thereby facilitating the formation of subsequent epitaxial layers with improved flatness and crystalline quality [17].

3.3 Ultrathin Quantum Wells

Ultrathin quantum wells (UTQWs) refer to quantum wells whose thickness is reduced to the scale of a single layer or a few atomic layers (monolayer, or ≤1–2 nm). At this scale, electrons and holes become strongly quantized with large energy level separation and significant bandgap engineering, and the interaction between the electric field within the quantum well (e.g., the built-in field generated by polarization) and quantum confinement effects differs significantly from that in conventional thicker quantum wells. UTQWs can be formed from genuine monolayer GaN/AlN or thin AlGaN structures, or approximate “ultrathin well” effects can be achieved through short-period superlattices/digital-alloy structures (alternating several monolayers) [18].

When the thickness of the quantum well (QW) is significantly smaller than the length required to generate a potential drop, the “total potential difference” within the well decreases, resulting in reduced separation between electrons and holes. Concurrently, quantum confinement causes the wave function to become more localized, increasing the transition matrix elements. Experiments demonstrate that the radiative properties of ultra-thin (single-layer or few-layer) QWs are significantly enhanced [19, 20]. Narrow wells and high barriers, such as AlN barriers, better confine electrons, preventing them from leaking into the p-region under appropriate designs. Simultaneously, higher overlap enables equivalent radiation output at lower currents, reducing power consumption and thermal effects. The EL/IV performance and lifetime of related devices have been validated in several studies [21].

4. Analysis of Device Architecture Optimization Applied:

The advantages of the tunneling junction are those we discussed: improved light extraction efficiency in the optical domain and more uniform current distribution in the electrical domain, enabling more thorough tunneling and enhancing hole injection efficiency. However, it also faces challenges and trade-offs: tunneling junctions typically require nanometer-level thickness control and high-quality interfaces, as any interface states may increase resistance or introduce leakage or non-radiative channels [22]. In addition, achieving p^+-doping in high-Al-content AlGaN is challenging, limiting the feasibility of homogenous tunneling junctions relying solely on doping. In high-Al-content DUV devices, polarization engineering is often required to address their first disadvantage for the future development prospects of tunneling junctions. Future objectives may involve using ultra-thin (several nanometer-level) GaN, extremely thin InGaN intercalations, or short-period AlGaN/GaN superlattices. This approach reduces barrier height and width while controlling intercalation thickness to avoid significant absorption of deep ultraviolet (DUV) light. It can circumvent absorption points with flip-chip and back-illumination designs [11, 24]. Achieving stable growth of nanometer-scale intercalation layers in MOCVD/MBE while avoiding phase separation and interfacial states. Experimentally, Pandey et al. have already obtained promising results [11].

On the one hand, NPS can enhance LEE and reduce TDD through optical mechanisms and regulation of epitaxial growth. Still, on the other hand, deep-UV LEDs operate at wavelengths between 200 and 280 nm, necessitating effective scattering/coupling pattern sizes typically ranging from tens to hundreds of nanometers. Achieving periodic photonic crystals or regular NPSS requires high-precision processes such as nanoimprint lithography (NIL), electron beam lithography (EBL), and nanosphere lithography. These methods are costly or suffer from insufficient large-area uniformity [25]. The following future development directions address this bottleneck: First, adopt advanced nanoimprinting for large-area replication to resolve cost issues. Second, nanosphere self-assembly can be combined with etching control to balance low cost and random scattering enhancement. Third, atomic layer etching (ALE) should be integrated with atomic layer deposition (ALD) to provide nanometer-scale control while minimizing etching damage [14][25]. These approaches correspond to three parallel future manufacturing pathways for NPS: industrialization, commercialization, and high-end optimization, which may ultimately converge.

For ultrathin quantum wells, they effectively reduce QCSE, preventing electrons and holes from being strongly separated, while quantum confinement localizes the wave function. However, they also have limitations and require trade-offs. When the barrier is extremely thin relative to the gate, electrons or holes may reduce their recombination probability through tunneling or thermal escape, a phenomenon particularly pronounced at high temperatures and currents. A balance must be achieved between barrier thickness, gate thickness, and height [26]. Additionally, UTQW offers optical advantages, but if the top layer or electrodes—such as the p-layer or metal—still exhibit significant absorption, the improvement in EQE remains limited. Typically, this requires combined optimization with structures like flip-chip packaging, transparent electrodes, or tunnel junctions. Advancements in molecular beam epitaxy (MBE) and atomic layer deposition (ALD) technologies have enabled more precise control over layer thickness and composition. These techniques reduce defect density and enhance the overall quality of UTQWs, thereby improving their performance in deep ultraviolet LEDs [7][17].

5. Conclusion

This paper first reviews the current status of deep-UV LEDs, analyzing the underlying bottlenecks and their origins from the perspectives of materials and structural principles. The primary bottlenecks are threefold: First, difficulties in p-type doping and low hole injection efficiency; second, low LEE and high material defect density; third, strong polarization electric fields and electron-hole wavefunction separation. To address these challenges, we focus on exploring three device-structural optimization approaches: Tunnel Junctions (TJ), Nanopatterned Structures (NPS), and Ultrathin Quantum Wells (UTQWs). We then delve into each approach, detailing its mechanisms for enhancing Deep-UV LED performance and the resulting improvements. We also address their limitations and trade-offs, concluding with their respective future development prospects and potential for complementary synergies. This paper aims to elucidate the current state of deep-UV LED development and elaborate on structural approaches to enhance their performance. It provides a reference for their expanded applications in public health, environmental protection, and industrial manufacturing.

References

[1] R. Xu, Y. Sun, W. Wang, Z. Xu, J. Zhang, Z. Deng, K. Ding, and L. Wang, “Research progress of AlGaN-based deep ultraviolet light-emitting diodes,” Micromachines, vol. 14, no. 4, p. 844, 2023, doi: 10.3390/mi14040844.

[2] European Union, “Commission Delegated Directive (EU) 2022/280 of 13 December 2021 amending…,” EUR-Lex, 2022.

[3] Ministry of the Environment, Japan, “Minamata Convention on Mercury: Meeting Bulletin No. 11,” 2020.

[4] Y. Chen, “Review on the progress of AlGaN-based ultraviolet light emitting diodes,” Mater. Today Phys., vol. 19, p. 100389, 2021, doi: 10.1016/j.mtphys.2021.100389.

[5] E. López-Fraguas et al., “Tripling the light extraction efficiency of a deep ultraviolet LED using a nanostructured p-contact,” Sci. Rep., vol. 12, Art. no. 11480, 2022, doi: 10.1038/s41598-022-15499-7.

[6] J. Hwang, W. J. Schaff, L. F. Eastman, S. T. Bradley, L. J. Brillson, D. C. Look, J. Wu, W. Walukiewicz, M. Furis, and A. N. Cartwright, “Si doping of high-Al-mole fraction AlxGa1-xN alloys with rf plasma-induced molecular-beam-epitaxy,” Appl. Phys. Lett., vol. 81, no. 27, pp. 5192–5194, 2002, doi: 10.1063/1.1534395.

[7] X. Liu et al., “Highly efficient AlGaN-based deep-ultraviolet light-emitting diodes: from bandgap engineering to device craft,” Microsyst. Nanoeng., vol. 10, no. 110, 2024, doi: 10.1038/s41378-024-00737-x.

[8] Q. Zhao, Z. Liu, *et al.*, “Band engineering of III-nitride-based deep-ultraviolet light-emitting diodes: A review,” *J. Semicond.*, vol. 40, no. 12, p. 12160, 2019, doi: 10.1088/1361-6463/ab4d7b.

[9] D. Cameron et al., “The influence of threading dislocations propagating through an AlGaN UVC LED,” Appl. Phys. Lett., vol. 120, no. 16, Art. no. 162101, 2022, doi: 10.1063/5.0086034.

[10] P. R. Berger and A. Ramesh, “Negative Differential Resistance Devices and Circuits,” Comprehensive Semiconductor Science and Technology, vol. 1-6, Elsevier Inc., 2011, pp. 176–241, doi: 10.1016/B978-0-44-453153-7.00013-4.

[11] A. Pandey, W. J. Shin, J. Gim, R. Hovden, and Z. Mi, “High-efficiency AlGaN/GaN/AlGaN tunnel junction ultraviolet light-emitting diodes,” Photon. Res., vol. 8, p. 331, 2020, doi: 10.1364/PRJ.383652.

[12] C. Kuhn, L. Sulmoni, M. Guttmann, J. Glaab, N. Susilo, T. Wernicke, M. Weyers, and M. Kneissl, "MOVPE-grown AlGaN-based tunnel heterojunctions enabling fully transparent UVC LEDs," Photon. Res., vol. 7, no. 5, pp. B7–B11, 2019, doi: 10.1364/PRJ.7.0000B7.

[13] R. Lin, P. Han, Y. Wang, R. Lin, Y. Lu, Z. Liu, X. Zhang, and X. Li, "Low Resistance Asymmetric III-Nitride Tunnel Junctions Designed by Machine Learning," Nanomaterials (Basel), vol. 11, no. 10, Art. no. 2466, 2021, doi: 10.3390/nano11102466.

[14] W. Wei, Y. Peng, Y. Yang, K. Xiao, M. Maraj, J. Yang, Y. Wang, and W. Sun, "Study of Defects and Nano-patterned Substrate Regulation Mechanism in AlN Epilayers," Nanomaterials (Basel), vol. 12, no. 22, Art. no. 3937, 2022, doi: 10.3390/nano12223937.

[15] Y. Guo, J. Yan, Y. Zhang, J. Wang, and J. Li, "Enhancing the light extraction of AlGaN-based ultraviolet light-emitting diodes in the nanoscale," J. Nanophoton., vol. 12, no. 4, Art. no. 043510, 2018, doi: 10.1117/1.JNP.12.043510.

[16] P. Dong, J. C. Yan, J. X. Wang, Y. J. Li, P. P. Cong, J. M. Li, S. Zhao, J. H. Yang, J. F. Wang, Z. X. Qin, S. F. Li, S. Nakamura, and S. P. DenBaars, "282-nm AlGaN-based deep ultraviolet light-emitting diodes with improved performance on nano-patterned sapphire substrates," Appl. Phys. Lett., vol. 102, no. 24, Art. no. 241113, 2013, doi: 10.1063/1.4812237.

[17] C. Zhang, K. Jiang, X. Sun, and D. Li, "Recent Progress on AlGaN-Based Deep Ultraviolet Light-Emitting Diodes below 250 nm," Crystals, vol. 12, no. 12, Art. no. 1812, 2022, doi: 10.3390/cryst12121812.

[18] V. Jmerik, D. Nechaev, K. Orekhova, N. Prasolov, V. Kozlovsky, D. Sviridov, M. Zverev, N. Gamov, L. Grieger, Y. Wang, T. Wang, X. Wang, and S. Ivanov, "Monolayer-Scale GaN/AlN Multiple Quantum Wells for High Power e-Beam Pumped UV-Emitters in the 240-270 nm Spectral Range," Nanomaterials, vol. 11, no. 10, Art. no. 2553, 2021, doi: 10.3390/nano11102553.

[19] Y. Wang, X. Rong, S. Ivanov, V. Jmerik, Z. Chen, H. Wang, T. Wang, P. Wang, P. Jin, Y. Chen, V. Kozlovsky, D. Sviridov, M. Zverev, E. Zhdanova, N. Gamov, V. Studenov, H. Miyake, H. Li, S. Guo, X. Yang, F. Xu, T. Yu, Z. Qin, W. Ge, B. Shen, and X. Wang, "Deep Ultraviolet Light Source from Ultrathin GaN/AlN MQW Structures with Output Power Over 2 Watt," Adv. Opt. Mater., vol. 7, Art. no. 1801763, 2019, doi: 10.1002/adom.201801763.

[20] C. R. Haughn, G. Rupper, T. Wunderer, Z. Yang, N. M. Johnson, M. Wraback, and G. A. Garrett, "Highly radiative nature of ultra-thin c-plane Al-rich AlGaN/AlN quantum wells for deep ultraviolet emitters," Appl. Phys. Lett., vol. 114, no. 10, Art. no. 102101, 2019, doi: 10.1063/1.5087543.

[21] S. M. Islam, K. Lee, J. Verma, V. Protasenko, S. Rouvimov, S. Bharadwaj, H. (Grace) Xing, and D. Jena, "MBE-grown 232–270 nm deep-UV LEDs using monolayer thin binary GaN/AlN quantum heterostructures," Appl. Phys. Lett., vol. 110, Art. no. 041108, 2017, doi: 10.1063/1.4975068.

[22] Q. Zhou, J. Song, K. Sun, Y. Sun, S. Liu, and S. Zhou, "Recent progress in III-Nitride tunnel junction light-emitting diodes," Phys. Status Solidi RRL, vol. 17, no. 12, Art. no. 2300413, 2023, doi: 10.1002/pssr.202300413.

[23] K. Nagata, T. Matsubara, Y. Saito, K. Kataoka, T. Narita, K. Horibuchi, et al., "A review on the progress of AlGaN tunnel homojunction structures," Crystals, vol. 13, no. 3, Art. no. 524, 2023, doi: 10.3390/crystals13030524.

[24] S. Zhou et al., "High-Power AlGaN-Based Ultrathin Tunneling Junction Deep-UV Light Emitting Diodes," Laser Photon. Rev., vol. 18, no. 3, Art. no. 2300464, 2024, doi: 10.1002/lpor.202300464.

[25] Y. Guo, J. Dai, H. Zhang, H. Zhao, and J. Zhang, "Enhancing the light extraction of AlGaN-based ultraviolet light-emitting diodes by using nano-patterned sapphire substrates and highly transparent p-AlGaN contact layers," J. Nanophotonics, vol. 12, no. 4, Art. no. 043510, 2018, doi: 10.1117/1.JNP.12.043510.

[26] X. Li, N. Pant, S. I. Rahman, R. Armitage, S. Rajan, E. Kioupakis, and D. Feezell, "Impact of quantum well thickness on efficiency loss in c-plane InGaN/GaN LEDs: Challenges for thin-well designs," Appl. Phys. Lett., vol. 126, no. 13, Art. no. 132102, 2025, doi: 10.1063/5.0258108.